Annual Report 2023

Jožef Stefan Institute, Ljubljana, Slovenia

Annual Report 2023

Jožef Stefan Institute, Ljubljana, Slovenia

Jožef Stefan Institute

Annual Report 2023

CONTENTS

INTRODUCTION

A BRIEF HISTORY OF THE JOŽEF STEFAN INSTITUTE

1946

~ Decision taken by the Slovenian Academy of Science and Arts to establish a Physics Institute

1949

~ Research connected to the peaceful use of atomic energy started, financed by the Federal Government

1952

~ Institute renamed the Jožef Stefan Physics Institute and moved to new laboratories on its present site

1954

~ The betatron and an electron microscope installed as the institute's first major pieces of equipment

1956

~ Van de Graaff accelerator, constructed at the institute, started operation

1958

~ Institute reorganised and new fields of activity defined: nuclear physics, solid-state physics, chemistry, and radiobiology

1959

~ Institute renamed the Jožef Stefan Nuclear Institute. The major source of income was provided by the Yugoslav Atomic Energy Commission

Mass spectrometer at the JSI (about 1960)

1962

~ One of the first compounds of a noble gas, XeF_6, synthesised at the institute

~ The first computer for research, ZUSE Z23, installed

1966

~ Nuclear research reactor TRIGA starts operation

1968

~ Yugoslav Atomic Energy Commission ceases to operate; The Republic of Slovenia becomes the institute's dominant source of research funding

1969

~ Institute is renamed as the Jožef Stefan Institute

1970

~ University of Ljubljana becomes a co-founder of the Jožef Stefan Institute, together with the Federal Executive Council

1971

~ A new unit, INOVA, established with the aim of applying the institute's expertise and output to productive use in the national economy

Institute buildings after the opening in 1953

1972

~ New computer Cyber 72 purchased, and the Republic Computer Centre established as an independent unit of the Jožef Stefan Institute

1974

~ Collaboration with the international centre CERN in the field of high-energy physics started

~ SEPO group for evaluating environmental interventions is established

1976

~ First Yugoslav 8-bit processor computer DARTA 80

1979

~ Contract defining cooperation between the Jožef Stefan Institute and the Nuclear Power Plant Krško is signed

~ First robot in Slovenia is constructed

1982

~ Ecological Laboratory with Mobile Unit established as a special unit of the Slovenian Civil Protection Organisation

1983

~ Stefin, a cysteine proteinase inhibitor named after Jožef Stefan, isolated and its primary structure determined

The Reactor Centre, Podgorica, built in 1966

1985

~ "2000 New Young Researchers" project established by the Slovenian Research Council

~ Centre for Hard Coatings established by the Jožef Stefan Institute and the firm SMELT

The beginnings of robotics at the JSI, in 1985

1987

~ INEA established by the Jožef Stefan Institute as an independent company to promote technology transfer in the fields of cybernetics and energy management

1989

~ Milan Čopič Nuclear Training Centre established

1990

~ The first Slovenian supercomputer, CONVEX, installed at the Jožef Stefan Institute

1992

~ New technology centres established by the Ministry of Science and Technology

~ Jožef Stefan Institute restructured by the Slovenian Government as a public research institution

~ Jožef Stefan Technology Park founded, later to become the Ljubljana Technology Park

1995

~ Jožef Stefan Institute is a co-founder of the international postgraduate school for environmental sciences, the Nova Gorica Polytechnic

~ Research institutes in Velenje, ERICo and Valdoltra established by the Institute

1997

~ 3.5-MeV electrostatic accelerator, TANDETRON, installed

1999

~ Jožef Stefan Institute celebrates its 50th anniversary

2004

~ Jožef Stefan International Postgraduate School established

~ Jožef Stefan Institute is chosen as the coordinator of four Research Centres of Excellence

2007

~ Nanomanipulation of single atoms using low-temperature scanning tunneling microscope

~ New ERDA/RBS beamline installed at the TANDETRON accelerator at the Microanalytical center

2013

~ First ERC Grant awarded to researcher at JSI

2015

~ New research infrastructure, including new and renovated laboratory and office space with high-tech instrumentation for environmental research

2020

~ International Research Centre for Artificial Intelligence was established under the auspices of UNESCO

~ Center for Technology Transfer and Innovation spearheaded Innovation Fund initiative resulting in funding for six successful JSI research projects to increase the technology TRL

High-tech instrumentation for environmental research at the JSI in 2015

FORMER DIRECTORS

Prof. Anton Peterlin,
first Director of the Jožef Stefan Institute

Prof. Anton Peterlin, Founder and first Director of the Jožef Stefan Institute, 1949–1955

Karol Kajfež, 1955–1958

Lucijan Šinkovec, B. Sc., 1959–1963

Prof. Milan Osredkar, 1963–1975

Prof. Boris Frlec, 1975–1984

Prof. Tomaž Kalin, 1984–1992

Prof. Danilo Zavrtanik, 1992–1996

Prof. Vito Turk, 1996–2005

Prof. Jadran Lenarčič, 2005–2020

Jožef Stefan Institute

ORGANISATION OF THE JOŽEF STEFAN INSTITUTE

BOARD OF GOVERNORS

DIRECTOR

SCIENTIFIC COUNCIL

RESEARCH DEPARTMENTS

Physics

Theoretical Physics (F-1)
Prof. Jernej Fesel Kamenik
Low and Medium Energy Physics (F-2)
Prof. Primož Pelicon
Thin Films and Surfaces (F-3)
Prof. Miha Čekada
Surface Engineering (F-4)
Prof. Alenka Vesel
Solid State Physics (F-5)
Prof. Denis Arčon
Gaseous Electronics (F-6)
Prof. Uroš Cvelbar
Complex Matter (F-7)
Prof. Dragan Dragoljub Mihailović
Reactor Physics (F-8)
Prof. Luka Snoj
Experimental Particle Physics (F-9)
Prof. Borut Paul Kerševan

Chemistry and Biochemistry

Inorganic Chemistry and Technology (K-1)
Asst. Prof.Gašper Tavčar

Physical and Organic Chemistry (K-3)
Prof. Ingrid Milošev

Electronic Ceramics (K-5)
Prof. Barbara Malič

Nanostructured Materials (K-7)
Prof. Sašo Šturm

Synthesis of Materials (K-8)
Prof. Darko Makovec

Advanced Materials (K-9)
Prof. Matjaž Spreitzer

Biochemistry, Molecular and Structural Biology (B-1)
Prof. Boris Turk
Molecular and Biomedical Sciences (B-2)
Prof. Igor Križaj
Biotechnology (B-3)
Prof. Boris Rogelj
Environmental Sciences (O-2)
Prof. Milena Horvat

Electronics and Information Technology

Automation, Biocybernetics and Robotics (E-1)
Prof. Aleš Ude
Systems and Control (E-2)
Asst. Prof. Gregor Dolanc
Artificial Intelligence (E-3)
Prof. Dunja Mladenić
Open Systems and Networks (E-5)
Asst. Prof. Tomaž Klobučar
Communication Systems (E-6)
Prof. Mihael Mohorčič
Computer Systems Department (E-7)
Prof. Gregor Papa
Knowledge Technologies (E-8)
Prof. Sašo Džeroski
Intelligent Systems (E-9)
Prof. Matjaž Gams

Reactor Techniques and Energetics

Reactor Engineering (R-4)
Prof. Leon Cizelj

CENTRES

Reactor Centre (RIC) *Prof. Borut Smodiš* **Networking Infrastructure Centre (NIC)** *Dr. Jan Jona Javoršek* **Science Information Centre (SIC)** *Dr. Luka Šušteršič* **Energy Efficiency Centre (EEC)** *Stane Merše, M. Sc.* **Centre for Knowledge Transfer in Information Technologies (CT-3)** *Mitja Jermol, M. Sc.* **Milan Čopič Nuclear Training Centre (ICJT)** *Dr. Igor Jenčič* **Centre for Electron Microscopy and Microanalysis (CEMM)** *Prof. Miran Čeh* **Smart Cities and Communities Centre (CSC & C)** *Dr. Nevenka Cukjati* **Center Factory of the Future (CFoF)** *Asst. Prof. Igor Kovač* **Microanalytical Instrumental Centre (MIC)** *Prof. Primož Pelicon* **Combined Atomic Microscope (UHV-AFM/STM)** *Prof. Maja Remškar*	**Helium Liquifier with Superconducting Magnet and Helium Regeneration System** *Prof. Janez Dolinšek* **Mass Spectrometry Centre** *Dr. Dušan Žigon* **National Centre for Microstructure and Surface Analysis** *Prof. Miran Čeh* **National Centre for High-Resolution NMR Spectroscopy** *Prof. Janez Dolinšek* **Centre for Protein Structure** *Prof. Dušan Turk* **Nanolithography and Nanoscopy** *Prof. Dragan Dragoljub Mihailović* **For Experimental Particle Physicis in International Laboratories** *Prof. Marko Mikuž* **Hot Cells Facility** *Prof. Borut Smodiš* **Video-Conferencing Centre** *Dr. Dušan Gabrijelčič*

ADMINISTRATION, SERVICES AND SUPPORT UNITS

Administration and Services

Legal and Personnel (U-2) *Tamara Kotnik, LL. B.* **Purchasing Department (U-3)** *Dejan Ratković, B. Sc.* **Finance and Accounting (U-4)** *Regina Gruden, M. Sc.* **Service for Business Informatics (U-5)** *Jože Kašman, B. Sc.* **International Project Office (U-6)** *Marja Mali, M. Sc.* **Office for substantive project support, technology transfer and innovation (U-7)** *Dr. Levin Pal[1], Robert Blatnik[2], M. Sc.* **Office for industrial liaison (U-8)** *France Podobnik, B. Sc.*	**Office for project informatics, organization of thematic events and conferences (U-9)** *Marjeta Trobec, M. Sc.* **Technical Services (TS)** *Aleš Cesar, B. Sc.* ## Support Units **Radiation Protection Unit (SVPIS)** *Matjaž Stepišnik, M. Sc.* **Quality Assurance (QA)** *Dr. Andrej Prošek* **Workshops** *Matjaž Nimac*

PARTICIPATION IN THE REGIONAL DEVELOPMENT OF RESEARCH

Ljubljana Technology Park Ltd.

University of Nova Gorica

Jožef Stefan International Postgraduate School

Technology Centres

Nanotesla Institute Ljubljana

Development Centre for Hydrogen Technologies

Technology Centre for Production Automation, Robotics and Informatics (ARI)

Centres of Excellence

Nanocenter - Center of Excellence in Nanoscience and Nanotechnology

Centre of Excellence for Integrated Approaches in Chemistry and Biology of Proteins (CIPKeBiP)

Centre of Excellence NAMASTE

Centre of Excellence for Polymer Materials and Technologies (PoliMaT)

EN-FIST Centre of Excellence

CEBIC Centre of Excellence for Biosensors, Instrumentation and Process Control

CO NOT: Centre of Excellence for Low-Carbon Technologies

Centre of Excellence for Space Sciences and Technologies SPACE-SI

[1] until 30 June 2023   [2] since 1 July 2023

MANAGEMENT

DIRECTORATE

Director JSI
Prof. Boštjan Zalar

Assistant Directors
Dr. Romana Jordan, for EU Affairs
Dr. Špela Stres, MBA, LLM, for evaluation and quality

Adviser
Marta Slokan, LL. B.

SCIENTIFIC COUNCIL

Prof. Boris Turk, *President*
Prof. Denis Arčon, *Deputy President since 26. 01. 2023*
Prof. Leon Cizelj
Prof. Miran Čeh
Prof. Sašo Džeroski, *Deputy President*
Prof. Svjetlana Fajfer, *until 26.01.2023*
Prof. Milena Horvat
Prof. Borut Paul Kerševan, *since 26. 01. 2023*
Asst. Prof. Tomaž Klobučar, *since 26. 01. 2023*
Prof. Anton Kokalj, *since 26. 01. 2023*
Prof. Matej Lipoglavšek

BOARD OF GOVERNORS

Dr. Mark Pleško, *Chair, Cosylab, d. d., Ljubljana*
Dr. Gregor Kramberger, *JSI*
Prof. Ingrid Milošev, *Deputy Chair*
Janez Novak, *RLS, d.o.o.*
Peter Sterle, *Ministry of Higher Education, Science and Innovation*
Dr. Jernej Štromajer, *Ministry for Economic Development and Technology, until 08.05. 2023*
Prof. Aleš Švigelj, *JSI*
Vojmir Urlep, M. Sc.
Tanja Vertelj, *M. Sc., Ministry of Higher Education, Science and Innovation*

Dr. Mitja Luštrek, *until 26.01.2023*
Prof. Barbara Malič
Prof. Dragan Dragoljub Mihailovič, *until 26.01.2023*
Prof. Mihael Mohorčič, *until 26.01.2023*
Prof. Igor Muševič, *Deputy President until 26.01.2023*
Prof. Gregor Papa, *since 26. 01. 2023*
Asst. Prof. Gašper Tavčar, *until 26.01.2023*
Prof. Aleš Ude
Prof. Boštjan Zalar, *Director*
Prof. Rok Žitko, *since 26. 01. 2023*

INTERNATIONAL ADVISORY BOARD

Prof. Robert Huber, *Nobel Prize Winner*, Max-Planck-Institut, Martiensried, Germany
Prof. Ernst Günther Afting, GSF, Neuherberg, Germany
Prof. Akito Arima, Riken, Tokyo, Japan
Prof. John H. Beynon, University of Wales Swansea, Swansea, United Kingdom
Prof. Richard Brook, EPSRC, Swindon, United Kingdom
Prof. Julio Celis, Aarhus University, Aarhus, Denmark
Prof. Brian Clark, Aarhus University, Aarhus, Denmark
Prof. Børge Diderichsen, Novo Nordisk, Bagsvaerd, Denmark
Prof. Jean Etourneau, Institut de Chimie de la Matière Condensée de Bordeaux, CNRS, Pessac, France
Prof. Reinosuke Hara, Seiko Instruments, Tokyo, Japan
Prof. Oleg Jardetzky, Stanford University, Stanford, California, USA

Prof. Sergey P. Kapitza, Russian Academy of Sciences, Moscow, Russia
Prof. Karl-Hans Laermann, Bergische Universität, Wuppertal, Germany
Prof. Egon Matijević, Clarkson University, Potsdam, New York, USA
Prof. Federico Mayor, Madrid, Spain
Prof. Dietrich Munz, Universität Karlsruhe, Karlsruhe, Germany
Prof. Günther Petzow, Max-Planck-Institut für Metallforschung, Stuttgart, Germany
Prof. Bernard Roth, Stanford University, Stanford, California, USA
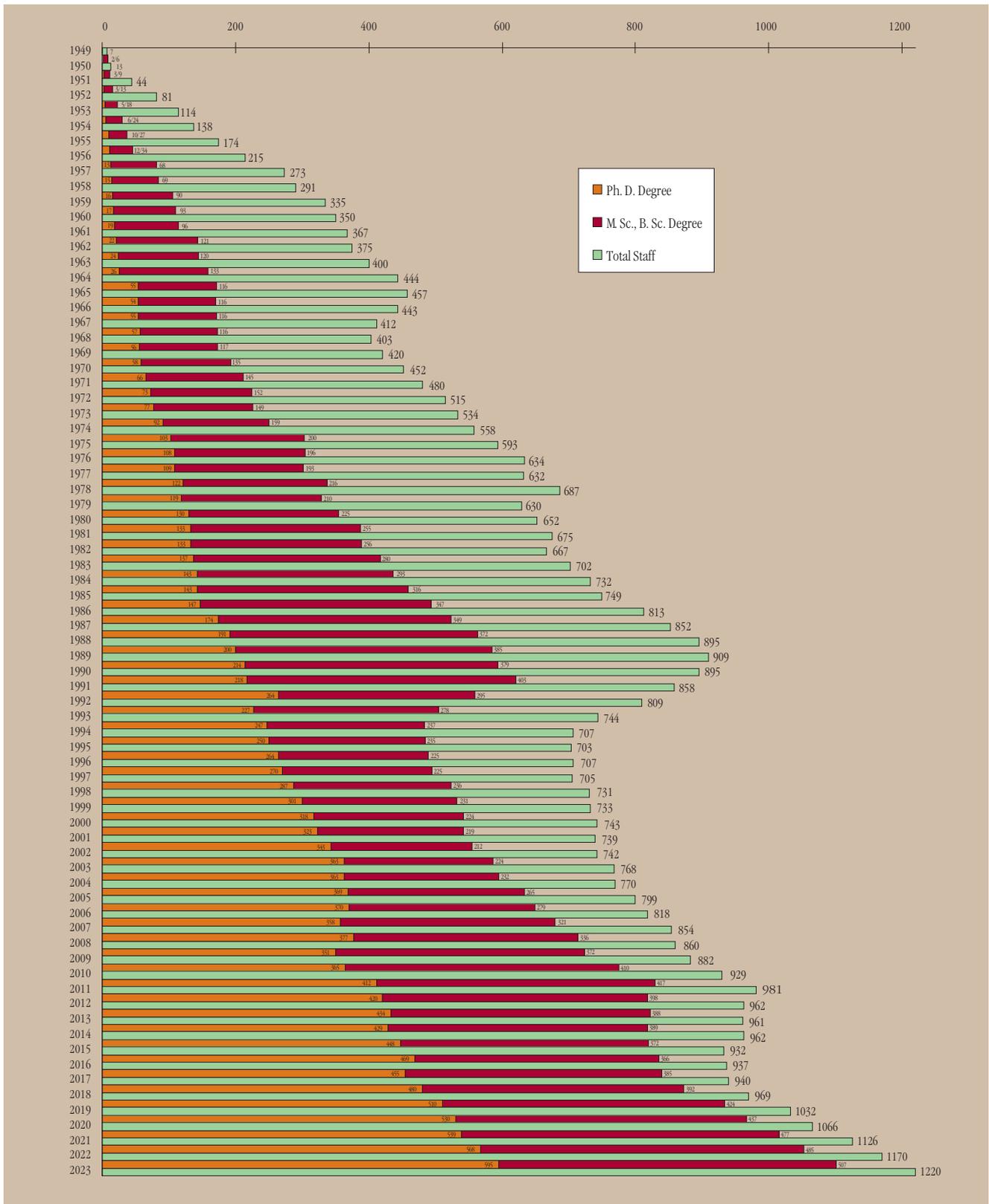Prof. John Ryan, University of Oxford, Oxford, United Kingdom
Prof. Volker Sörgel, Ruprecht-Karis-Universität, Heidelberg, Germany
Prof. H. Eugene Stanley, Boston University, Boston, Massachusetts, USA
Prof. Thomas Walcher, Universität Mainz, Mainz, Germany

STAFF QUALIFICATIONS

1949-2023

RECIPIENTS OF THE JSI AWARDS AND TITLES

HONORARY MEMBERS

Prof. Robert Blinc⊕, President of the Scientific Council of the Jožef Stefan Institute from 1992 to 2007 (1933 - 2011)

Prof. Jean-Marie Dubois, Institut Jean Lamour, CNRS - Centre National de la Recherche Scientifique, Paris and Université Lorraine, Nancy, France

Prof. Boris Frlec, Director of the Jožef Stefan Institute from 1975 to 1984

Prof. Robert Huber, Nobel Prize Winner, Max-Planck-Institut für Biochemie, Munich, Germany

Prof. Milan Osredkar⊕, Director of the Jožef Stefan Institute from 1963 to 1975 (1919 - 2003)

Prof. Anton Peterlin⊕, Founder and First Director of the Jožef Stefan Institute from 1949 to 1955 (1908 - 1993)

Prof. Vito Turk, Director of the Jožef Stefan Institute from 1996 to 2005

ASSOCIATE MEMBERS

Prof. David C. Ailion, University of Utah, Salt Lake City, Utah, USA

Prof. Neil Bartlett⊕, University of California, Berkeley, California, USA

Prof. John H. Beynon, University of Wales Swansea, Swansea, United Kingdom

Prof. Wolfram Bode, Max-Planck-Institut für Biochemie, Munich, Germany

Prof. Oscar D. Bonner⊕, University of South Carolina, Columbia, South Carolina, USA

Dr. Horst Borrmann, Max-Planck-Institut für chemische Physik fester Stoffe, Dresden, Germany

Prof. Henrik Buchowsky, Politechnika Warszawska, Warszawa, Poland

Prof. Rüdiger Dillmann, Karlsruher Institut für Technologie, Karlsruhe, Germany

Prof. Joseph W. Doane, Liquid Crystal Institute, Kent State University, Kent, Ohio, USA

Prof. Hans Fritz, Universität München, Munich, Germany

Prof. Oskar Glemser⊕, Universität Göttingen, Göttingen, Germany

Prof. Paul Hagenmuller⊕, Université de Bordeaux I, Bordeaux, France

Prof. John Holloway, University of Leicester, Leicester, United Kingdom

Prof. Rudolf Hoppe⊕, Universität Giessen, Giessen, Germany

Prof. Robert J. Jaeger⊕, National Institute on Disability and Rehabilitation Research, US Department of Education, Washington, D. C., USA

Prof. Nikola Kallay⊕, University of Zagreb, Zagreb, Croatia

Prof. Nobuhiko Katunuma, Tokushima Bunri University, Tokushima, Japan

Prof. Raymond Kind, ETH, Zurich, Switzerland

Prof. Jože Koller, University of Ljubljana, Faculty of Chemistry and Chemical Technology, Ljubljana, Slovenia

Prof. Rüdiger Mews, Universität Bremen, Bremen, Germany

Prof. Donald Michie⊕, Edinburgh University, Edinburgh, United Kingdom

Dr. Fani Milia, National Centre for Scientific Research "Demokritos", Athens, Greece

Prof. Tsuyoshi Nakajima, Aichi Institute of Technology, Toyota, Japan

Prof. Vincenzo Parenti - Castelli, University of Bologna, Bologna, Italy

Prof. Herbert W. Roesky, Universität Göttingen, Göttingen, Germany

Prof. John A. Rupley, The University of Arizona, Tucson, Arizona, USA

Prof. Findlay E. Russell, The University of Arizona, Tucson, Arizona, USA

Prof. Hugo V. Schmidt, Montana State University, Bozeman, Montana, USA

Prof. Lev A. Shuvalov⊕, Institute for Crystallography, Russian Academy of Sciences, Moscow, Russia

Prof. Neil W. Tanner⊕, University of Oxford, Oxford, United Kingdom

Dr. Alain Tressaud, Institut de Chimie de la Matière Condensée de Bordeaux, CNRS, Pessac, France

Prof. Vlado Valković, Zagreb, Croatia

Prof. John Waugh, M.I.T., Cambridge, Massachusetts, USA

EMERITUS SCIENTISTS

Prof. France Bremšak⊕

Prof. Mihael Drofenik

Prof. Peter Gosar⊕

Prof. Darko Jamnik⊕

Prof. Gorazd Kandus

Prof. Gabrijel Kernel

Prof. Borut Mavko

Prof. Miodrag V. Mihailović⊕

Prof. Raša Matija Pirc

Prof. Marjan Senegačnik⊕

Prof. Saša Svetina

Prof. Boštjan Žekš

Prof. Boris Žemva⊕

EXTERNAL ADVISORS

Prof. Savo Bratoš, Université Pierre et Marie Curie, Paris, France

Marko Bulc⊕, B. Sc., Ljubljana, Slovenia

Prof. Davorin Dolar⊕, Slovenian Academy of Sciences and Arts, Ljubljana, Slovenia

Zdravko Gabrovšek, B. Sc., Slovenia

Prof. Dušan Hadži⊕, National Institute of Chemistry, Ljubljana, Slovenia

Prof. Karl A. Müller⊕, *Nobel Prize Winner*, IBM Research Laboratory, Zurich, Switzerland

Prof. Bogdan Povh, Max-Planck-Institut für Kernphysik, Heidelberg, Germany

Dr. Lev Premrú⊕, Lek, d. d., Ljubljana, Slovenia

Prof. Momčilo M. Ristić⊕, Academy of Science of Serbia, Belgrade, Serbia

Milan Slokan⊕, M. Sc., Ljubljana, Slovenia

Prof. dr. Petar Strohal⊕, Zagreb, Croatia

Dr. Novak Zuber⊕, Nuclear Regulatory Commission, Washington D. C., USA

Prof. Črt Zupančič⊕, Ludwig-Maximillians-Universität, Munich, Germany

Prof. Andrej Župančič⊕, Slovenian Academy of Sciences and Arts, Ljubljana, Slovenia

INTERNATIONAL COOPERATION

Multilateral international cooperation	No. of projects
HORIZON EUROPE (HE, EDF, EIT) AND HORIZON EUROPE - EURATOM	72
H2020 (EUROPEAN INSTITUTE OF INNOVATION AND TECHNOLOGY, EXCELLENT SCIENCE, INDUSTRIAL LEADERSHIP, SOCIETAL CHALLENGES, SPREADING EXCELLENCE AND WIDENING PARTICIPATION, SCIENCE WITH AND FOR SOCIETY) AND H2020 - EURATOM	72
ESRR AND ESI (RR, ADRION, NM & EGP, INTERREG, EKS, ESTS)	7
OTHER INTERNATIONAL AND EU PROJECTS (COST, IAEA, ICTP, JRC, ESA, CEF, EMPIR, ERASMUS+, LIFE+,...)	114
INTERNATIONAL MARKETING PROJECTS	23
OTHER PROJECTS (CERN, KEK, UNESCO, CEA,...)	89
TOTAL	**377**

Bilateral cooperation	No. of projects
Austria	4
Germany	3
France	7
Croatia	7
India	4
Japan	2

Bilateral cooperation	No. of projects
Montenegro	2
Serbia	13
Turkey	1
USA	29
TOTAL	**72**

INTERNATIONAL COOPERATION AGREEMENT

In 2023, international cooperation agreement was signed between the Jožef Stefan Institute and Institute of Physics Belgrade, Serbia.

ERC PROJECTS

1. HE - DrumS; Weakly Driven Quantum Symmetries
   Dr. Zala Lenarčič (F-1)
2. H2020 - Cell-Lasers; Intracellular Lasers: Coupling of Optical Resonances with Biological Processes
   Asst. Prof. Matjaž Humar (F-5)
3. H2020 - LOGOS; Light-Operated Logic Circuits from Photonic Soft-Matter
   Prof. Igor Muševič (F-5)
4. H2020 - FAIME; Flavour Anomalies with advanced particle Identification MEthods
   Prof. Peter Križan (F-9)
5. HE - CherPET; Cherenkov Light for Total-Body Positron Emission Tomography
   Prof. Peter Križan (F-9)
6. H2020 - HiPeR-F; Challenging the Oxidation-State Limitations of the Periodic Table via High-Pressure Fluorine Chemistry
   Asst. Prof. Matic Lozinšek (K-1)

Jožef Stefan Institute

COOPERATION WITH HIGHER-EDUCATION ESTABLISHMENTS

FULL-TIME FACULTY MEMBERS

Professors

1. **Prof. Denis Arčon**, University of Ljubljana, Faculty of Mathematics and Physics
2. **Prof. Iztok Arčon**, University of Nova Gorica
3. **Asst. Prof. Rok Bojanc**, University of Primorska, Faculty of Mathematics, Natural Sciences and Information Technologies
4. **Prof. Janez Bonča**, University of Ljubljana, Faculty of Mathematics and Physics
5. **Asst. Prof. Marko Bračko**, University of Ljubljana, Faculty of Mathematics and Physics; University of Maribor, Faculty of Chemistry and Chemical Engineering
6. **Prof. Dean Cvetko**, University of Ljubljana, Faculty of Mathematics and Physics
7. **Prof. Mojca Čepič**, University of Ljubljana, Faculty of Education
8. **Asst. Prof. Rok Dolenec**, University of Ljubljana, Faculty of Mathematics and Physics
9. **Prof. Janez Dolinšek**, University of Ljubljana, Faculty of Mathematics and Physics
10. **Prof. Irena Drevenšek Olenik**, University of Ljubljana, Faculty of Mathematics and Physics
11. **Prof. Boštjan Golob**, University of Ljubljana, Faculty of Mathematics and Physics
12. **Prof. Ke Guan**, Beijing Jiaotong University, Beijing, China
13. **Prof. Tomaž Gyergyek**, University of Ljubljana, Faculty of Electrical Engineering
14. **Prof. Polona Jaki Mekjavić**, University of Ljubljana, Medical Faculty
15. **Asst. Prof. Branko Kavšek**, University of Primorska, Faculty of Mathematics, Natural Sciences and Information Technologies
16. **Prof. Borut Paul Kerševan**, University of Ljubljana, Faculty of Mathematics and Physics
17. **Asst. Prof. Jure Kokalj**, University of Ljubljana, Faculty of Civil and Geodetic Engineering
18. **Prof. Samo Korpar**, University of Maribor, Faculty of Chemistry and Chemical Engineering
19. **Prof. Janko Kos**, University of Ljubljana, Faculty of Pharmacy
20. **Prof. Samo Kralj**, University of Maribor, Faculty of Education
21. **Prof. Peter Križan**, University of Ljubljana, Faculty of Mathematics and Physics
22. **Prof. Zoran Levnajić**, Faculty of Information Studies, Novo mesto
23. **Prof. Andrej Lipej**, University of Novo mesto, Faculty of Mechanical Engineering
24. **Asst. Prof. Maciej Matyka**, University of Wrocław, Wrocław, Poland
25. **Prof. Marko Mikuž**, University of Ljubljana, Faculty of Mathematics and Physics
26. **Prof. Matija Milanič**, University of Ljubljana, Faculty of Mathematics and Physics
27. **Prof. Igor Muševič**, University of Ljubljana, Faculty of Mathematics and Physics
28. **Asst. Prof. Natan Osterman**, University of Ljubljana, Faculty of Mathematics and Physics
29. **Asst. Prof. Veljko Pejović**, University of Ljubljana, Faculty of Computer and Information Science
30. **Prof. Uroš Petrovič**, University of Ljubljana, Biotechnical Faculty
31. **Asst. Prof. Tomaž Podobnik**, University of Ljubljana, Faculty of Mathematics and Physics
32. **Asst. Prof. Paula Pongrac**, University of Ljubljana, Biotechnical Faculty
33. **Prof. Saša Prelovšek Komelj**, University of Ljubljana, Faculty of Mathematics and Physics
34. **Prof. Anton Ramšak**, University of Ljubljana, Faculty of Mathematics and Physics
35. **Asst. Prof. Tomaž Rejec**, University of Ljubljana, Faculty of Mathematics and Physics

36. **Prof. John Shawe-Taylor**, University College London, Centre for Computational Statistics and Machine Learning, London, UK
37. **Asst. Prof. Urban Simončič**, University of Ljubljana, Faculty of Mathematics and Physics
38. **Asst. Prof. Lea Spindler**, University of Maribor, Faculty of Mechanical Engineering
39. **Asst. Prof. Andrej Studen**, University of Ljubljana, Faculty of Mathematics and Physics
40. **Prof. Simon Širca**, University of Ljubljana, Faculty of Mathematics and Physics
41. **Asst. Prof. Primož Škraba**, Queen Mary University of London, London, UK
42. **Prof. Borut Štrukelj**, University of Ljubljana, Biotechnical Faculty and Faculty of Pharmacy
43. **Prof. Ivan Tomašić**, Mälardalen University, Västerås, Sweden
44. **Prof. Nataša Vaupotič**, University of Maribor, Faculty of Natural Sciences and Mathematics
45. **Prof. Katarina Vogel-Mikuš**, University of Ljubljana, Biotechnical Faculty
46. **Prof. Danilo Zavrtanik**, University of Nova Gorica
47. **Prof. Primož Ziherl**, University of Ljubljana, Faculty of Mathematics and Physics
48. **Asst. Prof. Dejan Žontar**, University of Ljubljana, Faculty of Health Sciences

Assistants and researchers

1. **Dr. Jurij Leskovec**, Stanford University, Palo Alto, California, USA
2. **Dr. Jure Pražnikar**, University of Primorska, Faculty of Mathematics, Natural Sciences and Information Technologies, Koper
3. **Dr. Jan Šuntajs**, University of Novo mesto, Faculty of Mechanical Engineering
4. **Dr. Lara Ulčakar**, University of Ljubljana, Faculty of Mathematics and Physics

PART-TIME FACULTY MEMBERS

Professors

1. **Prof. Jan Babič**, University of Ljubljana, Faculty of Electrical Engineering and IPS
2. **Prof. Andreja Benčan Golob**, IPS, Ljubljana
3. **Prof. Aleš Berlec**, University of Ljubljana, Faculty of Pharmacy
4. **Asst. Prof. Anton Biasizzo**, IPS, Ljubljana
5. **Prof. Vid Bobnar**, IPS, Ljubljana
6. **Prof. Marko Bohanec**, University of Nova Gorica, School of Enginnering and Management and IPS, Ljubljana
7. **Prof. dr. Biljana Mileva Boshkoska**, Faculty of Information Studies, Novo mesto
8. **Asst. Prof. Klemen Bučar**, University of Ljubljana, Faculty of Mathematics and Physics and IPS, Ljubljana
9. **Prof. Leon Cizelj**, University of Ljubljana, Faculty of Mathematics and Physics
10. **Prof. Uroš Cvelbar**, IPS, Ljubljana
11. **Prof. Miran Čeh**, University of Ljubljana, Faculty of Chemistry and Chemical Technology and IPS, Ljubljana
12. **Prof. Miha Čekada**, IPS, Ljubljana
13. **Asst. Prof. Nina Daneu**, IPS, Ljubljana
14. **Prof. Marko Debeljak**, IPS, University of Ljubljana, University of Nova Gorica
15. **Asst. Prof. Tadej Debevec**, University of Ljubljana, Faculty of Sport
16. **Asst. Prof. Matjaž Depolli**, University of Novo mesto, Faculty of Mechanical Engineering
17. **Asst. Prof. Gregor Dolanc**, Faculty of Industrial Engineering, Novo mesto,

18. **Asst. Prof. Goran Dražić**, IPS, Ljubljana
19. **Prof. Jean-Marie Dubois**, IPS, Ljubljana
20. **Prof. Sašo Džeroski**, IPS, Ljubljana, University of Ljubljana, Faculty of Computer and Information Science
21. **Prof. Borka Džonova Jerman Blažič**, IPS, Ljubljana
22. **Asst. Prof. Tome Eftimov**, University of Ljubljana, School of Economics and Business
23. **Prof. Tomaž Erjavec**, IPS, Ljubljana
24. **Prof. Svjetlana Fajfer**, University of Ljubljana, Faculty of Mathematics and Physics
25. **Asst. Prof. Ingrid Falnoga**, University of Ljubljana, Faculty of Maritime Studies and Transport, Biotechnical Faculty
26. **Prof. Jernej Fesel Kamenik**, University of Ljubljana, Faculty of Mathematics and Physics
27. **Prof. Andrej Filipčič**, University of Nova Gorica, School of Applied Sciences
28. **Prof. Bogdan Filipič**, University of Ljubljana, Faculty of Computer and Information Science, University of Nova Gorica, Faculty of Engineering and Management, IPS, Ljubljana
29. **Prof. Marko Fonović**, IPS, Ljubljana
30. **Asst. Prof. Andrej Gams**, IPS, Ljubljana
31. **Prof. Matjaž Gams**, University of Ljubljana, Faculty of Computer and Information Science, IPS, Ljubljana
32. **Prof. Marko Gerbec**, IPS, Ljubljana
33. **Asst. Prof. Evgeny Goreshnik**, IPS, Ljubljana
34. **Asst. Prof. Anton Gradišek**, University of Ljubljana, Faculty of Mathematics and Physics
35. **Asst. Prof. Sašo Gyergyek**, University of Maribor, Faculty of Chemistry and Chemical Engineering
36. **Prof. Ester Heath**, University of Ljubljana, Faculty of Pharmacy, Faculty of Chemistry and Chemical Engineering, Faculty of Mechanical Engineering, Faculty of Civil and Geodetic Engineering, Biotechnical Faculty, Faculty of Health Sciences; University of Nova Gorica, School of Environmental Sciences and IPS, Ljubljana
37. **Prof. Milena Horvat**, IPS, Ljubljana, University of Maribor, Faculty of Mechanical Engineering
38. **Prof. Andrej Hrovat**, IPS, Ljubljana
39. **Prof. Tomaž Javornik**, IPS, Ljubljana
40. **Prof. Robert Jeraj**, University of Ljubljana, Faculty of Mathematics and Physics, University of Wisconsin, School of Medical Physic, Madison
41. **Asst. Prof. Ita Junkar**, IPS, Ljubljana
42. **Prof. Đani Juričić**, University of Nova Gorica, Faculty of Engineering and Management, IPS, Ljubljana
43. **Prof. Viktor Kabanov**, IPS, Ljubljana
44. **Asst. Prof. Matjaž Kavčič**, IPS, Ljubljana
45. **Asst. Prof. Ivo Kljenak**, University of Ljubljana, Faculty of Mathematics and Physics
46. **Asst. Prof. Tomaž Klobučar**, IPS, Ljubljana, DOBA Faculty of Applied Business and Social Studies, Maribor, Faculty of Commercial and Business Sciences, Celje
47. **Prof. Spomenka Kobe**, IPS, Ljubljana
48. **Prof. Juš Kocijan**, University of Nova Gorica, School of Engineering and Management and IPS, Ljubljana
49. **Prof. Andraž Kocjan**, University of Ljubljana, Faculty of Natural Sciences and Engineering, Faculty of Medicine, IPS, Ljubljana
50. **Asst. Prof. Robert Kocjančič**, IPS, Ljubljana
51. **Prof. Ivan Aleksander Kodeli**, University of Maribor, Faculty of Energy Technology
52. **Prof. Anton Kokalj**, IPS, Ljubljana
53. **Asst. Prof. Matej Andrej Komelj**, University of Ljubljana, Faculty of Mathematics and Physics
54. **Asst. Prof. Boštjan Končar**, University of Ljubljana, Faculty of Mathematics and Physics
55. **Prof. Nataša Kopitar Jerala**, IPS, Ljubljana
56. **Prof. Dušan Kordiš**, University of Ljubljana, Biotechnical Faculty, Faculty of Chemistry and Chemical Technology, Medical Faculty, IPS, Ljubljana
57. **Prof. Barbara Koroušić Seljak**, IPS, Ljubljana
58. **Asst. Prof. Tina Kosjek**, University of Ljubljana, Faculty of Pharmacy, Faculty of Chemistry and Chemical Engineering, Faculty of Mechanical Engineering, Faculty of Civil and Geodetic Engineering, Biotechnical Faculty, Faculty of Health Sciences; University of Nova Gorica, School of Environmental Sciences and IPS
59. **Prof. Nejc Košnik**, University of Ljubljana, Faculty of Mathematics and Physics
60. **Asst. Prof. Igor Kovač**, Fachhochschule Joaneum, Graz, Austria
61. **Prof. Janez Kovač**, University of Ljubljana, Faculty of Natural Sciences and Engineering and IPS, Ljubljana
62. **Asst. Prof. Petra Kralj Novak**, Central European University, Vienna, Austria
63. **Asst. Prof. Slavko Kralj**, University of Ljubljana, Faculty of Pharmacy
64. **Prof. Igor Križaj**, University of Ljubljana, Faculty of Chemistry and Chemical Technology, Biotechnical Faculty, Medical Faculty, IPS, Ljubljana
65. **Asst. Prof. Marjan Kromar**, University of Maribor, Faculty of Energy Technology
66. **Prof. Danjela Kuščer Hrovatin**, IPS, Ljubljana
67. **Prof. Zdravko Kutnjak**, University of Ljubljana, Faculty of Mathematics and Physics and Faculty of Mechanical Engineering, IPS, Ljubljana
68. **Prof. Nada Lavrač**, University of Nova Gorica, IPS, Ljubljana, University of Ljubljana
69. **Asst. Prof. Adrijana Leonardi**, University of Ljubljana, Biotechnical Faculty
70. **Asst. Prof. Luka Leskovec**, University of Ljubljana, Faculty of Mathematics and Physics
71. **Prof. Darja Lisjak**, University of Nova Gorica, School of Science and IPS, Ljubljana
72. **Prof. Sonja Lojen**, University of Nova Gorica, School of Environmental Sciences, IPS, Ljubljana
73. **Prof. Boris Majaron**, University of Ljubljana, Faculty of Mathematics and Physics
74. **Prof. Darko Makovec**, University of Maribor, Faculty of Chemistry and Chemical Engineering and Faculty of Medicine, IPS, Ljubljana
75. **Prof. Barbara Malič**, IPS, Ljubljana
76. **Asst. Prof. Sabina Markelj**, IPS, Ljubljana
77. **Prof. Igor Mekjavić**, Simon Fraser University, British Columbia, Canada
78. **Asst. Prof. Alenka Mertelj**, University of Ljubljana, Faculty of Mathematics and Physics and IPS, Ljubljana
79. **Asst. Prof. Tomaž Mertelj**, University of Ljubljana, Faculty of Mathematics and Physics
80. **Prof. Dragan Dragoljub Mihailović**, University of Ljubljana, Faculty of Mathematics and Physics and IPS, Ljubljana
81. **Asst. Prof. Andrej Mihelič**, University of Ljubljana, Faculty of Mathematics and Physics
82. **Asst. Prof. Miha Mihovilovič**, University of Ljubljana, Faculty of Mathematics and Physics, Johannes Gutenberg Universität, Mainz, Germany
83. **Prof. Radmila Milačič**, IPS, Ljubljana
84. **Prof. Ingrid Milošev**, University of Zagreb, Croatia, Faculty of Chemical Engineering and Technology and IPS, Ljubljana
85. **Asst. Prof. Ana Mitrović**, University of Ljubljana, Faculty of Pharmacy
86. **Prof. Dunja Mladenić**, IPS, Ljubljana and University of Zagreb, Croatia, University of Ljubljana, Faculty of Education, University of Nova Gorica, University of Primorska, Koper
87. **Prof. Mihael Mohorčič**, IPS, Ljubljana
88. **Asst. Prof. Helena Motaln**, University of Ljubljana, Biotechnical Faculty
89. **Prof. Miran Mozetič**, IPS, Ljubljana
90. **Asst. Prof. Jernej Mravlje**, University of Ljubljana, Faculty of Mathematics and Physics
91. **Asst. Prof. Bojan Nemec**, IPS, Ljubljana
92. **Prof. Miha Nemevšek**, University of Ljubljana, Faculty of Mathematics and Physics
93. **Asst. Prof. Roman Novak**, IPS, Ljubljana
94. **Prof. Saša Novak Krmpotič**, IPS, Ljubljana
95. **Prof. Nives Ogrinc**, IPS, Ljubljana
96. **Asst. Prof. Mojca Otoničar**, IPS, Ljubljana

97. **Asst. Prof. Panče Panov**, Faculty of Information Studies, Novo mesto; IPS, Ljubljana
98. **Prof. Gregor Papa**, IPS, Ljubljana
99. **Asst. Prof. Matija Perne**, Faculty of Industrial Engineering, Novo mesto
100. **Prof. Rok Pestotnik**, University of Ljubljana, Faculty of Mathematics and Physics
101. **Prof. Toni Petan**, University of Ljubljana, Biotechnical Faculty, Faculty of Chemistry and Chemical Technology, IPS, Ljubljana
102. **Prof. Maja Ponikvar-Svet**, IPS, Ljubljana
103. **Prof. Peter Prelovšek**, University of Ljubljana, Faculty of Mathematics and Physics
104. **Asst. Prof. Gregor Primc**, IPS, Ljubljana
105. **Prof. Jože Pungerčar**, University of Ljubljana, Faculty of Medicine, IPS, Ljubljana
106. **Prof. Matthew Purver**, Queen Mary University of London, School of Electronic Engineering & Computer Science
107. **Asst. Prof. Aleksandra Rashkovska Koceva**, Faculty of Information Studies in Novo mesto
108. **Prof. Aleksander Rečnik**, IPS, Ljubljana
109. **Prof. Maja Remškar**, IPS, Ljubljana
110. **Asst. Prof. Peter Rodič**, IPS, Ljubljana
111. **Prof. Boris Rogelj**, University of Ljubljana, Faculty of Chemistry and Chemical Technology, Faculty of Pharmacy, Faculty of Medicine, Biotechnical Faculty
112. **Prof. Tadej Rojac**, University of Ljubljana, Faculty of Natural Sciences and Engineering, IPS, Ljubljana
113. **Prof. Igor Serša**, University of Ljubljana, Faculty of Natural Sciences and Engineering, IPS, Ljubljana
114. **Prof. Borut Smodiš**, IPS, Ljubljana
115. **Prof. Luka Snoj**, University of Ljubljana, Faculty of Mathematics and Physics and Virginia Tech University, USA
116. **Prof. Matjaž Spreitzer**, University of Ljubljana, Faculty of Chemistry and Chemical Technology; IPS, Ljubljana
117. **Prof. Veronika Stoka**, IPS, Ljubljana
118. **Asst. Prof. Luka Šantelj**, University of Ljubljana, Faculty of Mathematics and Physics
119. **Prof. Janez Ščančar**, IPS, Ljubljana
120. **Asst. Prof. Srečo Davor Škapin**, IPS, Ljubljana
121. **Prof. Miha Škarabot**, University of Ljubljana, Faculty of Chemistry and Chemical Technology and Faculty of Mathematics and Physics
122. **Asst. Prof. Zdenka Šlejkovec**, IPS, Ljubljana
123. **Prof. Janez Štrancar**, University of Ljubljana, Faculty of Pharmacy, University of Maribor, Faculty of natural sciences and mathematics and IPS, Ljubljana
124. **Prof. Sašo Šturm**, IPS, Ljubljana
125. **Prof. Aleš Švigelj**, IPS, Ljubljana
126. **Asst. Prof. Gašper Tavčar**, IPS, Ljubljana
127. **Prof. Iztok Tiselj**, University of Ljubljana, Faculty of Mathematics and Physics
128. **Prof. Andrej Trkov**, University of Ljubljana, Faculty of Mathematics and Physics and University of Maribor, Faculty of Energy Technology
129. **Prof. Boris Turk**, University of Ljubljana, Biotechnical Faculty, Faculty of Chemistry and Chemical Technology and IPS, Ljubljana
130. **Prof. Dušan Turk**, University of Ljubljana, Faculty of Chemistry and Chemical Technology and Faculty of Medicine and IPS, Ljubljana
131. **Asst. Prof. Livija Tušar**, University of Maribor, Faculty of Agriculture and Life Sciences
132. **Asst. Prof. Tea Tušar**, IPS, Ljubljana, University of Trieste, Trieste
133. **Prof. Aleš Ude**, University of Ljubljana, Faculty of Electrical Engineering and IPS
134. **Asst. Prof. Mitja Uršič**, University of Ljubljana, Faculty of Mathematics and Physics
135. **Asst. Prof. Hana Uršič Nemevšek**, IPS, Ljubljana
136. **Prof. Olga Vasiljeva**, IPS, Ljubljana
137. **Prof. Janja Vaupotič**, University of Nova Gorica and IPS, Ljubljana
138. **Asst. Prof. Matjaž Vencelj**, University of Ljubljana, Faculty of Mathematics and Physics and IPS, Ljubljana
139. **Prof. Alenka Vesel**, IPS, Ljubljana
140. **Prof. Lev Vidmar**, University of Ljubljana, Faculty of Mathematics and Physics
141. **Asst. Prof. Mojca Vilfan**, University of Ljubljana, Faculty of Mathematics and Physics
142. **Asst. Prof. Damir Vrančić**, Faculty of Industrial Engineering, Novo mesto, IPS, Ljubljana; University of Applied Sciences, Campus 02, Graz, Austria
143. **Prof. Boštjan Zalar**, IPS, Ljubljana
144. **Asst. Prof. Rok Zaplotnik**, IPS, Ljubljana
145. **Prof. Marko Zavrtanik**, University of Nova Gorica
146. **Prof. Aleksander Zidanšek**, University of Maribor, Faculty of Education and IPS
147. **Asst. Prof. Benjamin Zorko**, IPS, Ljubljana
148. **Asst. Prof. Kristina Žagar Soderžnik**, IPS, Ljubljana
149. **Asst. Prof. Bernard Ženko**, Faculty of Information studies Novo mesto, Faculty of Industrial Engineering Novo mesto, IPS, Ljubljana
150. **Prof. Eva Žerovnik**, IPS, Ljubljana
151. **Prof. Rok Žitko**, University of Ljubljana, Faculty of Mathematics and Physics
152. **Prof. Matjaž Žitnik**, University of Ljubljana, Faculty of Mathematics and Physics
153. **Asst. Prof. Leon Žlajpah**, IPS, Ljubljana
154. **Asst. Prof. Martin Žnidaršič**, Faculty of Industrial Engineering, Novo mesto; IPS
155. **Prof. Slobodan Žumer**, University of Ljubljana, Faculty of Mathematics and Physics
156. **Prof. Kristina Žužek Rožman**, IPS, Ljubljana

Assistants and researchers

1. **Dr. Tilen Brecelj**, University of Ljubljana, Faculty of Mathematics and Physics
2. **Dr. Martin Draksler**, University of Ljubljana, Faculty of Mathematics and Physics
3. **Dr. Samir El Shawish**, University of Ljubljana, Faculty of Mathematics and Physics
4. **Dr. Blaž Fortuna**, IPS, Ljubljana
5. **Dr. Denis Golež**, University of Ljubljana, Faculty of Mathematics and Physics
6. **Dr. Dejan Gradišar**, University of Ljubljana, Faculty of Electrical Engineering; Faculty of Industrial Engineering, Novo mesto
7. **Dr. Radojko Jaćimović**, IPS, Ljubljana
8. **Dr. Peter Jeglič**, University of Ljubljana, Faculty of Mathematics and Physics
9. **Dr. Petra Jenuš**, IPS, Ljubljana
10. **Dr. Matej Kanduč**, University of Ljubljana, Faculty of Mathematics and Physics
11. **Dr. Martin Klanjšek**, University of Ljubljana, Faculty of Mathematics and Physics
12. **Dr. Dragi Kocev**, IPS, Ljubljana
13. **Dr. Janez Kokalj**, University of Ljubljana, Faculty of Mathematics and Physics
14. **Dr. Matej Krajnc**, University of Ljubljana, Faculty of Mathematics and Physics
15. **Dr. Igor Lengar**, University of Maribor, Faculty of Energy Technology
16. **Dr. Mitja Luštrek**, IPS, Ljubljana
17. **Dr. Aljaž Osojnik**, University of Ljubljana, Faculty of Mathematics and Physics
18. **Dr. Matej Petković**, University of Ljubljana, Faculty of Mathematics and Physics
19. **Dr. Senja Pollak**, IPS, Ljubljana
20. **Dr. Andrej Prošek**, University of Ljubljana, Faculty of Mathematics and Physics
21. **Dr. Vladimir Radulović**, University of Ljubljana, Faculty of Mathematics and Physics
22. **Dr. Adam Rambousek**, Faculty of Informatics, Masaryk University, Brno, Czech Republic
23. **Dr. Jošt Stergar**, University of Ljubljana, Faculty of Mathematics and Physics
24. **Dr. Špela Stres**, University of Ljubljana, Faculty of Electrical Engineering
25. **Dr. Andrej Šali**, IPS, Ljubljana
26. **Dr. Jelena Vesić**, University of Ljubljana, Faculty of Mathematics and Physics
27. **Dr. Darko Vrečko**, University of Nova Gorica, School of Environmental Sciences
28. **Dr. Andrej Zorko**, University of Ljubljana, Faculty of Chemistry and Chemical Technology and Faculty of Mathematics and Physics
29. **Dr. Andrej Žohar**, University of Ljubljana, Faculty of Mathematics and Physics

IPS: Jožef Stefan International Postgraduate School, Ljubljana

FINANCING

REVENUES JSI (€) AND NUMBER OF PROJECTS

| | Contribution | | Contribution | | | No. of Projects |
	2023	2023	2022	2022	Index 2023/2022	in 2023
National Agencies and Ministries	61,741,973	75.6 %	54,148,283	74.1 %	114.0	490
National Market	5,297,258	6.5 %	5,660,661	7.8 %	93.6	323
International Market	13,709,253	16.8 %	13,070,884	17.9 %	104.9	249
Other Revenues	958,108	1.2 %	146,524	0.2 %	653.9	
TOTAL	**81,706,592**	**100.0 %**	**73,026,352**	**100.0 %**	**111.9**	**1062**

Revenues 2021/2022 (€M))
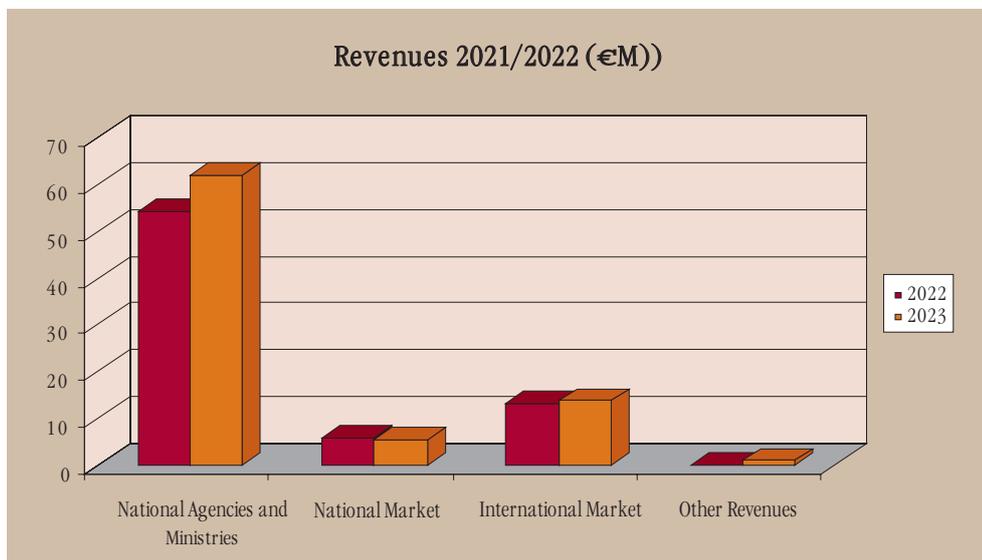
POSTGRADUATES FINANCED   1985-2023

by Slovenian Research Agency
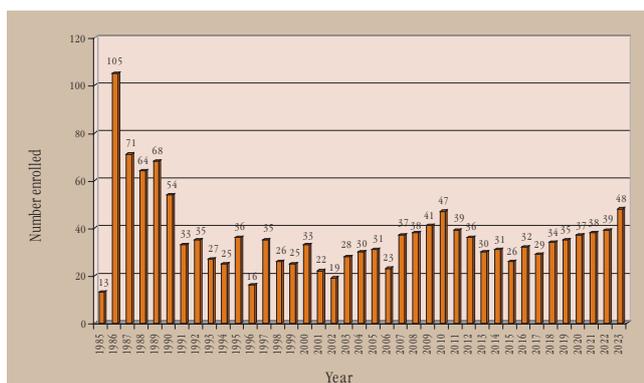
JSI UNDERGRADUATE SCHOLARSHIPS

1977-2023

Year	FMF		FKKT UNI LJ	FKKT UNI MB	NTF	FDV	FA	BF	FE and FRI	Other UNI LJ	FG and FERI	UNG	IPS	Total
	Physics	Mathematics												
... 1990	268	80	155					6	206	21	5			741
1991	23	2	9					2	24	2	1			63
1992	22	3	16					3	17	1				62
1993	21	1	15					3	13	1				54
1994	7	1	8					3	6					25
1995	2		9					3	5					19
1996	2		9					3	5					19
1997	2		12					1	4		1			20
1998	1		6					1	7		1			16
1999	2		7					4	7					20
2000	1		5					3	9					18
2001	3		13					3	10					29
2002	4		20					3	10					37
2003	3		18					2	12	1				36
2004	4		17					1	15	1	2	2		42
2005	3		12			1		2	19		2	1		40
2006	2		12			1		1	17		2	2		37
2007	3		14			1		2	18		2	1		41
2008	2	1	13	3		1		2	15		1	1		39
2009	2	1	17	4		1		5	16		1	2		49
2010	2		11	5	2	1	1	3	10		1	2	5	43
2011	2	1	11	5	4	1	1	4	7		1		6	43
2012	2		10	6	3	1		3	6				5	36
2013	3	2	3	2	1		1		2	2			6	22
2014	14	6	3		2		1		3	2			1	32
2015	21	6	4		1				9	1			10	52
2016	16	2	5						7	1			15	46
2017	11	2	4					2	7				12	38
2018	9	3	5					2	6	1	1		7	34
2019	16	1	5						7		1		12	42
2020	17	1	4						5	1			8	36
2021	19		3						5	1			6	34
2022	15	2	2						4	1			4	28
2023	10	3	2		1				3	3			2	24
TOTAL	534	118	459	25	14	8	4	67	516	40	22	11	99	1917

FMF	Faculty of Mathematics and Physics, University of Ljubljana	FE	Faculty of Electrical Engineering, University of Ljubljana
FKKT (Uni-Lj)	Faculty of Chemistry and Chemical Technology, University of Ljubljana	FRI	Faculty of Computer and Information Science, University of Ljubljana
FKKT (Uni-Mb)	Faculty of Chemistry and Chemical Technology, University of Maribor	FG	Faculty of Civil Engineering, University of Maribor
NTF	Faculty of Natural Sciences and Engineering, University of Ljubljana	FERI	Faculty of Electrical Engineering and Computer Science, University of Maribor
FDV	Faculty of Social Sciences, University of Ljubljana	UNG	University of Nova Gorica
FA	Faculty of Administration, University of Ljubljana	IPS	Jožef Stefan International Postgraduate School
BF	Biotechnical Faculty, University of Ljubljana	Other UNI LJ	Faculty of Pharmacy, Faculty of Mechanical Engineering, Faculty of Economics, Faculty of Medicine, University of Ljubljana

Jožef Stefan Institute

PATENTS GRANTED

1. Luiz A. DaSilva, Jernej Hribar, Method and system for energy aware scheduling for sensors, US 11,762,446 B2, US Patent Office, 19. 9. 2023

2. Primc, Gregor, Zaplotnik, Rok, Mozetič, Miran, Filipić, Arijana, Gutiérrez-Aguirre, Ion, Dobnik, David, Dular, Matevž, Petkovšek, Martin, Method and device for disinfection of liquid, US11,807,555 (B2), United States Patent and Trademark Office, 7. 11. 2023

3. Matjaž Lukač, Franci Bajd, Marko Kazič, Zdenko Vižintin, Tadej Perhavec, Apparatus and method for tissue regeneration, US 11,648,417 B2, US Patent Office, 16. 5. 2023

4. Aswathy Vasudevan, Gregor Filipič, Janez Zavašnik, Uroš Cvelbar, Method for in-situ synthesis and deposition of metal oxide nanoparticles with atmospheric pressure plasma, EP 3 960 703 B1, European Patent Office, 7. 6. 2023

5. Dragan Mihailović, Damjan Svetin, Anže Mraz, Rok Venturini, Memory device and method for its operation, EP 3 881 365 B1, European Patent Office, 11. 1. 2023

6. Adam Krzyszrof Budniak, Piotr J. Leszczyński, Zoran Mazej, Wojciech Rafal Grochala, Sposób oksydatywnego sprzęgania cząsteczek węglowodorów posiadających atomy węgla podstawione wodorem, PL 243170 B1, Urząd patentowy Rzeczypospolitej Polskiej, 10. 7. 2023

ART EXHIBITIONS AT THE JSI

Luka Širok, 9. January–9. February

Drago Metljak, 13. February–16. March

Nande Vidmar, 20. March–20. April

Silva Karim, 24. April–11. May

Matjaž Stopar, 15. May–8. June

Karmen Bajec, 12. June–6. July

Andrejka Čufer, 17. July–3. August

Leonida Goropevšek, 7. August–7. September

Franc Golob, 11. September–5. October

Dominik Olmiah Križan, 9. October–2. November

Marjan Verč, 6.–30. November

Janez Boljka, 11. December–11. January 2024
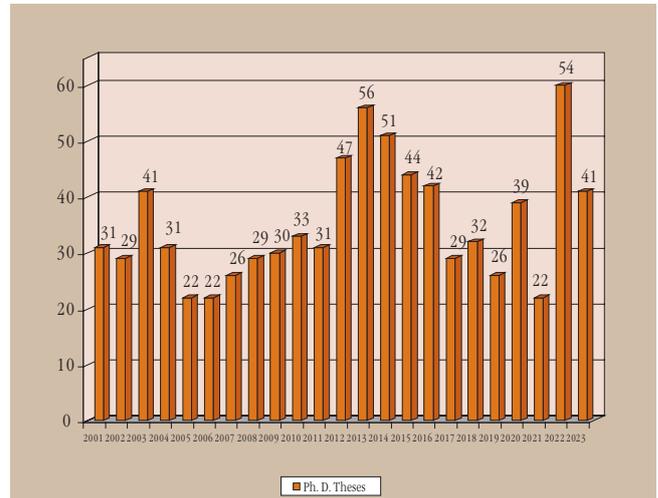

Franc Golob at the opening of his exhibition

Jožef Stefan Institute

REVIEW OF PUBLICATIONS

FOR 2023

Department	Original Articles*	Books	Patent Appl. and Grants	Ph. D. Theses
Department of Theoretical Physics (F-1)	67	1		2
Department of Low and Medium Energy Physics (F-2)	64			1
Department of Thin Films and Surfaces (F-3)	18			
Department of Surface Engineering and Optoelectronics (F-4)	52		2	2
Department of Solid State Physics (F-5)	107	2	4	5
Department of Gaseous Electronics (F-6)	26	1	1	1
Department for Complex Matter (F-7)	59		2	3
Department of Reactor Physics (F-8)	94			1
Department of Experimental Particle Physics (F-9)	210			3
Department of Inorganic Chemistry and Technology (K-1)	28		2	
Department of Physical and Organic Chemistry (K-3)	20			1
Electronic Ceramics Department (K-5)	47			1
Department for Nanostructured Materials (K-7)	43			
Department for Synthesis of Materials (K-8)	29		1	1
Department for Advanced Materials (K-9)	38			3
Department of Biochemistry, Molecular and Structural Biology (B-1)	19		1	3
Department of Molecular and Biomedical sciences (B-2)	10			1
Department of Biotechnology (B-3)	21			1
Department of Environmental Sciences (O-2)	87	1		3
Department of Automation, Biocybernetics and Robotics (E-1)	55		1	4
Department of Systems and Control (E-2)	22		1	1
Artificial Intelligence Laboratory (E-3)	25	1		
Laboratory for Open Systems and Networks (E-5)	10			
Department of Communication Systems (E-6)	31	2	1	1
Computer Systems Department (E-7)	20			2
Department of Knowledge Technologies (E-8)	51			
Department of Intelligent Systems (E-9)	20	1		
Department of Reactor Engineering (R-4)	15			1
Reactor Infrastructure Centre (RIC)	2			
Energy Efficiency Centre (EEC)	2	3	1	
Centre for Electron Microscopy and Microanalysis (CEMM)	8			
Centre for Knowledge Transfer in Information Technologies (CT-3)	1			
Centre Factories of the Future (CFOF)	4			
Jožef Stefan Institute	1198	10	16	41

* Articles in Journals and Conference Proceedings, and Chapters in Books

COMPLETED THESES

UNTIL 2023

Year	Ph. D. Theses
...2001	591
2002	29
2003	41
2004	31
2005	22
2006	22
2007	26
2008	29
2009	30
2010	33
2011	31
2012	47

Year	Ph. D. Theses
2013	56
2014	51
2015	44
2016	42
2017	29
2018	32
2019	26
2020	39
2021	22
2022	**54**
2023	**41**
TOTAL	1368

AWARDS AND APPOINTMENTS

AWARDS MADE TO JSI RESEARCHERS BY THE REPUBLIC OF SLOVENIA

Zois and Puh Awards and Zois Certificate of Recognition

Danilo Zavrtanik
Presented with the Zois Lifetime Achievement Award in the field of physics and astrophysics of elementary particles

Uroš Cvelbar
Presented with the Zois Certificate of Recognition for outstanding achievements in plasma physics

Igor Križaj
Presented with the Zois Award for outstanding achievements in toxinology

JSI AWARDS AND APPOINTMENTS

Blinc Award

Svjetlana Fajfer
Blinc Award for lifetime achievements in physics

Tomaž Prosen
Blinc award for outstanding achievement in physics

Lev Vidmar
Blinc Award for physicist at the beginning of their career

The winners of Zois Awards: Prof. Igor Križaj, Prof. Danilo Zavrtanik and Prof. Uroš Cvelbar

The Jožef Stefan Golden Emblem Prize

presented to the following for doctoral theses with high impact :

Neelakandan Marath Santhosh
Plasma-Enabled Design of Hybrid Carbon Nanostructures for Energy Storage Applications

Arijana Filipić
Inactivation of viruses in water by cold atmospheric plasma

Bojan Hiti
Radiation hardness of CMOS detector prototypes for ATLAS Phase-II ITk upgrade

OTHER SELECTED AWARDS TO JSI RESEARCHERS

The CitieS-Health Project received an Honorary Mention in the European Union Citizen Science Award in Linz, Austria, September 2023.

Khaled Al-Athel, **Abdulaziz Alyamani**, **Mohanad Alzahrani**, **Jan Kren**, **Blaž Mikuž**, **Afaque Shams**, Best poster award (3rd price) for "Experimental investigation of heating a turbulent flow in a square duct using a heated foil", International Conference on Nuclear Power Engineering-SCOPE, Dhahran, Saudi Arabia.

Adna Alilović received the ERASS prize in the Specialty Section Award, Chemical Risk Assessment Research category, at the EUROTOX 2023 conference for her research on methyl mercury after ingesting tuna in Ljubljana, September 2023.

Andrejaana Andova, **Tobias Benecke**, **Harald Ludwig**, **Tea Tušar**, Best poster award at EvoStar 2023, Brno, Czech Republic, 12–14 April 2023, paper "Towards constructing a suite of multi-objective optimization problems with diverse landscapes"

Eirini Andreasidou won 1st Place in the Science Slam of the ISO-FOOD Symposium: From Food Source to Health in Portorož, Slovenia, April 2023.

Eirini Andreasidou was the winner of the Public Engagement Activity Competition at the FoodTraNet Summer School 2 in Almeria, Spain, June 2023.

Marko Bohanec won the best paper award at the conference CECIIS 2023 for the paper Inter- and intra-personal differences, and consistency of decision rules, in multi-criteria modelling method DEX: a preliminary study.

Tina Černič, Krka's award, Novo mesto, 20 October 2023

Mirela Dragomir, **Mojca Otoničar**, **Tadej Rojac**, "Edward C. Henry Award" for outstanding contribution published in the Journal of the American Ceramic Society, Awards and scholarships committee of the Journal of the American Ceramic Society

Bojan Evkoski received the Best Student Paper award for his paper 'XAI in Computational Linguistics: Understanding Political Orientations in the Slovenian Parliament' at LTC23 in Poznan, Poland, which is based on the ParlaMint corpus.

Bogdan Filipič, **Tea Tušar**, **Aljoša Vodopija**, **Jordan Cork**, **Peter Korošec** and the company **MAHLE Electric Drives Slovenija, d. o. o.**, The TARAS award for successful collaboration of the economy and the research and development environment in the field of innovation, development and technology, Industrial forum IRT 2023, Portorož, 12–13 June 2023, project "Development of an electric motor for the automotive industry with an innovative simulation-based optimization procedure"

The winners of the Jožef Stefan Golden Emblem Prize: Dr. Neelakandan Marath Santhosh, Dr. Arijana Filipić and Dr. Bojan Hiti

Bogdan Filipič, Best paper award at the International Technology Transfer Conference, 26th International Multiconference Information Society, IS 2023, Ljubljana, 9–13 October 2023, paper "Randomized optimization: From algorithmic studies to industrial applications"

Tanja Goričanec, Award for Best Young Authors, Portorož, International Conference »32nd International Conference Nuclear Energy for New Europe – NENE 2023,« September 2023, for the paper titled »Intermediate Range Detectors for Control Rod Worth Measurements with Rod Insertion Method,« co-authored with Luka Snoj and Marjan Kromar.

Suraj Gupta, Best Poster Award, Singapore, Singapore, granted by Elsevier at the Materials Today Conference 2023, for poster titled SrTiO3-based two dimensional nanoplatelets for low-cost solar hydrogen generation

Blaž Jaklič, Best student poster presentation, Paris, France, granted by Organizing committee of the International Workshop on the Characterization & Quantification of Lithium

Peter Jeglič and **Erik Zupanič**, Special Prize for Innovations for the Economy, 16th International Technology Transfer Conference (ITTC16), Ljubljana, Slovenia

Polona Klemenčič was awarded the Krka Award for her master thesis on "Exposure to Cadmium in the Slovenian Population" in Novo Mesto, September 2023.

Tilen Knaflič, Award for the poster presentation with the title: Spin-dimer ground state in the mixed-valence compound Rb4O6 as revealed by electron spin resonance The international workshop "Magnetic Resonance of Correlated Electron Materials", Dresden, Germany

Boshko Koloski, **Perdih Stepišnik**, **Timen Robnik**, **Marko Šikonja**, **Senja Pollak**, **Blaž Škrlj**, Excellence in Science 2023 (field of linguistics), awarded by ARIS for "Knowledge graph informed fake news classification via heterogeneous representation ensembles." Neurocomputing, ISSN 0925-2312. Jul. 2022, vol. 496, pp. 208–226.

Mihael Boštjan Končar, **Matej Tekavčič**, **Mitja Uršič**, Prešeren award for MSc thesis "Modelling of severe accidents in sodium-cooled fast nuclear reactors", University of Ljubljana, Slovenia.

Nina Kostevšek is the recipient of the award for the best presentation entitled: "Magneto-Erythrocyte Membrane Vesicles as T2 MRI Contrast Agents" at the lecture "Nanotechnology for Imaging, Sensing and Diagnostics" on the conference

BioNanoMed2023 in Graz, Austria. The award is given by NanoMedicine-Austria and BioNanoNet Forschungsgesellschaft mbH (BNN), Austria.

Ana Kovačič and **Lidija Strojnik** achieved Summa Cum Laude, a prestigious distinction at the Jožef Stefan International Postgraduate School, for their extraordinary academic excellence in Ljubljana, July 2023.

Igor Križaj, Zois Award for outstanding achievements in toxinology. State award in the field of science, research and development, Committee of the Republic of Slovenia for the presentation of prizes and awards for outstanding achievements in science, research and development.

Monika Kušter is the recipient of the award for the best presentation entitled: "Composite material on polymer matrix reinforced with Al-based Quasycristal powder" on the 28th International Conference on Materials and Technology (28 ICM&T) in Portorož. The prize is awarded by the Institute for Metal Materials and Technologies (IMT) from Ljubljana, Slovenia.

Aleš Lapanje and **Tomaž Rijavec** achieved third place in the University of Ljubljana's Rector award for Best Innovation in the Researchers category, recognizing their outstanding work on the GumGuardian project in Ljubljana, October 2023.

Miha Mali, award for the best poster "Development of the BCM' system for beam abort and luminosity monitoring in ATLAS based on a segmented polycrystalline CVD diamond system and dedicated front-end ASIC", Oxford, Great Britain, 8 September 2023

Helena Motaln, **Urša Čerček**, **Boris Rogelj**, Excellent in science 2023, ARIS, for publication Motaln et al. Brain, 2023.Oct 3;146(10):4088-4104. doi: 10.1093/brain/awad130

Klemen Motaln, CCDC prize for the best lecture, 29th Slovenian-Croatian Crystallographic Meeting – SCCM29, june 2023, Topolšica, Slovenia

Sebastjan Nemec, Krka's recognition with special recommendation, Novo mesto, 20 October 2023

Alexandre Nominé, Jaean André Rist Medal, 2023.

Anže Pungerčič, Award for Best Poster, Portorož, International Conference „32nd International Conference Nuclear Energy for New Europe – NENE 2023," September 2023, with the title „Experimental and Computational Validation of Novel Depletion Algorithm in the RAPID Code System using JSI TRIGA reactor," co-authored with Alireza Haghighat and Luka Snoj.

Tina Radošević is the recipient of the award for the best poster presentation with the title: "Photocatalytic degradation of synthetic textile microplastic fibers with TiO2 as

photocatalysts" on the 28th International Conference on Materials and Technology (28 ICM&T) in Portorož. The prize is awarded by the Institute for Metal Materials and Technologies (IMT) from Ljubljana, Slovenia.

Miha Ravnik, Golden Plaque for Outstanding Contribution to the Development of Scientific, Pedagogical, or Artistic Creation and for Strengthening the Reputation of the University of Ljubljana, Ljubljana, Slovenia

Barbara Repič, student award "Alessandro de Vita" at the cross-border workshop for doctoral students in the field of nanoscience and nanotechnology CrossNano 2023, organizing committee CrossNano2023

Peter Rodič mentored several project tasks, which were carried out by high school students and were awarded in various competitions: Mija Kapun and Daniil Gainullov (Jože Plečnik Gymnasium) - 53rd Krka award and silver medal at the ZOTKS competitions; Ela Podboršek and Tim Strnad (Vič Gymnasium) - 53rd Krka award, the gold medal at the Genius Olympics in the USA and gold medal at the international project Olympics Vilnius Interna

Jose Martin Rožanec, Third-best paper at the 16th International technology transfer conference, 16th International Technology Transfer Conference, Fostering Research & Innovation in AI through Regulatory Sandboxes, JSI, Ljubljana

Jerica Sabotič, EBTNA Award for Poster Presentation, Ljubljana, European Biotechnology Congress 2023, poster presentation entitled Diabrotica v. virgifera resists the effect of entomotoxic fungal protease inhibitors in food

Gal Sajko, Prešeren Award for students, Ljubljana, Faculty of Electrical Engineering, University of Ljubljana, A climbing robot spider

Olha Sanko, Award for poster presentation, Slovenian Chemistry Days 2023, September 2023, Portorož, Slovenia

Vasyl Shvalya et al, Bacterial DNA recognition with advanced nanoplasmon sensor, Excellence in Science 2023, 21. 11. 2023, ARIS.

Spase Stojanov, Krka special recognition award for doctoral dissertation »Engineering of fluorescent vaginal Lactobacillus species for their monitoring in nanofibers and cell models«, Novo mesto, Krka d.d.

Cathrine Terro received the award for the best contribution at the 15th Jožef Stefan IPSS Conference in Kamnik, June 2023.

Iztok Tiselj, **Jan Kren**, **Blaž Mikuž**, Best paper award for "Experimental study of isothermal vertical slug flow", International Conference on Nuclear Power Engineering-SCOPE, Dhahran, Saudi Arabia.

Žiga Tkalec and colleagues received Excellent in Science 2023 award for their paper »Suspect and non-targeted screening-based human biomonitoring identified 74 biomarkers of exposure in urine of Slovenian children«, Ljubljana, November 2023

Tea Tušar, **Peter Korošec**, **Bogdan Filipič**, Best paper award at the Slovenian Conference on Artificial Intelligence, 26th International Multiconference Information Society, IS 2023, Ljubljana, 9–13 October 2023, paper »A multi-step evaluation process in electric motor design«

Erik Uran, Award for the best lecture, 29th Slovenian-Croatian Crystallographic Meeting – SCCM29, June 2023, Topolšica, Slovenija

Erik Uran, Award for poster presentation, Solid-State Science & Research meeting – SCIRES 2023, June 2023, Zagreb, Croatia

Anja Vehar was honored with the 10th Saubermacher Environmental Award for the best Master's thesis in the field of energy and the environment, titled "Monitoring the Efficiency of the Removal of Bisphenols from Wastewater in a Municipal Wastewater Treatment Plant" in Kidričevo, May 2023.

Andrej Zorko, APS Robert E.: Marshak Lectureship Award, American Physical Society, United States

Klara Žagar received an award for her contribution at the ISO-FOOD conference for her work on δ18O and δ2H fingerprinting of tap water, Portorož, April 2023.

INSTITUTE COLLOQUIA

January 11, 2023: **Igor Lengar**
Jožef Stefan Institute
Harnessing fusion energy and recent successful experiments

January 25, 2023: **Vladimir Vava Gligorov**
Sorbonne Université, CNRS, France
Coherent test of lepton universality in beauty to strange quark transitions

February 1, 2023: **Igor Serša**
Jožef Stefan Institute
Magnetic resonance microscopy

March 20, 2023: **Frédéric Mila**
Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland
Quantum spin liquids and their experimental realizations

March 21, 2023: **Lukáš Palatinus**
Institute of Physics of the Czech Academy of Sciences, Czech Republic
Crystallography in the 21st century: the age of the electron?

March 22, 2023: **Ester Heath**
Jožef Stefan Institute
Pollutants of concern: the journey from sources to the environment

March 23, 2023: **Nada Lavrač**, Jožef Stefan Institute, and **Marko Robnik-Šikonja**
Faculty of Computer and Information Science, University of Ljubljana
Machine learning from relational and textual data

April 5, 2023: **Miha Čekada**
Jožef Stefan Institute
Hard protective coatings: between science and industry

May 10, 2023: **Philippe Bouyer**
Quantum Quantum Delta NL, University of Amsterdam, Eindhoven University of Technology, Netherlands
Quantum sensors with matter waves

June 14, 2023: **Lev Ioffe**
Google Quantum AI, Google Research, USA
What can we learn from noisy quantum computers right now?

June 21, 2023: **Eduard Llobet Valero**
University of Tarragona, Tarragona, Spain
Gas sensors based on transition-metal dichalgogenides

June 29, 2023: **Thomas G. Dietterich**
Oregon State University, USA
What's wrong with large language models and what we should be building instead

September 20, 2023: **Qiwen Zhan**
University of Shanghai for Science and Technology, China
Dreams about dreams: topology with spatiotemporally sculptured light

September 27, 2023: **Igor Mandić**
Jožef Stefan Institute
Solid-state detectors for future colliders

October 18, 2023: **Andrew J. Bell**
The University of Leeds, United Kingdom
Take it to the limit: a story of piezoelectric materials and devices for extreme conditions

November 22, 2023: **Boris Majaron**
Jožef Stefan Institute and Faculty of Mathematics and Physics, University of Ljubljana
Development of photothermal radiometry techniques for use in biomedicine

November 29, 2023: **Svjetlana Fajfer**
Jožef Stefan Institute and Faculty of Mathematics and Physics, University of Ljubljana
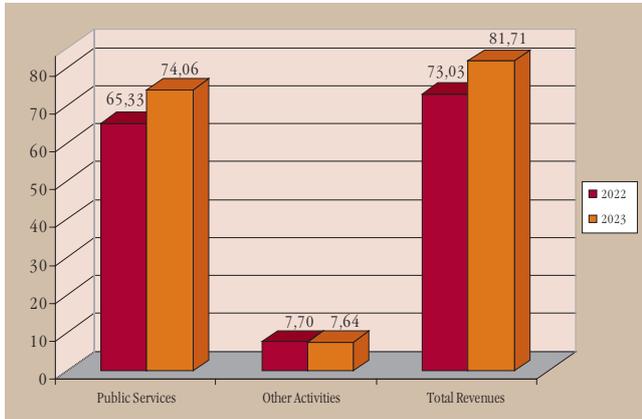***On the way from B meson anomalies to new physics***

December 6, 2023: **Lev Vidmar**
Jožef Stefan Institute and Faculty of Mathematics and Physics, University of Ljubljana
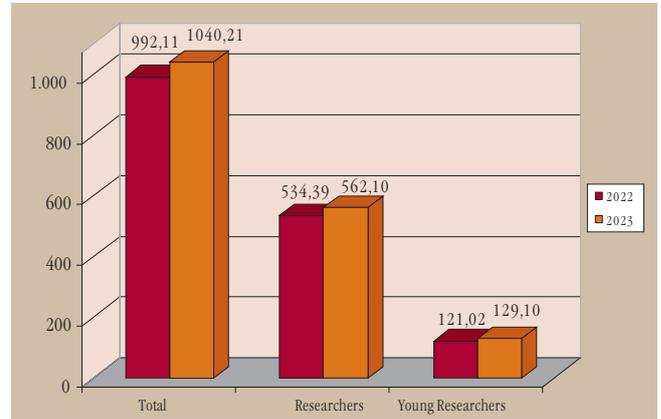***Physics at the edge of chaos***

INSTITUTE IN NUMBERS 2022–2023

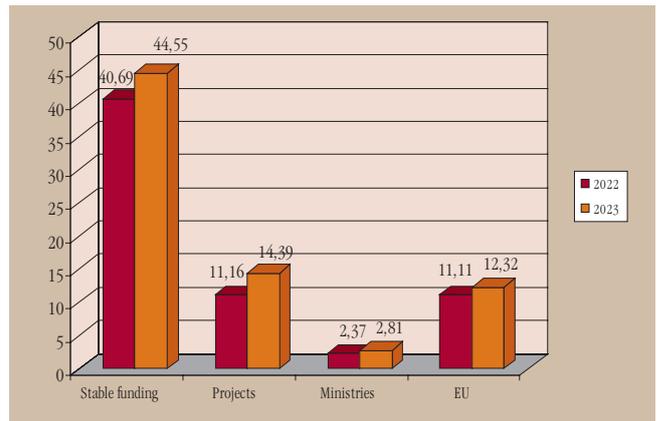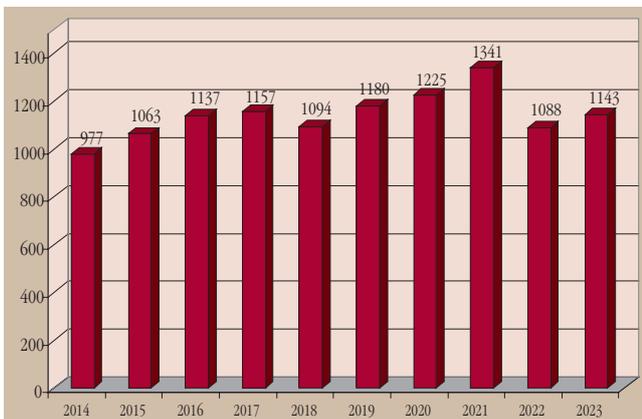## COMPARISON OF REVENUES (€M)

EMPLOYEES (FTE)

REVENUES FROM OTHER ACTIVITIES (€M)

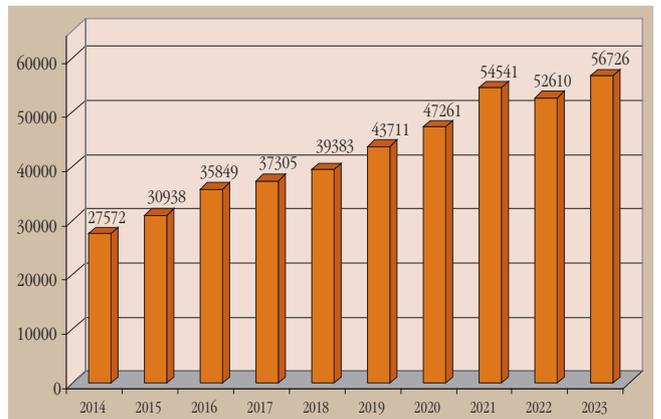## REVENUES FROM PUBLIC SERVICES (€M)

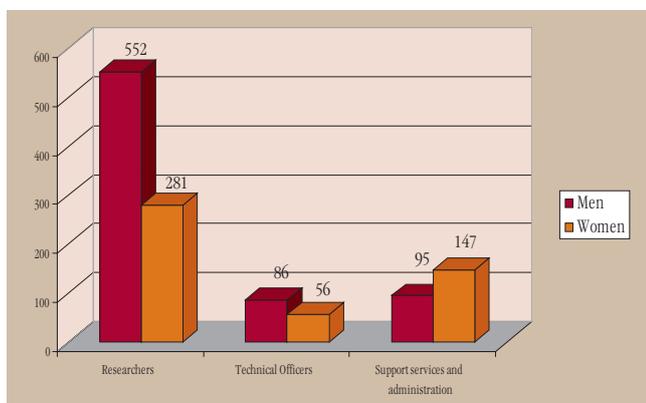## NUMBER OF PUBLICATIONS IN THE WEB OF SCIENCE*

* retrieved 5 November 2025
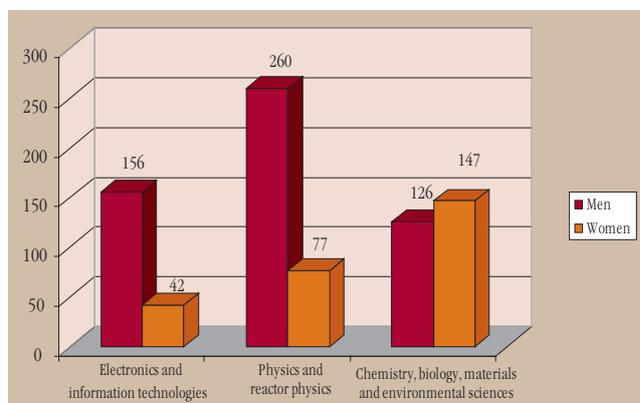
NUMBER OF CITATIONS IN THE WEB OF SCIENCE*

* retrieved 5 November 2025

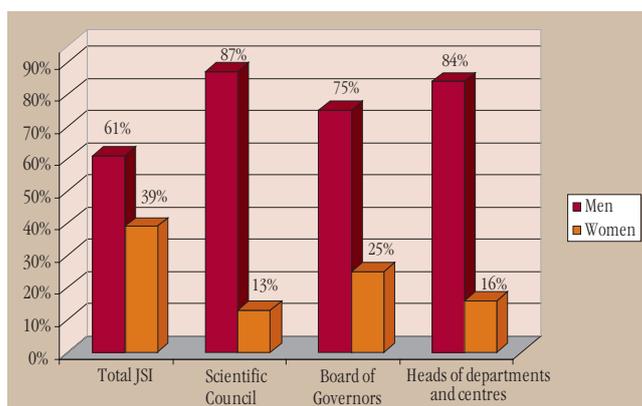# NUMBER OF EMPLOYEES, BY TYPE OF STAFF AND GENDER*

NUMBER OF RESEARCHERS, BY SCIENTIFIC FIELDS AND GENDER*

SHARE OF JSI EMPLOYEES AND MEMBERS OF DECISION-MAKING AND LEADERSHIP BODIES, BY GENDER*

	Number	Male	Female
Scientific council	15	87 %	13 %
Board of governors	8	75 %	25 %
Heads of departments and centres	37	84 %	16 %
JSI TOTAL	**1220**	**61 %**	**39 %**

RESEARCH DEPARTMENTS

DEPARTMENT OF THEORETICAL PHYSICS

F-1

In 2023 members of the program group THEORY OF NUCLEI, ELEMENTARY PARTICLES AND FIELDS continued research in the physics of quark and lepton flavors and CP violation, particle phenomenology at high-energy colliders, a unified theory of gauge interactions, neutrino physics, particle astrophysics and cosmology, as well as research in nuclear and hadron physics using quantum chromodynamics on the lattice, and machine learning in high-energy physics with an emphasis on physics beyond the Standard Model.

Head:
Prof. Jernej Fesel Kamenik

We extended the ab-initio study of doubly heavy tetraquarks to other flavors by adding diquark-antidiquark operators and incorporating effects from the so-called left-hand cut. We calculated how the properties of the doubly charm tetraquark vary with the quark masses. We determined the energy regions where the lattice data for the charmonium-like channel ccud can be reconciled with experimental via the effective field theory. We studied the nontrivial interplay of heavy quark spin symmetry-preserving and breaking effects in the decays of heavy quarkonia that resulted in experimentally observed line shapes. We employed quark model calculations to evaluate chromopolarizabilities of fully heavy baryons, which define the strength of their interactions, and concluded on the possible existence of bound systems composed of two fully heavy baryons. We studied the role of the pion exchange in the doubly charmed tetraquark state Tcc+ and established a potentially important role of the left-hand cut associated with the pion exchange in interpreting lattice data on this and similar near-threshold exotic states.

We derived constraints on left-handed dimension-6 interactions affecting semileptonic and leptonic decays of D mesons, kaons, pions, and nuclear beta decay. Utilizing a flavor covariant description of effective couplings, we identified universal CP phases of New Physics and established constraints based on decay rates and CP-odd quantities. Consequently, we were able to predict the maximum effects of such flavored New Physics in D decays from rigorous K decay constraints and vice versa. We explored CP-violating effects of heavy New Physics in flavor-changing quark dipole transitions within the framework of the Standard Model Effective Field Theory (SMEFT). We established relevant dimension six operators, investigated renormalization group (RG) induced correlations between different flavor-violating processes and electric dipole moments (EDMs), and set bounds on Wilson coefficients of dipole operators at low energies, connecting observable CPV effects at low energies to general NP at high scales. We showed that a time-dependent analysis of rare B and Bs meson decays mediated by b to s nu nu transitions enables the construction of novel observables sensitive to CP-odd phases. We also explored the sensitivity to CP violation in time-integrated measurements with flavor tagging. Using an effective Lagrangian approach, we related the decay widths of $N \rightarrow l\gamma$ to the decay widths of $N \rightarrow l\varpi$. Our result points out factor 10-3 suppression of the decay widths $\Gamma(p \rightarrow l+\gamma)$ and $\Gamma(n \rightarrow \bar{\nu}\gamma)$ compared to the decay widths $\Gamma(p \rightarrow l+\varpi 0)$ and $\Gamma(n \rightarrow \bar{\nu}\varpi 0)$, respectively. This result is independent of the model of new physics. We also studied the production of right-handed WR bosons and heavy neutrinos N at a future 100TeV high-energy hadron collider in the context of the left-right symmetry and found that with 3/ab of the integrated luminosity, the 3 sigma sensitivity extends up to MWR = 35 and 37TeV.

- **A general framework was established for studying near-threshold exotic states with heavy quarks, and analyzing the data provided for such states with the contemporary accelerator experiments and numerical simulations of QCD on the lattice.**
- **We were engaged in the search for new physics in the semi-leptonic decays of D and K mesons, and investigated the mechanisms of nucleon decays into pions and electrons, or photons and leptons.**
- **We have identified the universal new physics complex phase responsible for the CP-violating phenomena in kaon and charm meson decays.**
- **We studied the phase diagram of the E6 grand unified theory with a 650 dimensional scalar field.**
- **We applied statistical inference to the Pierre Auger Open Data to determine the mass composition of cosmic rays across various energy intervals.**
- **We found that a large class of dark-matter models is subject to a stringent cosmological constraint coming from large-scale structure data.**

We found choices of parameters, for which various intermediate stages, such as trinification, can be obtained as the lowest among the analyzed minima of the potential with the 650 dimensional Higgs in an E6 GUT. We studied the small temperature expansion of the CFT propagator as the solution of the Heun equation obtained through the AdS/CFT correspondence.

We extended the use of classification without labels for anomaly detection by employing a hypothesis test to reject the background-only hypothesis. Through testing the statistical independence of two discriminating dataset regions,

Figure 1: Fraction of primaries with atomic number Z>Z0 inferred with the EPOS hadronic interaction model, in the three energy bins. The solid black line and purple regions indicate the results taking n = 3 moments in the distribution decomposition, while the dashed black line and cyan regions show the effect of taking n = 4 moments.

we managed to exclude the background-only hypothesis without resorting to fixed-anomaly score cuts or extrapolations of background estimates between the regions.

We applied statistical inference to the Pierre Auger Open Data to determine the mass composition of cosmic rays across various energy intervals. Utilizing longitudinal electromagnetic profiles of cosmic ray showers, particularly their peaking depths Xmax, we utilized central moments of the Xmax distributions to distinguish between different shower compositions.

We studied the impact of constraints from the large-scale structure data on a wide class of models that utilize entropy dilution as a means to accommodate dark-matter candidates that were over-produced in the early universe. We found that the branching ratio of dilutors for the repopulation of dark matter needs to be very low, which brings in important restrictions, excluding a large portion of the parameter space for right-handed neutrino warm dark matter.

Some outstanding publications in the past year

1. Jernej F. Kamenik, Manuel Szewc, Null hypothesis test for anomaly detection, Phys. Lett. B 840 (2023), 137836
2. K.S. Babu, B. Bajc, V. Susič, Trinification from E6 symmetry breaking, JHEP 07 (2023), 011, doi:10.1007/JHEP07(2023)011[arXiv:2305.16398 [hep-ph]]
3. M.-L. Du, A. Filin, V. Baru, X.-K. Dong, E. Epelbaum, F.-K. Guo, C. Hanhart, A. Nefediev, J. Nieves, Q. Wang, Role of left-hand cut contributions on pole extractions from lattice data: case study for Tcc(3875)+, Physical Review Letters 131 (2023), 131903, COBISS. si-ID 166479619
4. Nemevšek, Miha, Zhang, Yue, Dark matter dilution mechanism through the lens of large-scale structure. Physical Review Letters. [Print ed.]. 2023, vol. 130, no 12, pp. 121002-1-121002-6. ISSN 0031-9007. DOI: 10.1103/PhysRevLett.130.121002. [COBISS. SI-ID 146389251]
5. Fajfer, Svjetlana, Kamenik, Jernej, Korajac, Arman, Košnik, Nejc. Correlating New Physics effects in semileptonic ΔC=1 and ΔS=1 processes. The Journal of High Energy Physics. 2023, vol. 2023, iss. 7, art. no. 29, 28 pp., illustr. ISSN 1029-8479. DOI: 10.1007/ JHEP07(2023)029. [COBISS.SI-ID 159089155]

Figure 2: Bounds on the semileptonic operators are coupled to muons. The green and yellow regions correspond to the 68 and 95% confidence level allowed regions of the global fit.

Figure 3: The uud -> e annihilation diagram mediated by the triple-leptoquark coupling

Figure 4: Illustration of dark-matter repopulation

Researchers involved in the SOLID STATE THEORY AND STATISTICAL PHYSICS studied physical properties of correlated electrons in and out of equilibrium, disordered many-body systems, thermodynamic and transport properties of spin systems, nanosystems and quantum dots as well as complex networks and self-organized structures.

We continued our investigations of transport for disordered quantum systems; we also showed, in spin chains, a direct relation between the observed exponential decrease in diffusion with the intensity of random fields and the apparent drift of the transition to the many-body localized regime with increasing chain length. A member of the group was also the co-author of the paper, published in prestigious journal Nature, discussing a quantum effect, where the phase transition into crystal 1T-TaS$_2$ is shifted considerably when put in a cavity, indicating a strong coupling between cavity photons and electrons in the sample.

We studied the ergodicity of strongly disordered Anderson insulator chains, choosing different forms of the two-body interaction, for which the strength of true perturbation is of the same order of magnitude as that of the bare two-body interaction. Focusing on the strong-interaction regime, numerical results for the level statistics and the eigenstate thermalization hypothesis are consistent with the emergence of ergodicity at arbitrary strong disorder.

Within the quantum dynamics of isolated many-body quantum systems we demonstrated some universal properties of the dynamics at the ergodicity breaking phase transition. We proved for the quadratic models that the equilibration of the expectation values of few-body observables in many-body states is a consequence of the validity of single-particle eigenstate thermalization. We further explored the properties of the quantum sun model, proposed a year before as a toy model for the studies of ergodicity breaking transitions. We have shown that the quantum sun model shares similarities with the noninteracting ultrametric Anderson model. J. Šuntajs was awarded with the Jožef Stefan Golden Emblem Prize for his PhD thesis.

In materials with strong correlations, the interaction between electrons can cause a transition between the metal and insulators (Mott insulators). When such systems are excited by an external laser field, we can create new exotic quantum states, such as eta superconductivity, hidden many-particle states, etc., or search for additional microscopic information about these correlated systems. Among others, we have shown that we can create entanglement between exciton and spin degrees of freedom in Mott insulators, opening the way to new non-thermal states.

With colleagues from Caltech and Germany, we published a Nature Physics paper [19, 1876 (2023)] that experimentally confirmed the theoretical predictions regarding the existence of Hubbard excitons in Mott insulators. We have also shown that superdiffusion in the Heisenberg chain is surprisingly stable against symmetric perturbations. We also explored the connection between unitary and non-unitary current driving.

Within the framework of the non-equilibrium dynamics of many-body quantum systems we pioneered a novel approach integrating neural networks into algorithms aimed at reconstructing many-body Hamiltonians, which allowed us to glean valuable insights into the heating mechanisms inherent in Floquet systems. We investigated anomalous high-temperature transport phenomena within quantum spin chains. Specifically, leveraging sophisticated numerical methodologies including tensor networks, we made significant strides in elucidating the intricacies of sub-diffusion and super-diffusion within certain spin chains, relevant in the experimental domain of synthetic quantum matter. Finally, we studied how the concepts of quantum complexity can be used to diagnose scar eigenstates in quantum systems, which leave a deep imprint on the dynamics of these systems. Furthermore, we used a perturbative method to study weakly open nearly integrable quantum systems and proposed a method to construct conserved quantities that, in the leading order, provide an efficient description of the steady state.

- **We have studied ergodicity of strongly disordered Anderson insulator chains.**
- **We demonstrated some universal properties of quantum dynamics at the ergodicity-breaking phase transition.**
- **We confirmed theoretical predictions about the existence of metastable Hubbard excitons in photo-doped Mott insulators.**
- **Quasiparticles at high temperature become indistinguishable from the background due to the shortening of their lifetime, whereas, contrary to the naive picture, their relative weight grows.**
- **Thermoelectricity can significantly influence the diffusion behavior of both charge and temperature.**
- **The fate of superdiffusion in perturbed integrable systems strongly depends on the symmetry of the concerned perturbations.**
- **We found an asymptotic solution for the decoherence of a harmonic oscillator in the presence of spin-orbit interaction.**
- **The emergence of multifractal modulated cycles is an important feature of contagious human interactions. Higher-order geometric interactions in the synchronization of phase oscillators cause hysteretic behaviour specific to the supporting structure of simplicial complexes.**
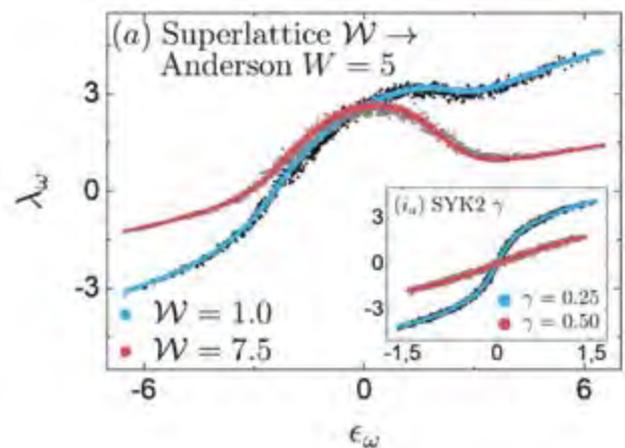

Figure 5: Construction of the generalized Gibbs ensemble in quadratic models with single-particle quantum chaos
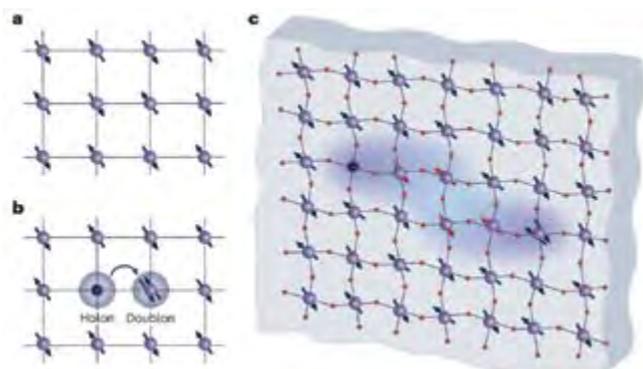
Figure 6: Metastable bound pair of holon and doublon, summarized in Nature Physics 19, 1876 (2023) in co-authorship with Zala Lenarčič
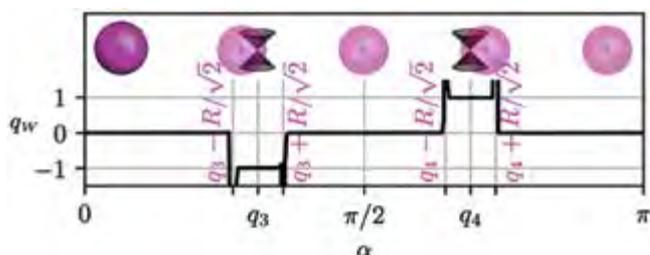

Figure 7: Result of the protocol, linking currents in a two-terminal Josephson junction with the topological charge of Weyl points
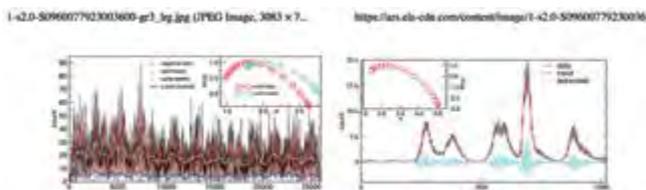

Figure 8: Emergent cycles in contagious human interactions with emotions (left) and infection contents (right), and their respective multifractal characterization with singularity spectra (insets)

In the field of correlated electron systems we investigated the coupling of thermal and charge currents and their influence on the diffusion of charge and temperature modulations via numerical simulations on the Hubbard model. We have shown that the impact of thermoelectric effects can be significant but does not substantially affect the conclusions of research on cold atoms, and that the coupling can lead to interesting resonance effects. We calculated the influence of oxygen impurities on the resistivity and thermal conductivity of iron in Earth's core.

In the framework of low-dimensional systems we investigated the anomalous high-harmonic generation (AHHG) in a model transitioning from a Weyl semimetal (WSM) to a semi-Dirac regime. We showed that deviations from linearity in the WSM dispersion are crucial for the AHHG, which is enhanced in the semi-Dirac regime. In a study involving a two-terminal Josephson junction with Rashba spin-orbit interaction, acting as a 1D chiral topological insulator, we proposed a protocol to measure the quantity linked to the system's topological invariants.

Within the research into complex systems and networks, we investigated out-of-equilibrium critical dynamics and some robust characteristics of collective behavior using numerical simulations and empirical data analysis. Our analysis of contagious human interaction data (online emotional communications and transmission of infections in real space) revealed the emergence of vigorous cyclical trends with characteristic multifractal properties. An extensive analysis of such cycles, supplemented by K-means time series clustering, helped identify some typical mortality patterns in the global data of the recent pandemic. Our simulations of the synchronization of phase oscillators on simplicial complexes of different architectures and spectral dimensions reveal that geometry-embedded higher-order interactions (triangles) induce hysteresis loops and partial synchronization patterns that are tightly related to the complex topology.

Some outstanding publications in the past year

1. Ulaga, M., Mravlje, J., Kokalj, J., Thermoelectric effect on diffusion in the two-dimensional Hubbard model. Phys. Rev. B 108, 155118 (2023) P. Lydzba, M. Mierzejewski, M. Rigol, L. Vidmar, Physical Review Letters 131, 060401 (2023)

2. Šuntajs, J., Prosen, T., Vidmar, L., Localization challenges quantum chaos in finite two-dimensional Anderson model, Phys. Rev. B 107, 064205 (2023)M. Hopjan, L. Vidmar, Physical Review Letters 131, 060404 (2023)Omar Mehio, Xinwei Li, Honglie Ning, Zala Lenarčič, Yuchen Han, Michael Buchhold, Zach Porter, Nicholas J. Laurita, Stephen D. Wilson, David Hsieh, A Hubbard exciton fluid in a photo-doped antiferromagnetic Mott insulator, Nature Physics 19, 1876 (2023)

3. Sourav Nandy, Zala Lenarčič, Enej Ilievski, Marcin Mierzejewski, Jacek Herbrych, Peter Prelovšek, Spin diffusion in a perturbed isotropic Heisenberg spin chain, Phys. Rev. B 108, L081115 (2023)Sarkar M., Ghosh R., Khaymovich I. M., Tuning the phase diagram of a Rosenzweig-Porter model with fractal disorder, Phys. Rev. B (Letters) 108, L060203 (2023)

4. Tatsuya Kaneko, Yuta Murakami, Denis Golež, Zhiyuan Sun, Andrew J. Millis, Phys. Rev. B 108, 205121 (2023)

5. Tadić, Bosiljka, Mitrović Dankulov, Marija, Melnik, Roderick, Evolving cycles and self-organised criticality in social dynamics, Chaos, Solitons and Fractals. [Print ed.]. 2023, vol. 171, pp. 113459-1-113459-10. DOI: 10.1016/j.chaos.2023.113459. [COBISS.SI-ID 150881283]

The group for THEORETICAL BIOPHYSICS AND SOFT MATTER PHYSICS investigated biopolymers and liquid crystals as well as lipid membranes, vesicles, viruses, and epithelial tissues.

We focused on the description of the RNA biomolecule as a randomly branching polymer. We studied both random RNA sequences as well as sequences that serve as the genomes of RNA viruses. Furthermore, we analyzed

the mutations in almost 2000 strains of SARS-CoV-2 viruses that change the charge on the spike protein and showed how it was changed during the course of its evolution.

We identified the "hydrophobicity threshold" for the spontaneous self-assembly of lipid monolayers on solid surfaces, showing that above a critical contact angle of 65±5° lipids can spontaneously adsorb in the form of a monolayer. This guideline is critical for improving biocompatibility and reducing unwanted adhesion. We introduced a novel framework that enhances atomistic MD simulations by combining them with general thermodynamic principles, overcoming previous limitations in predicting the surfactant behavior on timescales well beyond the traditional MD simulations (about ∼1 μs).

We analyzed the dielectric response of ferroelectric liquid crystals. We relaxed the strict coupling between the tilt and polarization of smectic layers, and discovered four relaxation modes, which include the Goldstone mode and three others with a nonlinear temperature dependence. We formulated a model of a polar nematic, which elucidates the observed transition from the continuous to discontinuous behavior in an electric field. We analyzed the behavior of these materials in thin parallel-plate capacitors and phase transitions in an external electric field, relevant for applications because of the strong birefringence that can be induced in a broad temperature range (several 10 K) in an optically isotropic phase.

We explored the structure of the triplets of lipid vesicles and we demonstrated that they can be theoretically interpreted in terms of the so-called two tension model, which permits differential stretching of the non-contact domain and the contact zones, and describes well both weakly and strongly bound aggregates. We theoretically studied the elasticity and the wrinkling mechanisms of unsupported epithelial tissues with apicobasal polarization. We showed that by introducing the so-called phantom substrate, these tissues can be mapped onto supported elastic films under in-plane compression.

The article by Vaupotič et al. was included in "2023 JCP Emerging Investigators Special Collection".
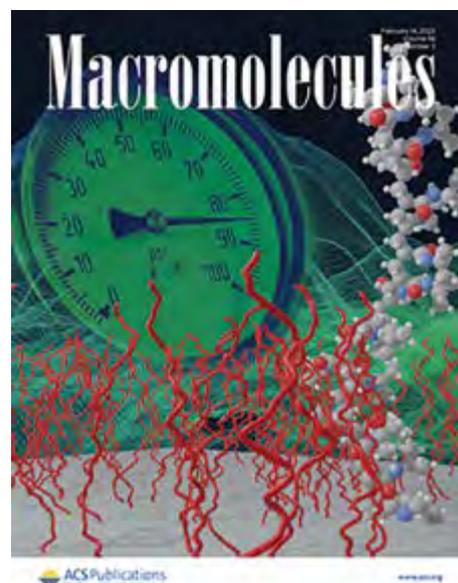
Figure 9: Featured on the cover of ACS Macromolecules: Our study uncovered that the conformational changes of nonionic polymer brushes and solutions under pressure and temperature can be universally predicted with thermodynamics, which can be used for the design of pressure-responsive materials.

Some outstanding publications in the past year

1. U. Andrenšek, P. Ziherl, M. Krajnc, Wrinkling Instability in Unsupported Epithelial Sheet, Phys. Rev. Lett. 130, 198401 (2023)

2. Szydłowska, Jadwiga, Čepič, Mojca, Vaupotič, Nataša, et al. Ferroelectric nematic-isotropic liquid critical end point. Physical Review Letters. [Print ed.]. 2023, vol. 130, no. 21, pp. 216802-1-216802-5. ISSN 0031-9007. DOI: 10.1103/PhysRevLett.130.216802

The members of the PHYSICS OF QUANTUM TECHNOLOGIES group studied the properties of hybrid semiconductor-superconductor devices as well as quantum impurity problems, in particular those involving adsorbed magnetic molecules and quantum dots.

We elucidated the phenomena in advanced Josephson junctions for superconducting quantum devices of the next generation.

We studied the phenomena in superconducting quantum devices. We elucidated the behavior of the magnetic field of hybrid super-semi devices made of nanowires, the Knight shift in quantum dot Josephson junctions and the exchange coupling through a superconducting island. We developed the theory of Andreev spin qubits. We explained the spectral properties of nickelocene molecules on a copper surface as topological quantum-phase transitions between two different Fermi liquid states.

Some outstanding publications in the past year

1. Marta Pita-Vidal, Arno Bargerbos, Rok Žitko, Lukas J. Splitthoff, Lukas Grünhaupt, Jaap J. Wesdorp, Yu Liu, Leo P. Kouwenhoven, Ramón Aguado, Bernard van Heck, Angela Kou, Christian Kraglund Andersen, Direct manipulation of a superconducting spin qubit strongly coupled to a transmon qubit, Nat. Phys. 19, 1110 (2023)

ERC project

1. HE - DrumS; Weakly Driven Quantum Symmetries
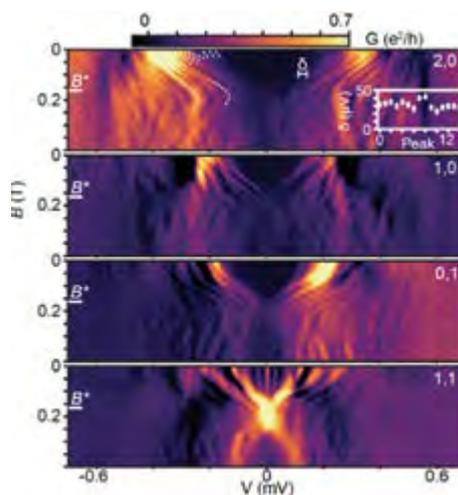   Dr. Zala Lenarčič
   European Commission

Figure 10: Discrete states in the superconducting energy gap of a hybrid quantum device

Awards and Appointments

1. Prof. Svjetlana Fajfer: Blinc Awards, Faculty of Mathematics and Physics, University of Ljubljana and Jožef Stefan Institute, Blinc Award for Lifetime Achievement
2. Prof. Lev Vidmar: Blinc Awards, Faculty of Mathematics and Physics, University of Ljubljana and Jožef Stefan Institute, Blinc Award for early-career physicists

Organization of conferences, congresses and meetings

1. International workshop: Structure and topology of RNA in living systems, Trento, Italy, 30. 1. – 2. 2. 2023
2. International workshop: Quantum Many-Body Systems In and Out of Equilibrium, Ljubljana, Slovenia, 13. 2. – 16. 2. 2023
3. International conference: Ljubljana - Trieste - Zagreb Nonequilibrium meeting, Ljubljana, Slovenia, 14. 3. 2023
4. International workshop: Workshop of solid-state physics, Medana, Slovenia, 12. 4. – 14. 4. 2023
5. International workshop: Particle Physics from Early Universe to Future Colliders, Portorož, Slovenia, 11. 4. – 14. 4. 2023
6. International symposium: MBL symposium, Ljubljana, Slovenia, 7. 6. – 9. 6. 2024
7. International conference: OpenQMBP2023: New perspectives in the out-of-equilibrium dynamics of open many/body quantum systems, Paris, France, 12. 6. – 30. 6. 2023
8. International symposium: Coarse-graining the finer structure of macromolecular interactions, Ljubljana, Slovenija, 27. 8. – 30. 8. 2023
9. School: School on Quantum Many-Body Phenomena out of Equilibrium: from Chaos to Criticality, Trieste, Italy, 21. 8. – 1. 9. 2023
10. Summer school: Ljubljana Summer School on Particle Physics and Cosmology, Ljubljana, Slovenia, 28. 8. – 2. 9. 2023
11. Workshop on random numbers, Ljubljana, Slovenia, 12. 9. 2023
12. International workshop: Brda 2023 – Illusive physics beyond the standard model, Medana, Slovenia, 11. 10. – 13. 10. 2023
13. International conference: Nonequilibrium Quantum workshop, Krvavec, Slovenia, 10. 12. – 14. 12. 2023

INTERNATIONAL PROJECTS

1. **ERC HE - DrumS; Weakly Driven Quantum Symmetries**
    Dr. Zala Lenarčič
    European Commission
2. Probing the Origin of Flavour through Precision
    Prof. Nejc Košnik
    Slovenian Research Agency
3. Machine Learning in High Energy Physics
    Prof. Jernej Fesel Kamenik
    Slovenian Research Agency
4. Exploring Boundaries of Quantum Many-Body Chaos
    Prof. Lev Vidmar
    Slovenian Research Agency
5. HE - SMASH; Machine Learning for Sciences and Humanities
    Prof. Jernej Fesel Kamenik
    European Commission
6. DIGITAL EU; SiQUID - Slovenian Quantum Communication Infrastructure Demonstration
    Prof. Rok Žitko
    European Commission
7. COST CA22130; COMETA - Comprehensive Multiboson Experiment-Theory Action
    Prof. Jernej Fesel Kamenik
    COST Association Aisbl
8. COST CA21106; CosmicWISPers - COSMIC WISPers in the Dark Universe: Theory, Astrophysics and Experiments
    Prof. Miha Nemevšek
    COST Association Aisbl

RESEARCH PROGRAMMES

1. Theory of the condensed matter and statistical physics
    Prof. Janez Bonča

2. Theoretical physics of nuclei, particles and fields
    Prof. Jernej Fesel Kamenik
3. Biophysics of polymers, membranes, gels, colloids and cells
    Prof. Primož Ziherl
4. Physics of quantum technologies
    Prof. Rok Žitko

R & D GRANTS AND CONTRACTS

1. The influence of additives on nanoscopic wetting
    Dr. Matej Kanduč
2. Multi-scale modeling of non-equilibrium quantum materials
    Dr. Denis Golež
3. Three advances towards realistic description of strongly correlated electron transport
    Asst. Prof. Jernej Mravlje
4. Symmetries and quantum pumping
    Dr. Zala Lenarčič
5. Diamond-assisted quantum processing of fullerene qubits
    Prof. Rok Žitko
6. Coulombic subgap states in superconducting quantum devices
    Prof. Rok Žitko
7. Nonlinear mechanics of biological tissues and their tumors
    Dr. Matej Krajnc
8. Advancing precision flavour studies with machine learning
    Prof. Jernej Fesel Kamenik
9. Lattice QCD study of electroweak transitions between heavy mesons and light hadronic resonances (raziskovalni projekt - Program AD)
    Asst. Prof. Luka Leskovec
10. FLAMENCO: Flavour, Lepton number, And Mass Explorations of Neutrinos at the COmpact muon solenoid
    Prof. Miha Nemevšek
11. Stability of biological liquids under tension
    Dr. Matej Kanduč

12. Neutrino mass origin: from colliders to gravitational waves
    Prof. Miha Nemevšek
13. Nonergodic dynamics in disorder-free systems
    Prof. Lev Vidmar
14. Eta-pairing as a glue
    Dr. Zala Lenarčič
15. Coloured scalars in physics beyond Standard Model
    Prof. Svjetlana Fajfer
16. Ergodicity breaking phase transitions
    Prof. Lev Vidmar
17. Anisotropic quantum magnetism in novel rare-earth materials
    Prof. Peter Prelovšek
18. Cryptographically secure random number generator
    Prof. Rok Žitko
19. Tensor Networks in Simulation of Quantum matter
    Dr. Zala Lenarčič
    Ministry of Education, Science and Sport

20. Slovenian Quantum Communication Infrastructure Demonstration"
    Prof. Rok Žitko
    Government Information Security Office
21. Quantium simulation with engineered dissipation
    Dr. Zala Lenarčič
    Ministry of Education, Science and Sport
22. Cryptographically secure random number generator
    Prof. Rok Žitko
    Government Office for the Protection of Classified Information
23. Physics of quantum technologies
    Prof. Rok Žitko
    Slovenian Research and Innovation Agency
24. Multi-scale modelling of nonequIlibrium quantum materials«
    Dr. Denis Golež
    Slovenian Research and Innovation Agency
25. Co-funding of the Project HE - SMASH; Machine Learning for Sciences and Humanities
    Prof. Jernej Fesel Kamenik
    Ministry of Higher Education, Science and Innovation

VISITORS FROM ABROAD

1. Alexander Osterkorn, University of Göttingen, Göttingen, Germany, 9. - 13. 1. 2023
2. Dr Vladimir Gligorov, National Centre for Scientific Research, CNRS, Paris, France, 24. 1. - 26. 1. 2023
3. Dr Marcus Aichhorn, Technical University in Vienna, Vienna, Austria, 26. 1. - 28. 1. 2023
4. Prof. Dr Sadamichi Maekawa, Institute of Physical and Chemical Research, RIKEN, Wako, Japan, 13. 2. - 16. 2.2023
5. Dr Michele Coppola, University of Lorraine, Le Laboratoire de Physique et Chimie Théoriques LPCT, Nancy, France, 23. 2. - 25. 2. 2023
6. Marc Domingo Cabasés, Institute of Materials Science in Barcelona, Barcelona, Spain, 28. 2. - 31. 5. 2023
7. Prof. Dr Michael Schmidt, Karlsruhe Institute of Technology, Karlsruhe, Germany, 8. 3. - 9. 3. 2023
8. Dr Andras Jozsef Grabarits, Institute of Physics in Budapest, Budapest, Hungary, 20. 3. - 22. 3. 2023
9. Dr Zhao Zhang, International School for Advanced Studies, SISSA, Trieste, Italy, 21. 3. 2023
10. Patrick Bolton, International School for Advanced Studies, SISSA, Trieste, Italy, 21. 3. 2023 - 24. 3. 2023
11. Dr Damir Bečirević, Institut Joliot Curie, Paris, France, 27. 3. - 10. 4. 2023
12. Prof. Dr Benjamin Fuks, Laboratory of Theoretical and High Energy Physics, LPTHE, Paris, France, 29. 3. - 31. 3. 2023
13. Dr Florian Goertz, Max-Planck Institute, Heidelberg, Germany, 3. 4. - 7. 4. 2023
14. Dr Yutaro Shoji, Racah Institute for Physics, Hebrew University in Jerusalem, Jerusalem, Israel, 10. 4. - 22. 4.2023
15. Dr Alexander Osterkorn, University in Göttingen, Göttingen, Germany, 11. 4. - 12. 4. 2023 in 14. 4. - 15. 04. 2023
16. Dr Leonid Poyurovskiy, Polytechnical school, Palaiseau, France, 18. 4. - 22. 4. 2023
17. Dr Marcus Aichhorn, Technical University in Vienna, Vienna, Austria, 20. 4. - 21. 4. 2023
18. Dr Paolo Benincasa, Max-Planck Institute, Munchen, Germany, 25. 4. - 27. 4. 2023
19. Dr Alexander Osterkorn, University of Göttingen, Göttingen, Germany, 1. 5. - 26. 5. 2023
20. Dr Ben Stefanek, University of Zurich, Zurich, Switzerland, 1. 5. - 5. 5. 2023
21. Ivan Khaymovich, University of Stockholm, Stockholm, Sweden, 3. 5. - 4. 5. 2023
22. Prof. Dr Mona Berciu, University of British Columbia, Vancouver, Canada, 17. 5. - 21. 5. 2023
23. Dr David Horvath, International School for Advanced Studies (SISSA), Trieste, Italy, 22. 5. - 24. 5. 2023
24. Dr Horacio Vargas Guzman, Autonomous University in Madrid, Madrid, Spain, 22. 5. - 29.5. 2023
25. Fabian Heidrich-Meisner, University of Gottingen, Gottingen, Germany, 23. 5. - 26. 5. 2023
26. Fran Ivan Vrban, University of Rijeka, Reka, Croatia, 25. 5. 2023
27. Simon   Jiricek, University of Göttingen, Göttingen, Germany, 5. 6. - 26. 6. 2023
28. Kohei Ogane, Tohoku University, Sendai, Japan, 7. 6. - 25. 8. 2023
29. Purushottam Sahu, Indian Institute of Technology Bhilai, Chhattisgarh, India, 7. 6. - 8. 6. 2023
30. Dr Santiago Tanco, Nacional University La Plata, La Plata, Argentina, 12. 6. - 18. 6. 2023

31. Dr Stephanie Matern, Center of Nanoscience, University of Lund, Lund, Sweden, 21. 6. - 23. 06. 2023
32. Dr Katarina Karlova, University Pavol Jozef Safarik, Košice, Slovakia, 21. 6. - 24. 6. 2023
33. Dr Jozef Strecka, University Pavol Jozef Safarik, Kosice, Slovakia, 21. 6. - 24. 6. 2023
34. Mateusz Lisiecki, University of Science and Technology in Wroclaw, Wroclaw, Poland, 10. 7. - 10.08.2023
35. Dr Maksimilian Šroda, University of Science and Technology in Wroclaw, Wroclaw, Poland, 10. 7. - 21. 7. 2023
36. Dr Arghyadip Mukherjee, Ecole Normale Superieure, Paris, France, 10.07.2023
37. Emanuel Schneck, Institute for Condensed Matter Physics, Technical University of Darmstadt, Darmstadt, Germany, 17. 7. -21.07.2023
38. Patrycja Lydzba, University of Science and Technology in Wroclaw, Wroclaw, Poland, 24. 7. - 29.07.2023
39. Xiansong Xu, Singapore University of Technology and Design, Singapore, Singapore, 24. 7. - 25. 7. 2023
40. Dr Martin Novoa Brunet, University of Bari Aldo Moro, Bari, Italy, 25. 7. - 4. 8. 2023
41. Prof. Dr Ilja Doršner, University of Split, Split, Croatia, 29. 7. - 4. 8. 2023
42. Ahmed Youssef, University of Cincinnati, Cincinnati, Ohio, USA, 2. 8. - 7. 8. 2023
43. Prof. Dr Jure Zupan, University of Cincinnati, Cincinnati, Ohio, USA, 7. 8. - 11. 8 .2023
44. Thomas Blommel, Department of Physics, University of Michigan, Michigan, USA, 12. 8. - 17. 8. 2023
45. Dr Horacio Vargas Guzman, Autonomous University in Madrid, Madrid, Spain, 27. 8. - 1. 9. 2023
46. Luca Tubiana, University of Trento, Trento, Italy, 28. 8. - 31. 8. 2023
47. Antonio Torres Manso, University of Granada, Granada, Spain, 1. 9. - 1. 12. 2023
48. Dr Christian Johansen, Max Planck Institute for the Physics of Complex Systems, Dresden, Germany, 12. 9. - 16. 9. 2023
49. Dr Shoji Yutaro, Racah Institute for Physics, Hebrew University of Jerusalem, Jerusalem, Israel, 13. 9. - 13. 11. 2023
50. Dr Olcyr Sumensari, Institute Joliot Curie, Orsay, France, 25. 9. - 29. 9. 2023
51. Dr Giacomo Mazza, University of Pisa, Pisa, Italy, 23. 10. - 25. 10. 2023
52. Dr Peter Zalom, Institute of Physics of Czech Academy of Science, Prague, Czech Republic, 12. 11. - 1. 12 .2023
53. Dr Renwick James Hudspith, Helmholtz center za Schwerionenforschung (GSI), Darmstadt, Germany, 14. 11. - 15. 11. 2023
54. Paulo Ferraz, University of Granada, Granada, Spain, 17. 11. - 24. 11. 2023
55. Dr Claudia Cornella, Mainz Institute for Theoretical Physics, Mainz, Germany, 20. 11. - 22. 11. 2023
56. Dr Michele Coppola, University of Lorraine, Le Laboratoire de Physique et Chimie Théoriques, LPCT, Nancy, France, 1. 12. - 31. 12. 2023
57. Dr Dmitry Kiselyov, Weizmann Institute for Science, Rehovot, Israel, 4. 12. - 8. 12. 2023
58. Dr Florentin Jaffredo, National Institute for Nuclear Physics, INFN, Pisa, Italy, 11. 12. - 13. 12. 2023
59. Lukas Allwicher, University of Zurich, Zurich, Switzerland, 13. 12. - 16. 12. 2023
60. Dr Shaikh Ahmed Saad, University of Basel, Basel, Switzerland, 18. 12. - 21. 12. 2023
61. Prof. Jure Zupan, University of Cincinnati, Cincinnati, Ohio, USA, 20. 12. - 22. 12. 2023

STAFF

1. **Researchers**
2. Dr. Adam Bacsi
3. Prof. Borut Bajc
4. Dr. Pietro Baratella
5. Dr. Patrick Douglas John Bolton
6. Prof. Janez Bonča*
7. *Dr. Banhi Chatterjee, left 01.10.23*
8. Dr. Michele Coppola
9. Prof. Mojca Čepič*
10. Dr. Ilja Doršner
11. Prof. Svjetlana Fajfer
12. **Prof. Jernej Fesel Kamenik, Head**
13. Dr. Denis Golež
14. Dr. Miroslav Hopjan
15. Dr. Matej Kanduč
16. Asst. Prof. Jure Kokalj*
17. Prof. Nejc Košnik
18. Dr. Matej Krajnc
19. Dr. Gianluca Lagnese
20. Dr. Zala Lenarčič
21. Asst. Prof. Luka Leskovec
22. Asst. Prof. Jernej Mravlje
23. Dr. Sourav Nandy
24. Dr. Alexey Nefediev
25. Prof. Miha Nemevšek
26. Dr. Alexander Osterkorn
27. Prof. Peter Prelovšek
28. Prof. Saša Prelovšek Komelj*
29. Prof. Anton Ramšak*
30. Dr. Anže Rapoš Božič
31. Asst. Prof. Tomaž Rejec*
32. Dr. Tanmoy Sarkar
33. Dr. Madhumita Sarkar
34. Prof. Bosiljka Tadić
35. Dr. Lorenzo Ubaldi
36. Prof. Nataša Vaupotič*
37. Prof. Lev Vidmar
38. Prof. Primož Ziherl*
39. Prof. Rok Žitko

Postdoctoral associates
40. *Dr. German Gabriel Blesio, left 01.12.23*
41. Dr. Jonathan Kriewald
42. Dr. Emmanuel Ortiz Pacheco
43. Dr. Fabio Staniscia
44. Dr. Jan Šuntajs*
45. *Dr. Michele Tammaro, left 01.10.23*
46. Dr. Lara Ulčakar*

Postgraduates
47. Urška Andrenšek, B. Sc.
48. Blaž Bortolato, B. Sc.
49. Veronika Bukina, B. Sc.
50. Jože Gašperlin, M. Sc.
51. Arman Korajac, M. Sc.
52. Klemen Kovač, B. Sc.
53. Marco Matteini, M. Sc.
54. Luka Medic, B. Sc.
55. *Dr. Luka Pavešić, left 01.11.23*
56. Lovre Pavičić, M. Sc.
57. Rok Pintar, B. Sc.
58. Don Rolih, B. Sc.
59. Rafal Piotr Swietek, M. Sc.
60. Marin Šako, M. Sc.
61. Katarina Trailović, M. Sc.
62. Martin Ulaga, B. Sc.
63. Iris Ulčakar, B. Sc.
64. Domen Vaupotič, B. Sc.
65. Ivan Vujmilović, B. Sc.
66. Urban Železnik, B. Sc.
67. **Technical officers**
68. Tjaša Lazič Mihelič, B. Sc.

Technical and administrative staff
69. Nevenka Hauschild
70. Alma Mehle, B. Sc.

Note:

* part-time JSI member

DEPARTMENT OF LOW AND MEDIUM ENERGY PHYSICS F-2

The Department of Low and Medium Energy Physics actively pursues research in nuclear, atomic, molecular and optical physics. Our focus extends to a comprehensive exploration of fundamental physical phenomena and processes, underpinning the interdisciplinary nature of our research endeavours. These encompass a wide spectrum of fields, including environmental radiological monitoring, material research, fusion, biology, energy storage, medicine, pharmacology, environmental sciences, and archaeometry.

Head:
Prof. Primož Pelicon

We leverage a robust infrastructure of experimental equipment, featuring an ion-beam accelerator with dedicated beamlines. Furthermore, our capabilities include specialized detectors for ionizing radiation, precisely calibrated radiation fields, and experimental setups tailored for nuclear, atomic, and molecular physics.

Researchers from our department are regular users of large experimental facilities worldwide, such as particle accelerators, synchrotrons, free-electron lasers and tokamaks. These facilities are accessed either through international collaborations, research networks or through self-initiated research proposals. To counterweight the process of engagement of national human resources at research facilities abroad, we are providing Transnational access (TNA) to the tandem ion accelerator at the Jožef Stefan Institute for international users within the EU research infrastructure projects.

We have continued our work within the A1 Collaboration at the three-spectrometer facility of the Mainz Microtron (MAMI), with the focus on analysing and publishing results on the data acquired during recent production runs. We performed a systematic study of the monopole transition form factor of the α-particle by using electron scattering in a broad Q2 range (Kegel et al., 2023). By confronting the data with state-of-the-art calculations, we observed that modern descriptions of nuclear forces, including those derived within chiral effective field theory, fail to reproduce this excitation. We have continued our studies of radiative corrections to elastic scattering, where they represent a dominant part of the background. By developing a new event generator (Mihovilovič et al., 2023) we have been able to describe the shape of the radiative tail of an elastic peak with a precision better than 10% over the whole energy range of the scattered electrons, allowing us to use this generator reliably in all analyses of electron scattering data and their interpretation. We have also continued to investigate the process of polarization transfer to a bound proton. For this purpose we study electron-induced knock-out reactions with polarized electrons combined by recoil polarization detection, which represent a powerful probe of in-medium, form-factor modifications (Kolar et al., 2023). While the calculations capture the essence of our data on double-polarization asymmetries, our statistical precision allows us to observe deviations that cannot be explained by simple scaling, including by varying the ratio of the electric and magnetic form-factors.

Our work at the Thomas Jefferson National Accelerator Facility (Jefferson Lab) has been focused on the analysis of data from several experiments performed during the 6-GeV CEBAF era, but we also have new results on data taken with the upgraded 12-GeV beam. In Jiang et al., (2023) we report on the first results of the E12-14-012 experiment in which we have measured the inclusive electron-scattering cross-section in parallel kinematics by using a natural titanium target. We have presented the analysis of the dataset spanning missing energies between 12 and 80 MeV, and missing momenta between 12 and 250 MeV/c, obtained with an electron-beam energy of 2.2 GeV. We measured the reduced cross-section with ~7% accuracy as a function of both the missing energy and the missing momentum.

Recently we have decided to join the initial efforts of envisioning and developing the experimental programme at the Electron-Ion Collider (EIC). The EIC will be a powerful, new, high-luminosity facility in the United States with the capability to collide high-energy electron beams with high-energy proton and ion beams, providing access to those regions in the nucleon and nuclei where their structure is dominated by gluons. Moreover, polarized beams in the EIC will give unprecedented access to the spatial and spin structure of the proton, neutron and light ions. We began the collaboration in the EIC Comprehensive Chromodynamics Experiment (ECCE), a consortium formed to develop a general detector concept that meets the design requirements laid out in the EIC Yellow Report (Bock et al., 2023; Seidl et al., 2023a; Seidl et al., 2023b; Bylinkin et al., 2023; Li et al., 2023; Zhang et al., 2023; Fanelli et al., 2023; Bernauer et al., 2023).

In parallel with the construction of the FAIR (Facility for Antiproton and Ion Research) accelerator centre, which is one of the largest projects for basic research in the world, the FAIR Phase-0 research programme is already taking place at the GSI premises in Darmstadt. Our primary focus here is the NUSTAR physics programme. We are heavily

engaged in the research of the High-Resolution In-Flight Spectroscopy / Decay Spectroscopy (HISPEC/DESPEC) and Superconducting Fragment Separator (Super-FRS) experiment sub-collaborations. HISPEC/DESPEC experiments that aim to address the key issues in nuclear structure, reactions and nuclear astrophysics at the limits of nuclear existence. For the DESPEC collaboration at GSI/FAIR we have developed BGO scintillation detectors. We have completed 18 BGO detectors. These BGO detectors provide active shielding for germanium detectors and reduce the spectral noise produced by Compton-scattered photons. The HISPEC-10 experiment will be part of the low-energy branch at FAIR and will be used for measurements involving slowed-down exotic ions. We have developed a cooled, segmented, silicon-detector setup that will be used to measure energy losses, trajectories and the total kinetic energy of ions in the HISPEC-10 experiment.
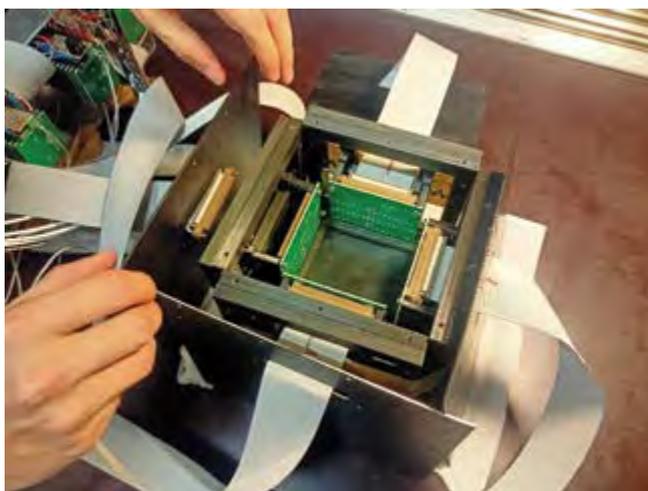
Figure 1: a new implantation detector FIMP (Fiber Implanter) for DESPEC experiments at FAIR facility in Darmstadt. The FIMP detector consists of scintillation fibres stacked in layers, whose signal is read by silicon photomultipliers.
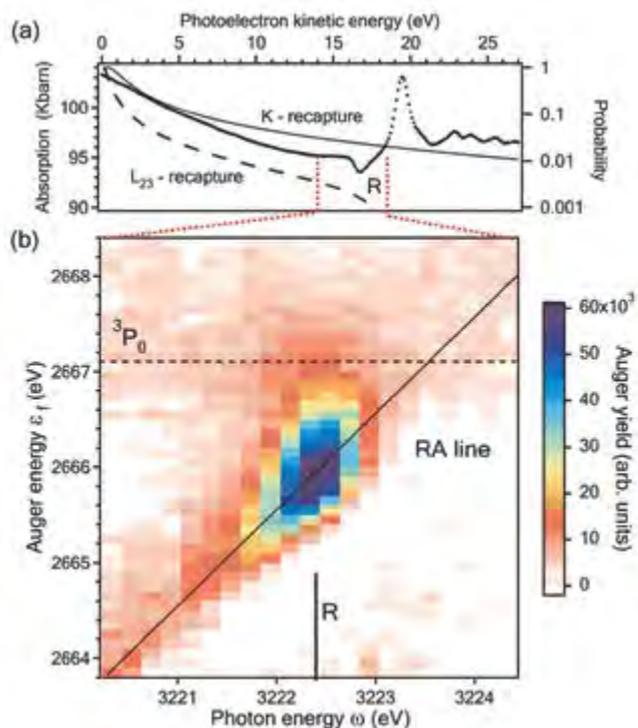
Figure 2: (a) Absorption spectrum in the vicinity of the 1s-13p-1nln'l' states in Ar and the probability of capturing a 1s photoelectron from the K shell (solid line) and the L shell (dashed line). (b) The asymmetric shape of the yield of resonant Auger electrons near the 1s-13p-14s2 resonance is caused by the presence of a new three-electron process ((Žitnik et al., Phys. Rev. Lett. 131, 2023, 203001).

We have finished the construction of a prototype of a new implantation detector FIMP (Fiber Implanter) for DESPEC experiments. The FIMP detector consists of scintillation fibres stacked in layers, whose signal is read by silicon photomultipliers. We have performed simulations of rare-isotope beams for the HISPEC/DESPEC experiments at the Super-FRS. We continued with the development of the Ion Motion Solver (IMS) software, which is designed to optimize the transport of ions through the ion optics line that makes up the FRS Ion Catcher (FRS-IC) of the SFRS collaboration. The key areas of the software package's development will be the calculation of electrostatic potentials for various complex electrostatic electrodes of different geometries, and the description of the calculated potentials with appropriate base functions.

In the field of atomic, molecular and optical physics we published a study of the decay paths of a double 2p hole in argon (Mailhiot et al., 2023). The work was a collaboration with French colleagues (F. Penent and P. Lablanquie) and required the detection of Auger electrons by the magnetic bottle spectrometer in coincidence with the charge state of Ar ions, determined by the time-of-flight detector. The way the experiment was performed at the GALAXIES beamline at the SOLEIL synchrotron enables a more detailed analysis of decays ending in the final ion states with charge +1 to +4. The sensitivity was high enough to make a new estimate of the decay ratio for a quite improbable decay of a double hole with the emission of a single Auger electron, which is consistent with the value we reported back in 2016.

In 2023 we completed a theoretical discussion and published the results on the resonant Auger decay of doubly excited states 1s^{-1}3p^{-1}nln'l' in argon. It is the first detailed treatment of this phenomenon, where the intermediate states are doubly excited atomic states, and we compare the characteristics of the non-radiative and radiative decay of these states, which we first reported back in 2009. The details of the extensive research were published in a longer paper (Žitnik et al., 2023), and the most interesting new findings in a related, shorter work in the journal Physical Review Letters (Žitnik et al, 2023). Among novelties is certainly evidence for the capture of the 1s photoelectron, in which three electrons are involved: in addition to the Auger electron, an electron in the outer shell of argon also participates in the discovered capture mechanism (Figure 1).

At the end of 2023, after long preparations, which included a detailed theoretical treatment (Chuchurka et al., 2023), we successfully performed experiment 20224028 "Self-amplification of spontaneous emission from helium autoionization states" with the Fermi free-electron laser at the EIS-TIMEX beamline (PI M. Žitnik). Thus, we saw for the first time that even for short-lived states, which decay non-radiatively with a 99.99% probability, in the same medium it is possible to amplify their own, extremely weak spontaneous emission through the mechanism of stimulated emission. Under certain conditions, a significant part of the strong incident light ($\approx$ 1%) with a wavelength of 19.5 nm was converted into light with a wavelength of 30.3 nm by passing the gas. The efficiency of the conversion depends on the density of the gas and the intensity of the light. A major challenge in the experiment was the preparation of a gaseous target, which must be windowless due to the strong absorption of solid matter at XUV wavelengths. For

this purpose, our colleagues from the IFN-CNR Institute in Milan (R. Martinez) produced a microcapillary, which can be used to achieve a pressure of over 100 mbar when installed in a vacuum chamber (Figure 2). Together with them and the Milan Polytechnic, we also prepared a plan for doctoral training on this issue as part of the SQUASH project, coordinated by the Jožef Stefan Institute, and obtained initial funding for the joint IJS-CNR project entitled "Collective emission from dense gas: the path to of new sources of coherent XUV light sources''.

In 2023 we continued with the analysis of the passage of weak light through dense gas in the spectral region of singly excited states of He, which we carried out at the GASPHASE beamline at the ELETTRA synchrotron. These measurements are complementary to intense light measurements and also reveal many interesting phenomena. Absorption spectra at high pressure show an increased importance of contributions where the absorption of a photon takes place in an instants, when a helium atom is located near a second (third,...) photon. Due to such a "molecular" geometry, the excitation energy for the transition to an excited "molecular" state below the ionization threshold changes and absorption occurs at energies where it would otherwise not be possible. The quotes above are used because this is not dealing with absorption in gas molecules or in clusters, but with transient molecular configurations that are established only for a short time due to the movement of atoms and are encountered by the photon more often in a denser gas. The interpretation of such spectra, therefore, requires new molecular calculations, which must be appropriately weighted and compiled into the final result.
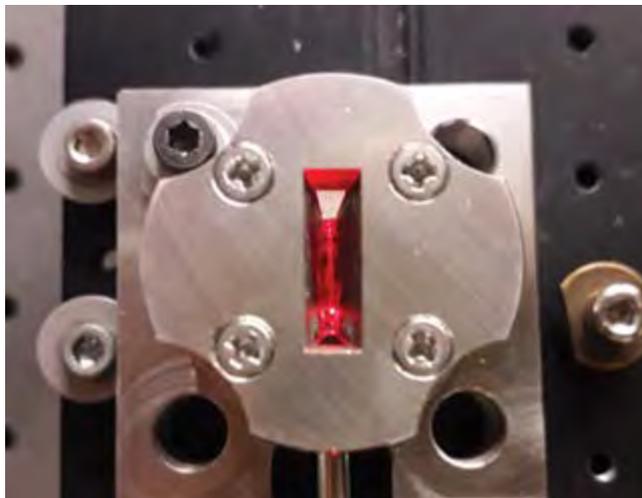

Figure 3: An open quartz capillary micromachined with a femtosecond laser was employed to generate short-wavelength light via stimulated emission in helium.

In 2023 we also made great progress in the analysis of the results of two-photon (two-colour) photoionization, in which we tested whether photoionization using first photon and excitation of the remaining ion by the second photon are two independent events. Experiment 20209086 "Strong coupling of the continuum via excitation of the core in above-threshold ionization'' (PI A. Mihelič) with the free electron laser light FERMI at the LDM beamline shows that the photoelectron "sees" the transition in the ion, and we also see a strong dichroic effect, which can only occur in the atom as a whole. Recently, the journal Nature wrote about this topic, and we expect a lively discussion of this issue in the future.

Within the field of X-ray spectroscopic methods applied for the study of novel electrochemical energy-storage materials, in 2023 we have continued with the X-Ray Raman Scattering (XRS) measurements on advanced post-lithium battery systems. The XRS endstation at the P01 beamline of the PETRA III synchrotron at DESY in Hamburg was used to record both C and Na K-edge absorption spectra from bulk Na-ion battery hard-carbon anodes at several points during battery cycle to study the process of sodiation and de-sodiation.

Later on, the XRS spectroscopy was also applied for the study of electrochemical mechanism in Al-organic battery systems. Both, *ex-situ* and *operando* XRS measurements of oxygen K and aluminum K and L absorption edges in cathodes made of different organic polymers were performed at the at ID20 beamline of the ESRF synchrotron in Grenoble. Particularly the measurements in *operando* mode will provide an accrate insight into the basic electrochemical mechanism of this promising novel multivalent organic battery system. Both experiments were carried out in collaboration with the Group for Modern Battery Systems from the National Institute for Chemistry.

Figure 4: Experimental setup at the ID20 beamline of the ESRF synchrotron hosting the XRS spectrometer with 72 spherically bent analyzer crystals arranged in six modular groups providing analysis of inelastically scattered X-rays with high energy resolution and a large detection solid angle.

Besides the application of X-ray spectroscopy using synchrotron light, we have worked extensively on the implementation of laboratory X-ray emission (XES) measurements as a tool used to transfer the spectroscopic analysis of advanced battery materials from synchrotrons to smaller laboratories. Previous *ex-situ* laboratory sulfur XES measurements on lithium-sulfur bulk battery cathodes performed at the Microanalytical Center using excitation with an accelerated ion beam were complemented with the *operando* sulfur XES measurements using an X-ray tube for the photoexcitation. Measurements were performed at the University of Fribourg using a von Hamos spectrometer. The analysis of the measured *operando* Kb XES spectra corresponding to electron transitions from occupied valence states, made it possible to follow the electrochemical conversion of sulfur in the cathode during two consecutive battery cycles. These results represent an important contribution within the process of development and implementation of advanced spectroscopic diagnostic tools that provide

laboratory analysis of electrochemical processes and material properties, without the restrictions imposed by the use of large research infrastructure such as synchrotrons.

As part of the experimental development of ion-beam analytical methods going on at the Microanalytical Center, the characterization study yielding basic properties and first applications of the newly developed PB-WDS (parallel-beam wavelength dispersive) X-ray spectrometer installed at the external proton beamline have been published in 2023 (Isaković et al., J. Anal. At. Spectrom., 2023, 38, 1164). Within this year, also the chemical sensitivity of the sulfur and phosphorus PIXE spectra measured with the new spectrometer has been probed. Together with the imaging capabilities of our external proton beamline, the chemical contrast provided by the spectrometer provides the possibility to map ultimately even the distribution of particular chemical state within spatially non-homogeneous sample.
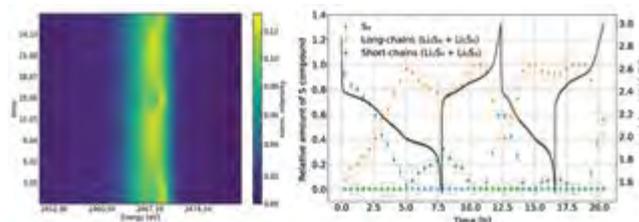
Figure 5: Time series of operando laboratory sulfur $K\beta$ spectra of LiS battery cathode measured during two consecutive cycles (left). The analysis of the measured spectra provided precise quantitative analysis of sulfur conversion within battery cathode during cycling (submitted to ACS Applied Energy Materials).

In our research with organic radical molecules for two-dimensional architectures of organic qubit networks we performed a combined experimental and theoretical study of azafullerene ($C_{59}N$) molecules UHV assembled in ordered layers on solid surfaces. Together with our colleagues from the Solid State Physics Department (F-5) and Faculty for Mathematics and Physics of the Ljubljana University we lead several experiments with synchrotron light at the Elettra Synchrotron at Trieste and performed X-ray spectroscopy and low-temperature scanning tunnelling microscopy of ultrathin films of $C_{59}N$ radicals. In the publication of *Tanuma et al., 2023*, we investigated the self-assembly of $C_{59}N$ molecules on gold with the most important result of this study being the discovery of the extraordinary stability of $C_{59}N$ radicals in the second non-contact layer, which opens many possibilities for manipulation of their spin (qubit) state.

The occurrence of spin active phase of azafullerenes in the supramonolayer films together with their long-term stability opens new ways for the design of organic architectures suitable for molecular spintronics. Based on our findings we have been granted several beamtimes also in 2023-2024 (ID 20225294 in ID 20220289) and we successfully applied for the NFFA Europe project (ID 447-2023).

In the Laboratory for Fusion Research we conducted several tasks that are coordinated within the EUROfusion consortium. Among them the influence of grain boundaries (GBs) on the deuterium (D) transport and the creation of defects in nano crystalline tungsten (W) films deposited on a W substrate was studied (Markelj et al., Nuclear Materials and Energy 37 (2023) 101509). Samples with three different grain sizes were produced for this purpose: a sample with a film having nanometre-size grains, a sample with hundred nanometre-grained film and a sample with micrometre-grained film. Samples were irradiated by 20-MeV W ions at 300 K to create displacement damage and exposed to 300-eV D ions at 450 K to populate the created and any pre-existing defects. The D transport and retention was assessed by measuring D depth profiles after certain exposure times by nuclear reaction analysis (NRA) using a ^{3}He ion beam. From the final D concentration in the damaged area, we could determine the concentration of defects that trap hydrogen, showing that the sample with the smallest grain size had the highest D concentration and it decreases with the increase of the grain size. Therefore,

Figure 6: Schematic figure of polycrystalline and nanocrystalline W sample and how the deuterium diffusion proceeds in both cases together with the self-interstitial diffusion and deuterium population of vacancies and vacancy cluster that were created within the grain due to W irradiation (Markelj et al. Nuclear Materials and Energy 37, 2023, 101509)

in nanocrystalline tungsten irradiated at 300 K, GBs do not improve the radiation resistance, which would lead to fewer defects. For the first time we showed experimentally, that D transport is faster inside the nanometre-grained sample as compared to the micrometre-grained sample, meaning that D atoms have enhanced bulk diffusion along the GBs, as schematically represented in **Figure 1**.

In 2021 we were awarded an Enabling research project ENR-MAT.01.JSI entitled "Detection of DEfects and HYDROgen by ion beam analysis in Channelling mode for fusion – DeHydroC". In 2023 we have analysed the data on the channelling measurement performed at The Centro de Microanálisis de Materiales (CMAM)–Universidad Autónoma de Madrid. Within this work we have studied radiation-induced defect production in tungsten by a combination of experimental and simulation methods. The analysis of structural defects was performed using multi-energy Rutherford backscattering spectroscopy in a channelling configuration (multi-energy C-RBS). Detailed transmission electron microscopy (TEM) analysis of the samples revealed the presence of dislocation lines and loops of different sizes. The RBSADEC code was used to simulate the measured C-RBS spectra, recorded with four different He beam energies along the ⟨111⟩ direction. For the first time with tungsten, molecular dynamics (MD) simulations

of overlapping cascades were used as the input. Very good agreement between the simulated and experimental spectra was obtained for the sample prepared at a lower dose, despite the fact that the absolute defect densities are two orders of magnitude higher than those found with TEM.

The JSI tandem accelerator provided 4000 beam hours to the users in 2023. The operation was dedicated to the realisation of number of national and international research projects. Part of the operation was dedicated to the Transnational access programme of EU within the H2020 project RADIATE (https://www.ionbeamcenters.eu/radiate/). In 2023 we executed eight TNA projects in total duration of 370 beam hours. The accelerator facility is a member of the ARIE (The Analytical Research Infrastructures in Europe) network. In 2023, ARIE started the execution of the ReMade@ARI project at the field of Circular Economy, as well as successfully submitted a proposal RIANA, which offers coordinated access to more than 50 European analytical research infrastructures to foster the research dedicated to nanotechnologies.

Intense research with high-energy focused-ion beams at the fields of biology and medicine took place at the JSI microbeam. Olive-tree leaves of Belica and Leccino cultvars were studied for the tissue-specific distribution of elements by micro-PIXE method (Pongrac et al., 2023). The potential of cold-plasma treatment of buckwheat sprouts for zinc biofortification was studied (Starič et al, 2023). In a continuous process of developing of the molecular imaging mass spectroscopy technique MeV-SIMS, we explored the chemical sensitivity of the technique (Vasić et al, 2023), the effect of the application of cationization agent (Jenčič et al, 2023), as well as the effects of gold film atop the organic samples (Jenčič et al., 2023) on the molecular yields in MeV-SIMS. The reconstruction of the sample topographical features from the asymmetries in the X-ray PIXE yields in the individual segments of the segmented X-ray Silicon Drift Detector (Hatam et al., 2023).

New efforts were invested in the extraction of low-energy ion beams from the region of injector, enabling the ion beams produced within Cs sputter ion source and duoplasmatron to be directed into a planned low energy branch. Several new applications will be potentially explored, including ion implantation and solar wind simulation.

In 2023 the Infrastructure Center for Ionizing Radiation Measurements (ICMIS) conducted numerous professional activities, including environmental radioactivity monitoring in Slovenia, personal dose measurements, and calibration of measuring instruments.

Figure 7: Installation of the new 6-axis goniometer for ion channeling in the JSI ion accelerator laboratory

We performed measurements using high-resolution gamma spectrometry and liquid scintillation spectrometry. Additionally, we measured personal and environmental doses of ionizing radiation using thermoluminescent dosimeters. Laboratories engaged in ionizing radiation measurements are accredited according to the SIST EN ISO/IEC 17025 standard. Related to accreditation requirements, we successfully participated in international intercomparisons in 2023, demonstrating an excellent level of professional competence.

Our activities included off-site radiological monitoring of the Krško Nuclear Power Plant (NEK), monitoring of radioactivity in living environment in Slovenia, measuring atmospheric effluents from NEK, monitoring radioactivity around the Central Radioactive Waste Storage in Brinje (ARAO), and independently verifying the operational radiological monitoring around NEK. We also monitored radioactivity in groundwater near the Low and Intermediate Level Radioactive Waste Repository (NSRAO) and measured the total activity of alpha and beta emitters in drinking water. Furthermore, we conducted radioactivity monitoring of drinking water in Slovenia.

Under the authorization of the Slovenian Radiation Protection Administration (URSVS), we measured personal doses (personal dose equivalent) using thermoluminescent dosimeters (TL dosimeters) for 2211 exposed workers, including 148 colleagues at the Jožef Stefan Institute. We regularly submit data to the SRPA central dose register. In 2023 we measured ambient dose equivalents using TL dosimeters at 132 different locations in Slovenia.

At the Secondary Standard Dosimetry Laboratory (NDS) we conducted a total of 249 calibrations: 162 for dose rate meters, 42 for electronic personal dosimeters, and 45 for contamination meters. We also performed 195 series of irradiations of passive dosimeters.

In the Laboratory for Radioactivity Measurements (LMR) we completed 697 measurements as part of regular monitoring programmes and an additional 83 measurements for sporadic external customers, compiled into 18 reports. Six of these reports were prepared for the Ministry of Agriculture, Forestry, and Food (MKGP) or the Administration for Food Safety, Veterinary Sector, and Plant Protection (UVHVVR).

As part of radiological monitoring around NEK and country-wide in Slovenia, we conducted 171 measurements of tritium content in water samples by liquid scintillation spectrometry. For sporadic external customers, we analyzed tritium content in 9 samples.

We also prepared various expert reports for different clients and customers:
- Implementation of the Program for Systematic Survey of the Workplace in activities involving materials containing naturally occurring radionuclides for 2023.
- Certifications of measuring instruments used by employees in nuclear and radiation facilities.

- On June 8, 2023, the Ecological Laboratory with a Mobile Unit (ELME) at IJS conducted a radiological survey at the Ljubljana-Polje railway station upon request from SNSA. Measurements of the dose rate of sand along the railway tracks showed that both specific and total activity exceeded exemption or clearance levels. The decision regarding remediation was made by the Chief Inspector for Nuclear and Radiation Safety from SNSA.
- For the Administration for Civil Protection and Disaster Relief, we prepared an expert report on short-term, medium-term, and long-term plans to strengthen our preparedness for CBRN threats and enhance emergency preparedness and response at the EU level.

In 2023 we continued collaboration with the Metrology Institute of the Republic of Slovenia (MIRS). As a designated institution within the European Association of National Metrology Institutes (EURAMET), we serve as the holder of the national standard for ionizing radiation in Slovenia. Our metrological activities included work on:
- EMPIR 2019, JNT-w08 supportBSS – Support to the European Metrology Network for Reliable Radiation Protection Regulation.
- PR-02570-1 – Preparation of reference and intercomparison samples, in collaboration with IARMA.

We participated in the European project *Partnership for Radiation Protection Research* (PIANOFORTE), where JSI (departments F2 and O2) is the competent institution for Slovenia. This provides ICMIS an opportunity to improve and strengthen capacities in our laboratories.

We also took part in the MEREIA programme under the auspices of the International Atomic Energy Agency (IAEA), which brings together scientists and experts in radiation protection and radioecology. IJS-F2 was given to

Figure 8: Preparation of salad for the analysis of its radionuclide contents (left two images) and in-situ measurements during the RUME exercise in May 2023 in Ormož (right).

coordinate *Working Group 3: Historical Marine Dumping of Radioactive Waste* activities.

We continued activities on project SLO9022 within the IAEA Technical Cooperation programme titled "*Strengthening the Capacity of Slovenia in Emergency Preparedness and Response Radiation Monitoring*."

With funding from the Administration for Civil Protection and Disaster Relief (URSZR), we purchased an ionization chamber in 2023—the most sensitive environmental dose rate meter. We replaced old radio communication equipment to contact the Notification Center (CORS) and NEK in our mobile radiological laboratory and also purchased a new, more powerful generator to ensure adequate power supply during field measurements.

Our research and development in gamma and X-ray radiation dosimetry, maintenance of standards, and testing of measurement systems used in radiation protection focused on improving measurement traceability procedures, reducing measurement uncertainty, and maintaining the existing systems. In 2023 the main emphasis was on developing new safety systems and creating a new control system for radioactive sources management.

Through the ARIS Equipment 2021 initiative we acquired new equipment for the Laboratory for Liquid Scintillation Spectrometry in 2023. The DEFORT system (Environmental Forensics with C14 and H-3) now includes a new electrolysis setup (bath with thermostat and controllers), two sets of heaters for primary and secondary distillation, a lyophilizer, and a decontamination system.

Organization of conferences, congresses and meetings

1. 9th DeHydroC meeting, Ljubljana, 29–31 March 2023

INTERNATIONAL PROJECTS

1. Max Planck Partner Group
   Dr. Andreja Šestan Zavašnik
   Max-Planck-Institut für Eisenforschung GmbH
2. EMPIR - supportBSS; Support for a European Metrology Network on Reliable Radiation Protection Regulation
   Denis Glavič Cindro, M. Sc.
   Euramet E.v.
3. EMPIR; AEROMET II; Advanced Aerosol Metrology for Atmospheric Science and Air Quality
   Asst. Prof. Klemen Bučar
   Euramet E.v.
4. COST CA18222; Attosecond Chemistry
   Asst. Prof. Andrej Mihelič
   COST Association Aisbl
5. COST CA18212; MD-GAS - Molecular Dynamics in the GAS Phase
   Prof. Matjaž Žitnik
   COST Association Aisbl
6. TC Regional Project RER/7/014: Improving Environmental Monitoring and Assessment for Radiation Protection in the Region
   Asst. Prof. Benjamin Zorko
   IAEA - International Atomic Energy Agency
7. Experiments and Modelling of In Situ Uptake, Transport and Release Studies of Hydrogen Isotopes in Irradiated Tungsten; Hydrogen Permeation in Fusion-Relevant Materials
   Asst. Prof. Sabina Markelj
   IAEA - International Atomic Energy Agency
8. Detection of Hydrogen Isotopes by NRA, Cross Sections and Best Practices; Development

and Application of Ion Beam Techniques for Materials Irradiation and Characterization Relevant to Fusion Technology
Asst. Prof. Sabina Markelj
IAEA - International Atomic Energy Agency

9. H2020 - RADIATE; Research and Development with Ion beams - Advancing Technology in Europe
Prof. Matjaž Kavčič
European Commission

10. H2020 - CleanHME; Clean Energy from Hydrogen-Metal Systems
Prof. Matej Lipoglavšek
European Commission

11. H2020 - HITRIplus; Heavy Ion Therapy Research Integration
Asst. Prof. Matjaž Vencelj
European Commission

12. HE - EUROfusion; WP07: ENR-DeHydroc-1,2,3_HE-FU
Asst. Prof. Sabina Markelj
European Commission

13. HE - EUROfusion; WP18: MAT_HE-FU, IREMEV-MAT-1_HE-FU, IREMEV-MAT-2_HE-FU, IREMEV-MAT-3_HE-FU
Asst. Prof. Sabina Markelj
European Commission

14. HE - EUROfusion; WP05: PWIE-1,2,3,_HE-FU, PWIE-4-Accelerator
Asst. Prof. Sabina Markelj
European Commission

15. HE - EUROfusion; WP24: TRED_HE-FU, EDU_HE-FU
Asst. Prof. Sabina Markelj
European Commission

16. HE - PIANOFORTE; European Partnership for Research in Radiation Protection and Detection of Ionising Radiation: Towards a Safer Use and Improved Protection of the Environment and Human Health
Asst. Prof. Benjamin Zorko
European Commission

17. HE - ReMade-at-ARI; Recyclable Materials Development at Analytical Research Infrastructures
Prof. Primož Pelicon
European Commission

18. HE - TITANS; Tritium Impact and transfer in Advanced Nuclear reactors
Asst. Prof. Sabina Markelj
European Commission

19. EMPIR; OpMetBat - Operando Metrology for Energy Storage Materials
Prof. Matjaž Kavčič
Euramet E.v.

20. COST CA18212; E-COST-GRANT-CA18212-c09b5731 - Single Electron Probe of Chemical Environment - Study of TEOE Decay in Simple Cl Containing Molecules
Prof. Matjaž Žitnik
COST Association Aisbl

RESEARCH PROGRAMMES

1. Archaeological heritage research
Dr. Eva Menart
2. Object and Prestige; taste, status, power (Researches of the material culture in Slovenia)
Dr. Marijan Nečemer
3. Structure of hadronic systems
Prof. Simon Širca
4. Studies of atoms, molecules and structures by photons and particles
Prof. Matjaž Žitnik
5. Fusion technologies
Asst. Prof. Sabina Markelj

R & D GRANTS AND CONTRACTS

1. Structured light as a tool for triggering and probing new states of matter
Prof. Matjaž Žitnik
2. Alternative approaches to assuring guality and security of buckwheat grain

microbiome
Prof. Primož Pelicon

3. Lessons from nutrient-use-efficient plants to benefit dietary mineral intake
Prof. Primož Pelicon

4. High-energy aluminium metal-organic batteries
Prof. Matjaž Kavčič

5. Novel proxies of the Holocene climate variability in stalagmites in Slovenia
Prof. Primož Pelicon

6. Developing tender X - ray spectroscopy probes to tackle problems in materials science and ultrafast science
Prof. Matjaž Kavčič

7. Detection of defects and hydrogen by ion beam analysis in channelling mode for fusion
Asst. Prof. Sabina Markelj

8. Precision studies of inclusive response of light nuclei
Prof. Simon Širca

9. Formation and Design of AM-processed Fe-Al alloys with self-forming Hydrogen Permeation Barriers for the harshest of environments
Asst. Prof. Sabina Markelj

10. Generation of isolated Nitrogen-vacancy centers in diamond by ion implantation
Dr. Žiga Barba

11. SiMBION – EuBI
Prof. Primož Pelicon
Slovenian Research Agency

12. FAIR
Dr. Jelena Vesić
Slovenian Research Agency

13. FAIR
Dr. Jelena Vesić

14. Slovenian Research Agency

15. Dr. Jasmina Kožar Logar
Ministry of Health

16. Radioactivity Monitoring in Drinking Water for the Year 2023 - PART 2
Asst. Prof. Benjamin Zorko
Ministry of Health

17. Monitoring of Central LILW Storage Facility at Brinje-Report for year 2023
Dr. Marijan Nečemer
ARAO - Agency for Radioactive Waste Management

18. Fusion technologies
Asst. Prof. Sabina Markelj
Slovenian Research Agency

19. Small Services
Branko Vodenik, M. Sc.

20. Calibrations
Boštjan Črnič

21. Different Analyses; Reference Materials
Dr. Jasmina Kožar Logar

22. CROSSING - Crossing Borders and Scales - An Interdisciplinary Approach
Prof. Primož Pelicon
Helmholtz-Zentrum Dresden-Rossendorf E.V.

NEW CONTRACTS

1. Maintaining emergency preparedness and response by ELME (2020-2023)
Asst. Prof. Benjamin Zorko
Krško Nuclear Power Plant

2. Qualitative and quantitative monitoring of groundwater in the impact area of the dam for HPP Mokrice
Asst. Prof. Benjamin Zorko
Irgo Consulting d. o. o.

3. LOT 1: Measurements of gaseous effluents - Specific analyzes of H-3 and C-14 in 2022, 2023, 2024 and 2025; LOT 2: Measurements of gaseous effluents - Gamma spectrometry and analysis of strontium Sr-89/90 in 2022, 2023, 2024 and 2025
Asst. Prof. Benjamin Zorko
Krško Nuclear Power Plant

4. Environmental radioactivity monitoring in the vicinity of the Krško Nuclear Power Plant in connection with Hydro Power Plant Brežice for the years 2022 and 2023
Asst. Prof. Benjamin Zorko
Krško Nuclear Power Plant

VISITORS FROM ABROAD

1. Prof. Dr. Jelena Ajtić, Jelena Krneta Nikolić, Darko Sarvan, Fakulty of Veterinary Medicine, Belgrade, Serbija, 10–13 September 2023
2. Prof. Dr. Jelena Ajtić, Fakulty of Veterinary Medicine, Belgrade, Serbija, 20–22 November 2023

3. Dr. Ivana Coha, IRB, Zagreb, Croatia, 1 February to 31 December 2023
4. Dr. Juergen Gerl, Hu Hao, FAIR/GSI, Darmstadt, Germany, 6 November 2023
5. Federica Pappalardo, University of Aix-Marseille, Marseille, France, 26 March to 6 May 2023

STAFF

Researchers
1. Prof. Iztok Arčon*
2. Asst. Prof. Klemen Bučar
3. Dr. Aleksandra Cvetinović
4. Prof. Dean Cvetko*
5. Dr. Helena Fajfar
6. Denis Glavič Cindro, M. Sc.
7. Dr. Darko Hanžel
8. Prof. Matjaž Kavčič
9. Dr. Jasmina Kožar Logar
10. Dr. Romana Krištof*
11. Prof. Matej Lipoglavšek
12. Asst. Prof. Sabina Markelj
13. Asst. Prof. Andrej Mihelič
14. Asst. Prof. Miha Mihovilovič
15. Dr. Marijan Nečemer
16. **Prof. Primož Pelicon**, Head
17. Asst. Prof. Marko Petric
18. Dr. Toni Petrovič
19. Asst. Prof. Paula Pongrac*
20. Dr. Jurij Simčič
21. Prof. Simon Širca*
22. Dr. Primož Vavpetič
23. Asst. Prof. Matjaž Vencelj
24. Dr. Jelena Vesić
25. Branko Vodenik, M. Sc.
26. Prof. Katarina Vogel-Mikuš*
27. Asst. Prof. Benjamin Zorko
28. Prof. Matjaž Žitnik

Postdoctoral associates
29. Dr. Žiga Barba
30. Dr. Boštjan Jenčič
31. Dr. Eva Menart*
32. Dr. Esther Punzon Quijorna
33. Dr. Andreja Šestan Zavašnik

Postgraduates
34. Žiga Brenčič, B. Sc.
35. Gregor Košir, B. Sc.
36. Eva Lovšin, B. Sc.
37. Ava Rajh, B. Sc.
38. Mirjana Sepahyar Lorentzen, M. Sc.
39. Janez Turnšek, B. Sc.

Technical officers
40. Boštjan Črnič, B. Sc.
41. *Polona Gerjol, B. Sc., left 20.11.23*
42. Dr. Mitja Kelemen
43. Klara Poiškruh, B. Sc.
44. Petra Prem, B. Sc.
45. Matevž Skobe, B. Sc.
46. Klemen Žagar, B. Sc.

Technical and administrative staff
47. Kristina Benko
48. Mojca Gantar
49. Sandi Gobec
50. Andrej Košiček, B. Sc.
51. Mirko Ribič, B. Sc.
52. Rok Roš Opaškar

Note:
* part-time JSI member

DEPARTMENT OF THIN FILMS AND SURFACES

The main research field of the department is the development, deposition and characterization of hard protective PVD coatings, while research is also conducted in other fields of thin films and surface physics. The basic research is the study of the physical and chemical properties of various multicomponent, multilayer and nanostructured coatings. Within the applied research, different coatings are developed for the protection of tools for various production processes in industry.

In 2023 the department continued to focus on transition-metal nitride hard coatings. We completed the investigation of the microstructural, mechanical and oxidation properties of the CrAlN nanolayer coating. The special feature of this coating was that it was deposited in an industrial device using triangular segmented targets. Thus, coatings with different Cr:Al atomic ratios were obtained in the course of a single disposition. In this study, $(Cr,Al)N$ nanolayer coatings with different compositions were deposited on different substrates (H11 and D2 tool steels). Oxidation tests showed that the $(Cr,Al)N$ coatings with a higher aluminium content resisted oxidation significantly better than those with a higher chromium content. We found that the oxidation layer that formed on the higher aluminium content coating consists of two layers: an upper chromium oxide layer and an inner mixed (Cr,Al) oxidation layer. In contrast, the oxidation layer on the higher chromium coating consists mainly of a Cr_2O_3 layer. We focused in particular on the oxidation process occurring at the sites of growth defects. We found that the first oxidation products on the coated substrate appeared at a temperature much lower than that at which the oxidation of the $(Cr,Al)N$ coating started. These products (iron oxides) formed only at the defect sites that extended through the entire thickness of the coating.

To a lesser extent, similar research was also carried out on the $(Cr,V)N$ nanolayer coating, where the main focus was on the study of tribological processes at a high temperature; this work was carried out in collaboration with the Institute of Metals and Technologies. In the field of nitride coatings, collaboration with the University of Trieste on the wear and corrosion resistance of CrN/Mo_2N and CrN/W_2N multilayer coatings is also worth mentioning.

Tribological experiments were carried out to study the wear of TiAlN coatings at elevated temperatures of up to 700 °C in different atmospheres (air, N_2, CO_2). The focus was on the coefficient of friction, the wear of the ball and disc and the microhardness of the coating on the disc before and after the elevated temperature tests. Tribological investigations were also carried out using liquid CO_2 as the coolant in a laboratory environment on a tribometer. In collaboration with the University of Novi Sad (Serbia), we also investigated the temperature conditions in contact and in the immediate surroundings. We also investigated the possibility of post-treatment and removal of coatings using a laser beam.

One of the important new research directions in our laboratory, and in the wider world, is thin films of high-entropy alloys and their nitrides. The following coatings have been deposited using an in-house-developed deposition system: TiVCrZrNbMo, (TiVCrZrNbMo)N, TiVCrHfTaW, (TiVCrHfTaW)N, ZrNbMoHfTaW and (ZrNbMoHfTaW)N. Their properties were thoroughly evaluated using the following techniques: scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), nanoindentation, profilometry, X-ray diffraction (XRD) and atomic force microscopy (AFM). These provided information on the microstructure, hardness, surface topography and chemical composition of the coatings. We found how different parameters of the deposition process affect the properties of the coatings, thus contributing to a better understanding and further optimisation of high-entropy alloys and their nitrides for use in different applications.
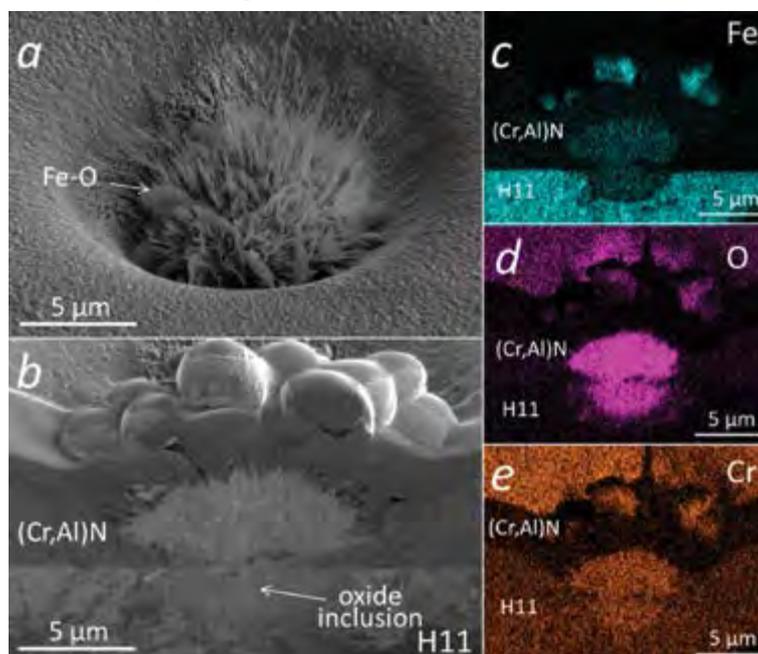
Head:
Prof. Miha Čekada

Figure 1: Top-view SEM image (a) and SEM image of FIB cross-section (b) of a pinhole in a (Cr,Al)N nanolayer coating deposited on an H11 tool steel substrate after short-term oxidation at 800 °C. The corresponding EDS elemental maps are presented in (c–e).

Oxide layers have also been dealt with to a lesser extent. In collaboration with other departments at the Institute, we have studied how annealing in air affects the microstructure and mechanical properties of thick $0{,}9Pb(Mg_{1/3}Nb_{2/3})O_3$–$0{,}1PbTiO_3$ layers prepared with aerosol deposition. Transmission electron microscopy revealed minor but detectable changes such as pore redistribution and grain growth after annealing at 500 °C. We also showed that the heat treatment had a strong effect on the stainless steel substrate. The hardness and Young's modulus of the layers increased after annealing. Oxide layers were also the subject of a collaboration with the University of Ljubljana, Biotechnical Faculty, within which we analysed a PVDF-HFP/PVP/MoO_3 nanocomposite that showed good properties for use on food contact surfaces. We also worked on the deposition of iridium-doped titanium thin films for electrocatalysis (in collaboration with the Department of Nano-structured Materials) and the deposition of very thin islands of platinum for photocatalysis (with the Department of Advanced Materials).

Figure 2: Tribological test with a simultaneous liquid CO_2 supply

In the past year, we carried out a series of experiments to study the influence of different parameters on the dynamics of ionisation zones in high-power impulse magnetron sputtering (HiPIMS). The investigations were carried out using a high-speed camera to analyse the behaviour of the zones for single pulses at different argon pressures (0.25–2 Pa) and discharge currents (10–400 A). We found that as the discharge current increases, the plasma passes through three characteristic phases. In phase I, which lasts from the onset of the pulse to a current of about 25 A, the dynamics of the ionisation zones are similar to those in DC discharges, the zones have an elongated triangular shape and rotate in the $-\mathbf{E}\times\mathbf{B}$ direction with a velocity of 4–15 km/s. The velocity depends on the increasing current, the argon pressure and the number of ionisation zones. In phase II, present between about 25 and 50 A, the plasma behaves chaotically, forming non-periodic patterns, while the zones rotate in the $-\mathbf{E}\times\mathbf{B}$ or $\mathbf{E}\times\mathbf{B}$ directions. At currents of above 50 A, the plasma enters phase III. Periodic patterns begin to form, the zones have a characteristic triangular shape and rotate in the $\mathbf{E}\times\mathbf{B}$ direction at a speed of 6–9 km/s. The velocity of the zones depends only on the pressure, while the discharge current and the number of zones do not affect the velocity.

The department is also actively involved in fusion research. In the past year, we focused on the X-ray photoelectron spectroscopy (XPS) analysis of various fusion-relevant materials. In collaboration with colleagues from the Department of Solid State Physics and researchers from the Vinča Institute of Nuclear Sciences (Serbia), we were investigating the magnetic properties of multilayer thin films. On Si/Ni/Si multilayers with a nickel thickness of more than 15 nm, we observed a strong orthogonal magnetic anisotropy, which usually occurs in much thinner layers. This multilayer structure might open up new possibilities for use in magnetic recording media, sensors, spintronics and other applications.
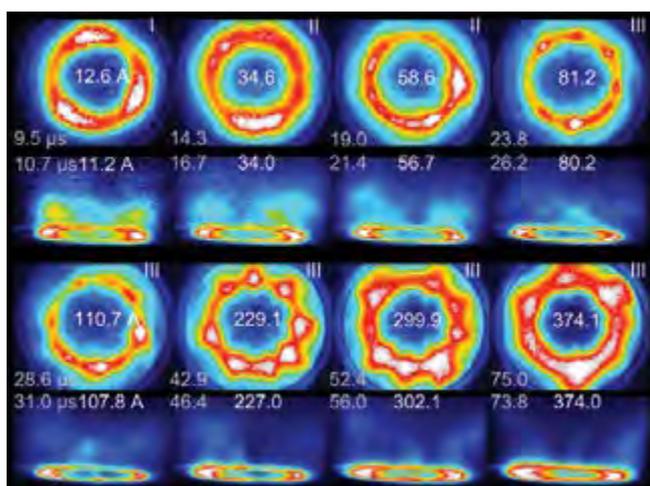

Figure 3: As the HiPIMS current increases, the plasma passes through the characteristic phases marked as I, II and III. The figure shows the characteristic plasma patterns of each phase, taken with a high-speed camera from frontal and side views.

We also continued to investigate the physical processes of sputtering. For the transition metals in groups 4–6 and 11 and selected light elements, the energy distributions of the sputtered atoms were calculated using the SRIM code. This was done using the optimised values of surface binding energies determined in the previous year. The SRIM simulations were compared with the analytical energy distribution equations developed by Sigmund and Thompson and with the experimental data from the literature. The results of the SRIM simulations of the energy distributions were realistic for transition metals, but were not correct for the elements lighter than Si. All energy distributions have a low-energy peak near one half of the surface binding energy and a high-energy tail that decreases approximately as E^{-2}. Trends were observed in the characteristics of the energy distributions, such as peak position and full-width half-maximum of the peak (FWHM), with respect to the atomic number, ion energy, and the group of the periodic system in which the element is located. For transition metals, we proposed an empirical equation to estimate the average energy based on the sputtering coefficient – the average energies of the sputtered atoms are inversely proportional to the sputtering coefficient, with transition metals showing the highest average energies and the elements in Group 11 showing the lowest average energies.

We also made sputtering-coefficient measurements for Ti, V, Cr and Cu and compared them with simulated values. The deviations between the SRIM simulations and the experimental sputtering coefficients were most pronounced at the lower energies of the argon ions. While the measurements for Cu and Cr agreed with the simulations above

100 eV, the deviations for V and Ti were more pronounced. We also measured the differential-sputtering coefficients for magnetron targets Al, Ti, V, Cr, Cu, Nb, Mo, Hf and Ta. The sputtering coefficient is maximum at 40–50° for all the measured elements and it decreases with the emission angle.

The department collaborates intensively with Slovenian industry. Companies turn to us for various challenges related to surfaces and thin films. These may include development tasks, more advanced analytics or finding the root cause of problems. In the past year, we performed such analyses for companies Cetis, Kovinos, Krka, Le-tehnika, Phos, Polident, Teroxal and Trelleborg. We also provide hard coating services for companies, applying hard coatings on their tools, which we do within the Hard Coating Centre, operating within the department. We have over a hundred partners a year, including large companies (e.g., SIJ, Kolektor, Mahle) as well as a multitude of small tool shops.

Some outstanding publications in the past year

1. N. Mahne, M. Čekada, M. Panjan, Energy distribution of sputtered atoms explored by SRIM (Stopping and Range of Ions in Matter) simulations, Coatings, 2023, vol. 13, no. 8, pp. 1448-1-1448-30. ISSN 2079-6412. DOI: 10.3390/coatings13081448
2. A. Drnovšek, D. Kukuruzović, P. Terek, A. Miletić, M. Čekada, M. Panjan, P. Panjan, Microstructural, mechanical and oxidation resistance of nanolayer sputter-deposited CrAlN hard coatings, Coatings, 2023, vol. 13, no. 12, pp. 2096-1-2096-20. ISSN 2079-6412. DOI: 10.3390/coatings13122096

INTERNATIONAL PROJECT

1. HE - EUROfusion; WP05: PWIE-1,2,3,_HE-FU, PWIE-4-Accelerator
   Dr. Matjaž Panjan
   European Commission

RESEARCH PROGRAMME

1. Thin film structures and plasma surface engineering
   Prof. Miha Čekada

R & D GRANTS AND CONTRACTS

1. Two-dimensional materials-based piezophotonic composites for tailor-made ultrasounds in biological systems (2D-UltraS)
   Dr. Aljaž Drnovšek

2. Self-organization of plasma in magnetron sputtering discharges
   Dr. Matjaž Panjan
3. Controllable broadband electromagnetic-radiation shielding
   Dr. Matjaž Panjan
4. Selected area functionalization of polymeric components by gaseous plasma
   Prof. Miha Čekada
5. Waterborne virus inactivation efficiency of a prototype device combining non-equilibrium plasma and hydrodynamic cavitation
   Prof. Miha Čekada
6. Nanostructured high entropy alloy coatings for tooling applications
   Dr. Aljaž Drnovšek
7. Deposition of Hard Coatings
   Prof. Miha Čekada

NEW CONTRACTS

1. Nanostructured high entropy alloy coatings for tooling applications" (L2-50059-1)
   Dr. Aljaž Drnovšek
   Phos BB, d. o. o.
   Kovinos d. o. o.

VISITORS FROM ABROAD

1. Vladimir Terek, University of Novi Sad, Novi Sad, Serbia, 16 January to16 February 2023
2. dr. Marin Tadić, Vinča nuclear institute, Belgrade, Serbia, 12–26 March 2023
3. dr. Marin Tadić, Vinča nuclear institute, Belgrade, Serbia, 17–30 June 2023

STAFF

Researchers
1. **Prof. Miha Čekada, Head**
2. Dr. Aljaž Drnovšek
3. Dr. Matjaž Panjan
Postgraduates
4. Matej Drobnič, B. Sc.
5. Žan Gostenčnik, B. Sc.
6. *Nastja Mahne, B. Sc., left 01.10.23*

Technical officer
7. Uroš Stele, B. Sc.
Technical and administrative staff
8. Jožko Fišer
9. Damjan Matelič
10. Andrej Mohar
11. Tomaž Sirnik
12. Tadej Stele

DEPARTMENT OF SURFACE ENGINEERING

The main activity of our department is tailoring the surface properties of materials using thermodynamically non-equilibrium gas plasma. The basic principle of processing materials with gas plasma is the following: first, we select a suitable gas or gas mixture, and then we create a discharge in the selected gas so that a suitable density of free electrons is reached. Gas molecules, which are close to the ground state under normal conditions and room temperature, are excited to different states with high potential and/or kinetic energy during inelastic collisions with free electrons. Molecules in such energy states then react with the surfaces of the materials. Interactions of molecules in energy states can lead to functionalization, etching or deposition of coatings.

Head:
Prof. Alenka Vesel

Our department's main activity remains the treatment of surfaces of solid materials with thermodynamically non-equilibrium gas plasma. The free electrons in our plasmas have a temperature of about 10,000 K, so they dissociate gas molecules abundantly, which leads to the formation of chemically, highly reactive radicals. Such radicals usually chemically bind to the surfaces of the materials already at room temperature and thereby change their functional properties. Molecular radicals in the gas phase are stable at low pressure, but with increasing pressure, they can combine into stable chemically non-reactive molecules. Due to the loss of radicals at elevated pressure, plasma reactors used in industry for the treatment of material surfaces usually operate at low pressures, typically between 0.1 and 10 mbar. Sometimes, we also want to use gas plasma to process materials at normal air pressure, i.e., around 1000 mbar. This is especially true for biological materials, which typically cannot withstand low-pressure conditions. Maintaining a non-equilibrium plasma with a high degree of dissociation of the H_2O molecules for the treatment of water containing biological material at room temperature represents both a scientific and a technological challenge.

Maintaining a gas plasma in a liquid is, by definition, impossible, but we can create bubbles in the liquid in which we excite the plasma. The bubbles move quickly towards the surface of the liquid water due to buoyancy and are usually too small to accommodate electrodes for plasma excitation. We solved the problem by creating a large, stable bubble in liquid water using hydrodynamic cavitation. The water was forced through a suitably designed nozzle from the container with a slightly elevated pressure into the container at normal pressure. In the limited range of the geometric shapes of the nozzle, a cavitation bubble with a volume of several cubic centimetres was formed behind the nozzle in the direction of the flow of liquid water. The water vapor saturated pressure at room temperature, i.e., around 30 mbar, was sustained in the bubble. At this pressure, we easily maintained a stable gas plasma with a simple DC glow discharge. We protected the innovative solution with a patent application, and in November 2023, the US Office granted a patent US11807555 (B2) [1]. A preferred embodiment is disclosed in Figure 1. Arrows (1) indicate the flow of water between two plates (2, 3). In the area after the narrowing in the direction of the water flow, a stable cavitation bubble (5) appears, in which we installed two electrodes (6, 7). The electrodes were covered with thin insulation (8), which prevented galvanic contact between the water and the electrodes. When a voltage was applied between the electrodes, a gas plasma was maintained in the part of the volume in the cavitation bubble (5) at a saturated water vapor pressure. Since the pressure in the bubble was much lower than the atmospheric pressure, the concentration of OH radicals in the gas phase was large despite a relatively low discharge power. The loss of radicals in the gas phase increases with the square of the pressure so that in a cavitation bubble, it is thousands of times less than it would be in a normal bubble in liquid water. The configuration in Figure 1 has another advantage, i.e., the continuous supply of liquid water to the volume between the bubble (5) and the housing (2). This is very important since the solubility of OH radicals in water is limited. Furthermore, when OH
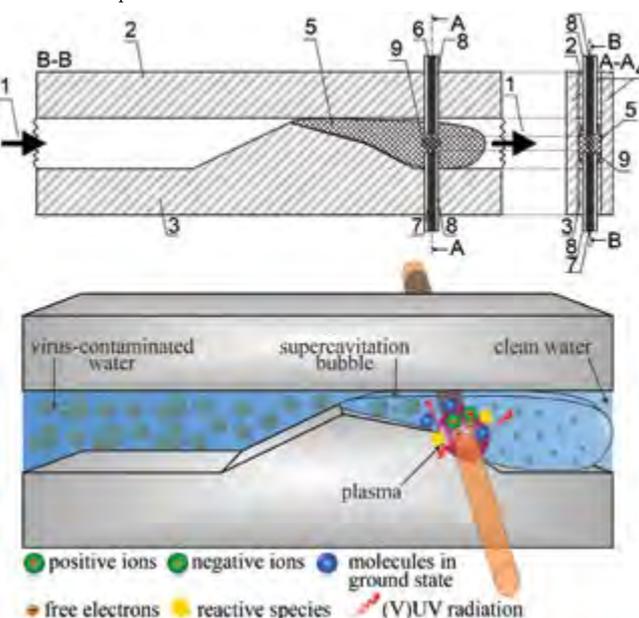

Figure 1: Embodiment that allows the excitation of a gas plasma at a pressure of about 30 mbar in liquid water, which is at a pressure of 1 bar or more [1] (drawing); the principle of operation of plasma cavitation for the inactivation of viruses (illustration).

radicals collide with each other in water, they are very likely to form hydrogen peroxide. The continuous supply of fresh water, therefore, enables an optimal concentration of OH radicals in the liquid water.

The scientific aspects of the innovative technology for supplying a large amount of OH radicals to running water were described in an article published in a reputable journal [2]. The OH radicals are particularly suitable for inactivating viruses because they irreversibly react with any organic material, as illustrated in Figure 1. Biological water pollution is becoming a growing problem even in the developed world, so many groups around the world are developing methods to inactivate micro-organisms in water. The ideal method would work at room temperature (or even lower), should not use chemicals, would consume little energy, and would not change the other properties of the

We have developed and patented a method for the rapid inactivation of viruses in water

water, such as the natural pH and the appropriate concentration of minerals. The method illustrated in Figure 1 comes very close to the ideal, as only OH radicals are introduced into the water. The radicals quickly react with organic material, and unreacted radicals decay with a half-life that is significantly less than a second. Some OH radicals (especially in excessive concentration in liquid water) form hydrogen peroxide, which also slowly reacts with organic impurities in water. In the scientific article [2] we very convincingly showed that OH radicals inactivate the selected type of virus even before the concentration of hydrogen peroxide becomes too high. The first author of this article received the Golden Emblem of the IJS for her outstanding work in the

field of plasma inactivation of viruses. The photograph in Figure 2 shows the winner. On the left-hand side is the head of the programme group (Miran Mozetič), and on the right -hand side is the head of the group in charge of research on plasma inactivation of viruses (Gregor Primc).

The extremely high oxidation potential of OH radicals is also used for the selective functionalization of synthetic polymers with hydroxyl groups. We studied in detail the kinetics of polystyrene functionalization during a treatment with OH radicals. The source of the radicals was a gas plasma, which was excited in water vapour in a remote plasma at low pressure. To measure the density of these radicals, we used a specially adapted sensor manufactured by our spin-off company Plasmadis Ltd. Figure 3 shows the concentrations of different functional groups versus the dose of OH radicals. At a very low dose of around 6×10^{19} m^{-3}, we observe a plateau on the curve, which corresponds to the surface hydroxyl groups. In the article [3], we presented a model that explains the rapid stabilization of the concentration

Figure 2: Postdoctoral fellow Arijana Filipić receives the IJS Golden Emblem Prize.

of hydroxyl functional groups on the surface of polystyrene at low doses. The OH radicals react with a hydrogen atom that is bound to carbon on the surface of polystyrene so that a water molecule is formed. The water molecule quickly desorbs since the pressure in the reaction vessel is much lower than the saturated water-vapor pressure at room temperature. The dangling bond is occupied by the next OH radical that reaches the polymer surface. When the surface is saturated with OH groups, further processing leads to the opening of the aromatic ring and, in the
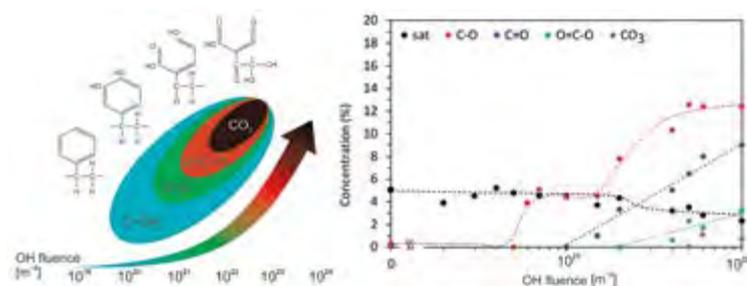
case of larger doses of radicals, to the cleavage of bonds in the polymer chain. Increasing the dose first causes the formation of carbonyl groups, and larger doses also enable the formation of functional groups with more than one oxygen atom bonded to the carbon.

The OH radicals also play an important role in gas conversion, as they chemically react with light hydrocarbons to form alcohols. Even more important is the conversion of nitrogen and hydrogen into ammonia. For a century, the Haber-Bosch process has been used on an industrial level, in which the gas mixture is heated, and ammonia is produced on the surface of the catalyst at high pressure. An alternative to this process is the dissociation

Figure 3: Kinetics of the formation of oxygen functional groups on the surface of polystyrene during treatment with OH radicals [3].

of N_2 and H_2 with gas plasma and the binding of atoms into NH_3 molecules. Numerous research groups worldwide are engaged in the plasma synthesis of ammonia, and they use various materials as catalysts for surface reactions. However, the surface synthesis of ammonia is not the only way of binding nitrogen atoms, but the heterogeneous recombination of nitrogen atoms into N_2 molecules also takes place on the surface. A carefully designed experiment made it possible to determine the coefficients for the conversion of nitrogen atoms into ammonia molecules. Atomic nitrogen and hydrogen were synthesized in separate plasmas powered by microwave discharges in the surfatron mode of operation. The atoms were fed into the reaction vessel where they either recombined into parent molecules or formed ammonia. Up to half of the nitrogen atoms are bound into ammonia, which does not disintegrate after the synthesis since we do not have a gas plasma in the reaction vessel, which would otherwise cause dissociation

of the ammonia. The research is important not only for the development of small ammonia synthesis reactors but also for determining the rate of conversion of nitrogen to ammonia in future fusion reactors. Some parts of fusion reactors are exposed to large flows of energetic hydrogen ions, which makes it necessary to cool the plasma near the surface. The best way of cooling hydrogen plasma is puffing nitrogen, but some of the nitrogen is converted into ammonia, which has a detrimental effect on the pumps for pumping fusion reactors. The known coefficients reported in the article [4] will enable the optimization of hot plasma cooling in future fusion reactors.

Figure 4: Scheme of the system for determining the coefficient for the conversion of nitrogen atoms into ammonia (left) and reaction sleeves (right) [4].

Hydroxyl surface groups on the surface of polymers enable considerable wettability but will never enable a super-hydrophilic surface finish. Super-wettability is often defined by an immeasurably small angle of a water drop deposited onto a sample surface, as the water spreads over a very large surface due to capillary forces, which are a result of the nanostructured surface and saturation with very polar groups, such as carboxyl groups. This state of the polymer surface is important for the excellent adhesion of the water-soluble coating. We investigated methods for applying a thin layer of water-soluble polysaccharides to the surface of polyvinyl chloride catheters. Polymers containing halogen atoms cannot be adequately hydrophilized using OH or O radicals because the binding energy between the halogen atom and the carbon atom is too large. Treatment with these radicals leads to the breaking of bonds in the polymer chain, but not to the substitution of chlorine with oxygen. To enable the super-wettability of polyvinyl chloride, we used a method that we developed and patented for Teflon years ago. The samples were first treated for a short time with hydrogen plasma and then with oxygen atoms. Hydrogen plasma is a very powerful source of vacuum ultraviolet radiation with a photon energy greater than the binding energy between the chlorine and the carbon in the polymer. As a result, photons cleave the C-Cl bonds in the thin surface layer of the polymer, and atomic hydrogen occupies the free bonds. Treatment with hydrogen plasma, therefore, enables the substitution of chlorine in the surface layer of the polymer with hydrogen. In the next step, we exposed the modified polymer to oxygen atoms and achieved super-wettability. The procedure is described in detail in a scientific article [5]. The upper graph in Figure 5 shows the contact angle of a water droplet on the polymer surface during exposure to oxygen atoms. The smallest achievable angle is around 40°, which is sound

We have developed a method to achieve the super-wettability of polyvinyl chloride

to observations reported by other authors. In the same picture, we also show the contact angle of a water droplet on the surface of polyvinyl chloride, which was exposed to hydrogen plasma for 1 second before using oxygen atoms (lower graph). We observed super-wettability (immeasurably small water droplet contact angles), which persists until the treatment time with oxygen atoms is almost a minute. A prolonged treatment with oxygen atoms causes etching of the surface layer of the polymer and, thus, the loss of excellent hydrophilicity, as the contact angle after more than 2 minutes is almost the same as if the polymer was treated with oxygen atoms only.

Radicals from oxygen plasma are important not only for the functionalization and improvement of surface wettability, but also for nanostructuring and the growth of oxide layers. The combination of low-pressure gas plasma, hydrothermal treatment, or electrochemical anodization allows the formation of biomimetic surfaces that have been shown to have a selective biological response. We have shown that the combination of gas plasma treatment
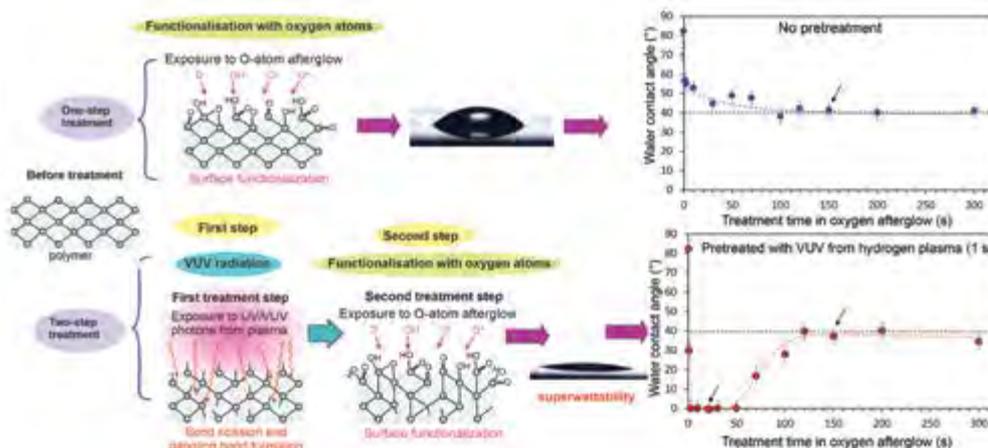

Figure 5: (left) Illustration of the method for achieving superhydrophilicity of the surface; (right) The water contact angle on the polyvinyl chloride surface versus the treatment time with atomic oxygen. The upper graph shows the wettability after treatment with only oxygen atoms, and the lower graph after treatment with hydrogen plasma and oxygen atoms.

and hydrothermal techniques increases the proliferation of human coronary artery endothelial cells (HCAECs), and the cells appear to interconnect with so-called tunnelling nanotubes (TNTs) strongly. These nanotubes are green in Figure 6. TNTs are membrane nanotubes that enable the direct connection of neighbouring cells and thus enable intercellular communication. TNTs contain actin filaments that begin to grow as filopodia (Figure 6). On the other hand, for HCASMCs (Primary Coronary Artery Smooth Muscle Cells), we observed a significant reduction in proliferation in the case of plasma-modified samples. These scientific results, published in the article [6], give great hope for the development of biomimetic surfaces of vascular implants, where the surface topography and chemistry
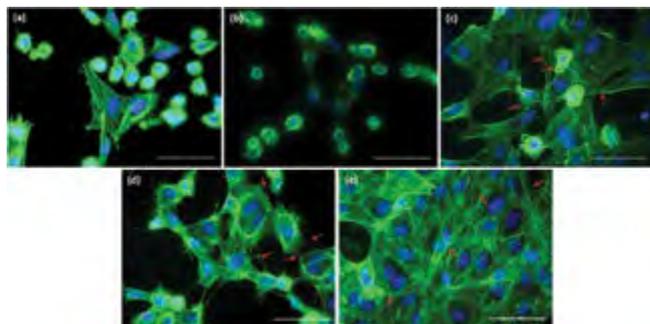

Figure 6: HCAEC on the surface of (a) untreated Ti6Al4V, (b) Ti6Al4V + P, (c) HT, (d) HT + P and (e) P + HT determined by immunofluorescence microscopy. F-actin is shown in green (FITC-phalloidin). Nuclei are visualized with DAPI (blue colour). The scale bar is 25 µm. The P designation means plasma treated, and the HT designation means hydrothermal treatment.

can be fine-tuned to achieve a specific biological response important for the prevention of restenosis (uncontrolled proliferation of smooth muscle cells) and at the same time improving endothelialization.

An important department activity with numerous projects, including two EU projects, is plasma agriculture. In 2023 we completed the CRP project: "The possibility of improving productivity and reducing dependence on the use of chemical fungicides in agriculture using gas plasma" in cooperation with the Agricultural Institute of Slovenia and the company Interkorn. The most important result of the project was the development of a low-pressure plasma approach for i) removing toxins from the surface of seeds, especially corn and wheat, ii) an approach to reduce blueberry infections by Drosophila suzukii and iii) systematic analysis of seed biochemistry, morphology, and physiology, which we published in a scientific article [7], where we observed differences in plasma treatment on different varieties of wheat. In the article [7] we reported that the plasma treatment of common buckwheat seeds does not change the ability of zinc uptake when soaking in an aqueous solution of zinc chloride. We also found that plasma treatment of buckwheat seeds

caused a decrease in the concentration of Zn in the sprouts. The benefits of cold plasma treatment need to be tested in further studies, where it may be necessary to optimize the soaking time of the grains to produce Zn-enriched sprouts. However, further optimization of the use of gas plasma in agriculture is still needed. So far, it seems that the removal of toxins is the most important. We performed systematic research on the plasma-stimulated decomposition of toxins in the framework of much larger projects than the completed CRP project and filed several patent applications. The Slovenian office published one of our patents on toxin decomposition with gas plasma [8]. In this patent we showed that even a short-term treatment of seeds with gas plasma, which operates within a limited range of parameters, reduces the concentration of toxins below the detection limit of the analytical technique.

Our department is equipped with modern instruments for surface and thin-film characterization, such as X-ray photoelectron spectroscopy (XPS), secondary-ion mass spectrometry (ToF-SIMS), Auger electron spectroscopy (AES), and atomic force microscopy (AFM). These instruments enable the determination of the chemical composition, molecular structure of surfaces, oxidation states of elements, various compounds, and electronic properties, and the surface morphology is analysed at the nanometre level. With the help of ion etching, we can remove surface layers in a controlled manner and measure XPS and SIMS depth profiles of the chemical composition in the area below the surface and in thin-layer structures. Our analyses help to understand phenomena in various fields, such as advanced surface treatments, catalysis, corrosion, nanomaterials, hard coatings, photovoltaic layers, microelectronics elements, tribology, biological materials and batteries. Our analytical methods are available to other departments of our institute, other Slovenian research and academic organizations, and Slovenian industrial partners. In cooperation with the Institute of Chemistry and other research groups, we investigated in detail the surfaces of catalytic materials made of thin nano-structured layers of TiO_xN_y, into which we embedded small clusters of Ir atoms. We prepared this type of structure using an innovative process. Due to the small amount of incorporated Ir, which is
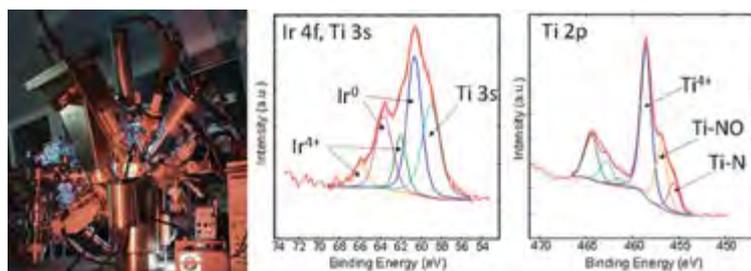

Figure 7: (left) XPS spectrometer enabling the identification of chemical bonds and examples of high-resolution XPS spectra of iridium Ir 4f (middle image) and titanium Ti 2p (right) from a TiOxNy-Ir catalyst showing oxidation states of Ir(0), Ir(4+), Ti(4+) and Ti-NO and Ti-N chemical bonds.

of limited availability and is an expensive raw material, such catalysts are very promising for use in hydrogen production. We reported results in a scientific article [9]. Catalytic layers were prepared by ion sputtering from a target made of a Ti-Ir alloy. The deposited layers were first anodically oxidized into an amorphous TiO_2-Ir phase and then heated in a nitrogen atmosphere to form a stable oxy-nitride layer with a large specific surface area and embedded clusters of Ir atoms. The catalyst showed excellent properties for the release of oxygen in an acidic medium, which is important for the development of new electro-catalysts. Apart from other analytical methods for the characterization of the catalytic layer, we also used XPS

and ToF-SIMS. Using the XPS, the oxidation states of the elements Ir(0), Ir(4+), Ti(4+) and the chemical bonds Ti-NO and Ti-N in the thin layer were determined from the spectra of Ir 4f, Ti 2p, O 1s and N 1s catalyst as shown in Figure 7. ToF-SIMS depth profiles of the distribution of elements in thin layers helped to understand the growth mechanism of thin layers of the catalyst in the form of a porous Ti-N-O-Ir structure.

Patent granted

1. Primc, Gregor, Zaplotnik, Rok, Mozetič, Miran, Filipić, Arijana, Gutiérrez-Aguirre, Ion, Dobnik, David, Dular, Matevž, Petkovšek, Martin, Method and device for disinfection of liquid, US11807555 (B2), United States Patent and Trademark Office, 7. 11. 2023

INTERNATIONAL PROJECTS

1. COST CA19110; Plasma Applications for Smart and Sustainable Agriculture
   Asst. Prof. Gregor Primc
   COST Association Aisbl
2. COST CA20114; PlasTHER - Therapeutical Action of Cold Atmospheric Plasmas
   Prof. Ita Junkar
   COST Association Aisbl
3. H2020 - ATHENA; Implementing Gender Equality Plans to Unlock Research Potential of RPOs and RFOs in Europe
   Prof. Ita Junkar
   European Commission
4. Promising Eco-Sterilization of Pathogenic Fungi on Seeds Using Reactive Species in Gaseous Plasma
   Prof. Miran Mozetič
   Slovenian Research Agency
5. Facile Preparation of Superhydrophobic Cellulose Nanofibers and Compounding with PLA for Packaging
   Prof. Miran Mozetič
   Slovenian Research Agency
6. Characterization of Oxygen Plasma Sustained with Powerful Discharges
   Prof. Miran Mozetič
   Slovenian Research Agency
7. Catalytic Probes for Characterization of Hydrogen Plasma
   Asst. Prof. Gregor Primc
   Slovenian Research Agency
8. Sustainable Food Processing for Tomorrow – Implementing Plasma on Multiple Levels
   Prof. Ita Junkar
   Slovenian Research Agency
9. Synthesis and characterizatiom of catalytic materials with interactive substrates based on doped titanium dioxide nanoparticles of various shapes for fuel cells
   Prof. Janez Kovač
   Slovenian Research Agency
10. HE - EUROfusion; WP05: PWIE-1,2,3,_HE-FU, PWIE-4-Accelerator
    Prof. Janez Kovač
    European Commission
11. HE - AgroServ; Integrated SERvices supporting a sustainable AGROecological transition
    Prof. Miran Mozetič
    European Commission

RESEARCH PROGRAMMES

1. Thin film structures and plasma surface engineering
   Prof. Miran Mozetič
2. Fusion technologies
   Asst. Prof. Rok Zaplotnik

R & D GRANTS AND CONTRACTS

1. Alternative approaches to assuring guality and security of buckwheat grain microbiome
   Prof. Miran Mozetič
2. Investigation of two-way interactions during plasma treatment of solid wood
   Prof. Janez Kovač
3. Cell membrane uptake of bacteria, virions and anorganic particles controlled by membrane mechanics and topology
   Prof. Ita Junkar
4. Removal of selected antimicrobials by plasma-cavitation hybrid technology from water matrices of varying complexity (Causma)
   Asst. Prof. Gregor Primc
5. Self-organization of plasma in magnetron sputtering discharges
   Prof. Miran Mozetič

6. New startegies for fabrication of biomimetic vascular implants
   Prof. Ita Junkar
7. Innovative procedures for advanced surface properties of medical stainless steel
   Dr. Metka Benčina
8. Novel Surface Modification of Dental Prosthetic Replacements by Gaseous Plasma
   Dr. Metka Benčina
9. Nanoparticle-reinforced new metal matrix composites manufactured by selective laser melting for tooling industry
   Prof. Miran Mozetič
10. A Novel High-strength Aluminium Alloy developed for Selective Laser Melting and Lightweight Applications
    Prof. Miran Mozetič
11. Hybrid SLM/DED Additive Manufacturing of Ti6Al4V Advanced Fuel System Components for Aerospace Industry
    Prof. Ita Junkar
12. Miniature fiber-optics sensors for free-radical detection in plasma assisted processe
    Asst. Prof. Rok Zaplotnik
13. Nanocellulose from eco-farms for optimal enforcement of bioplastics
    Asst. Prof. Gregor Primc
14. Selected area functionalization of polymeric components by gaseous plasma
    Prof. Miran Mozetič
15. Innovative method for purification of wastewater
    Asst. Prof. Gregor Primc
16. Development of safe multifunctional surfaces for catheters to combat biofilms (DemoCat)
    Prof. Alenka Vesel
17. Waterborne virus inactivation efficiency of a prototype device combining non-equilibrium plasma and hydrodynamic cavitation
    Asst. Prof. Rok Zaplotnik
18. Plasma VUV and UV radiation – a method for successful deactivation of Aflatoxins
    Dr. Nina Recek
19. Non-equilibrium plasma processing for superior composite magnets
    Prof. Miran Mozetič
20. Supercapacitors with graphene nanowalls synthesized from waste plastics
    Prof. Alenka Vesel
21. Nanostructured high entropy alloy coatings for tooling applications
    Asst. Prof. Gregor Primc
22. Use of gaseous plasma for higher yields and lower use of antifungal agents in agriculture
    Prof. Ita Junkar
23. Fusion technologies
    Asst. Prof. Rok Zaplotnik
    Slovenian Research Agency
24. Use of gaseous plasma for higher yields and lower use of antifungal agents in agriculture
    Prof. Ita Junkar
    Ministry of Agriculture, Forestry and Food
25. Income from Coowners of Invention for Reimbursement of Costs for IP Protection in the Case of EVT140_Mozetič_Carbon Nanowall
    Prof. Miran Mozetič
    Nagoya University
26. EVT770_Mozetič_CNW2_Reimbursement of the Costs for Patent; Income from Coowners of Invention for Reimbursement of Costs for IP Protection in the Case of EVT770_Mozetič_CNW2
    Prof. Miran Mozetič
    Nagoya University
27. CKPN LAPTP; Center for the analysis of surfaces and thin layers
    prof. Janez Kovač
    Slovenian Research Agency

NEW CONTRACTS

1. L-project co-financing: Innovative method for purification of wastewater
   Asst. Prof. Gregor Primc
   Induktio d. o. o.
2. L-project co-financing: Selected area functionalization of polymeric components by gaseous plasma
   Prof. Miran Mozetič
   Elvez, d. o. o.
3. Development of safe multifunctional surfaces for catheters to combat biofilms (DemoCat)
   Prof. Alenka Vesel
   Tik d. o. o.
4. Waterborne virus inactivation efficiency of a prototype device combining non-equilibrium plasma and hydrodynamic cavitation
   Asst. Prof. Rok Zaplotnik
   Kolektor Group d. o. o.
5. Co-financing L2-50052 Supercapacitors with graphene nanowalls synthesized from waste plastics
   Prof. Alenka Vesel
   Iskra, d. o. o.

VISITORS FROM ABROAD

1. Prof. Katsuhisa Kitano, Takashi Kunizawa, Osaka University, Osaka, Japan, 23.2.2023
2. Prof. Dr Tomoyuki Murakami, Seikei University, Tokyo, Japan, Prof. Dr. Kinga Kutasi, Budapest, Hungary, 13.5.2023
3. Prof. Jacek Jagielski, Łukasz Kurpaska, National Centre for Nuclear Research, Warsaw, Poland, 26.9.2023
4. Assis. Dr Lenka Zajičkova, Central European Institute of Technology (CEITEC), Brno, Czech Republic, 21.12.2023

STAFF

Researchers
1. Dr. Metka Benčina
2. Asst. Prof. Ita Junkar
3. Prof. Janez Kovač
4. Prof. Miran Mozetič
5. Asst. Prof. Gregor Primc
6. Dr. Nina Recek
7. **Prof. Alenka Vesel, Head**
8. Asst. Prof. Rok Zaplotnik

Postdoctoral associate
9. Dr. Parameswaram Ganji

Postgraduates
10. Jernej Ekar, B. Sc.
11. Domen Paul, B. Sc.
12. *Pia Starič, B. Sc., left 16.08.23*
13. Mark Zver, M. Sc.

Technical officers
14. Tatjana Filipič, B. Sc.
15. Maja Šukarov, B. Sc.

Technical and administrative staff
16. Janez Trtnik

DEPARTMENT OF SOLID STATE PHYSICS F-5

The research programme of the Department of Solid State Physics focuses on the physics of novel quantum and functional materials as well as on the structure and dynamics of disordered and partially ordered condensed matter, with a special emphasis on phase transitions. The purpose of these investigations is to discover the fundamental laws of physics governing the behaviour of strongly correlated materials and systems that represent the link between perfectly ordered crystals, on the one hand, and amorphous matter, soft condensed matter and living systems, on the other. Such knowledge provides the key to our understanding of the interplay between electronic and structural properties and the emerging dynamics at the microscopic scale. It also opens the path to the discovery and development of novel quantum and functional materials, nanomaterials and biomaterials and the emerging applications. An important part of the research activities is devoted to the development of new experimental methods and techniques in the fields of cold atoms, quantum magnetism, quantum optics, biophotonics and high-resolution fluorescence imaging. The department has numerous ongoing international collaborations and frequently uses large European research infrastructure.

Head:
Prof. Denis Arčon

The research programme of the Department of Solid State Physics at the Jožef Stefan Institute is performed in close collaboration with the Department of Physics at the Faculty of Mathematics and Physics of the University of Ljubljana, the Institute of Mathematics, Physics and Mechanics, and the Jožef Stefan International Postgraduate School. In 2023 the research was performed within four research programmes:
- Physics of quantum and functional materials
- Physics of soft matter, surfaces, and nanostructures
- Experimental biophysics of complex systems and imaging in biomedicine
- Physics of quantum technologies

I. Research Programme: Physics of quantum and functional materials

Quantum and topological magnetism

Andrej Zorko and **Matjaž Gomilšek**, in collaboration with partners from India and Germany, published a review paper, which provides an overview of recent advances in the field of quantum and topological states of materials that arise from magnetic frustration, such as spin ice (with magnetic monopole excitations), quantum spin liquids (potential platforms for robust quantum computers), and topological spin textures, such as skyrmions (for spintronic circuits – magnetic analogues of electronic circuits). The authors pointed out the characteristic signatures of these exotic but elusive states and the most suitable experimental characterization techniques are presented. The article also provides a comprehensive overview of possible future directions in the field, highlighting their potential, both for practical applications and important open questions in contemporary condensed matter physics. The work was published in J. Kathua et al., Experimental signatures of quantum and topological states in frustrated magnetism, Phys. Rep. 1041, 1 (2023).

Andrej Zorko and collaborators from India, the USA and South Korea published a paper on the interplay between spin-orbit coupling, anisotropic magnetic interaction, frustration-induced quantum fluctuations, and spin correlations in the honeycomb lattice $Ba_9Yb2Si_6O_{24}$. They demonstrated a spin-orbit entangled $J_{eff} = 1/2$ Kramers doublet of the Yb^{3+} ions and estimated an energy gap of 32.3(7) meV to the first excited Kramers doublet. No signatures of magnetic ordering or freezing were found down to 1.6 K in ^{29}Si NMR experiments. The work was published in J. Kathua et al., Magnetic properties of a spin-orbit entangled Jeff = 1/2 honeycomb lattice, Phys. Rev. B 108, 054442 (2023).

Tina Arh, **Matjaž Gomilšek** and **Andrej Zorko**, in collaboration with partners from Switzerland, determined the optimal experimental procedure for quantitatively determining muon Knight shifts. This determination is rather challenging as in most set-ups we do not have a direct way of measuring the external magnetic field applied

> **Quantum and (multi)functional materials are of utmost importance for sustainable development and our successful transition to a fully digital society. In this context we studied complex excitations in model systems for quantum spin liquids, spin dynamics in massive topological skyrmion lattices, investigated the properties of high-entropy alloys and the relaxor physics of epitaxial thin layers, and searched for the connection between magnetism and superconductivity.**

to the sample. The authors showed a way to overcome this problem and suggested a suitable sample mounting and scheme correcting. This enables quantitative determination of correct Knight-shift values even in extreme sample environments where a separate measurement of the externally applied magnetic field by means of NMR or additional µSR is not feasible or practical. The work was published in F. Hotz et al., An experimental procedure to determine quantitative muon Knight shifts, J. Phys.: Conf. Ser. 2462, 012041 (2023).

Figure 1: Theoretically predicted quadrupolar muon spectrum in solid nitrogen α–N_2 which includes the quantum effects of muons and the nearby atomic nuclei. The figure shows the frequency- (upper) and time- (lower) dependence of muon polarization (colour) versus the applied magnetic field (horizontal axis).

Matjaž Gomilšek, in collaboration with partners from the United Kingdom, published a paper on the quantum effects of muons in solids and their magnetic coupling to quadrupolar atomic nuclei. They established a new theoretical framework for the description of strong quantum effects of uncertainty in the muon position and quantum entanglement between the position of the muon and the positions of the nearby atomic nuclei (Figure 1). In the new framework they crucially exploited the large mass difference between the muon and atomic nuclei. The results are highly relevant for the correct interpretation of the results of muon spectroscopy measurements, which the researchers used to achieve a record-accurate determination of the quadrupolar coupling constant of ^{14}N nuclei in solid nitrogen α–N_2 via precision muon spectroscopy measurements on this material. The improvement in the accuracy, enabled by the new theoretical framework, was nearly threefold compared to the previously most-accurate measurements conducted on this material via other methods. The work was published in M. Gomilšek et al., Many-body quantum muon effects and quadrupolar coupling in solids, Commun. Phys. 6, 142 (2023).

Matej Pregelj and collaborators from India and Germany published a paper that focuses on a frustrated magnet $Yb_3Sc_2Ga_3O_{12}$. Here, Yb^{3+} ions form a three-dimensional network of corner-sharing triangles known as a hyperkagome lattice. The study finds that the ground state has an effective spin ½ and forms a Kramers doublet that is well separated from the excited states, as indicated by crystal electric field calculations. Magnetic susceptibility measurements rule out the presence of spin freezing down to 1.8 K and imply weak antiferromagnetic interactions. The electron spin resonance shows a broad, asymmetrically shaped line consistent with considerable magnetic anisotropy. The specific-heat data indicate an absence of long-range magnetic ordering, thus pointing to a dynamic liquid-like ground state at least down to 130 mK. The work was published in the article B. Sana et al., Magnetic properties of a spin-orbit entangled Jeff = 1/2 three-dimensional frustrated rare-earth hyperkagome material, Phys. Rev. B 108, 134413 (2023).

Tilen Knaflič and **Denis Arčon**, together with their colleagues from the University of Ljubljana, investigated the magnetic properties of iron-tetraporphyrin complexes, which are important in many biological systems. An extensive study published in the article by T. Knaflič et al., Impact of counter anions on structural and magnetic properties of iron(III) meso-tetraphenylporphyrin tetrahydrofurane solvates, J. Phys. Chem. Solids 181, 111514 (2023) focused on the connections between different anions, crystal structure and magnetic anisotropy. Using electron paramagnetic resonance, we have shown that magnetic anisotropy, the key parameter, decreases with the tetragonal distortion of the hexa-coordinated Fe(III) ion and that this is in accordance with ligand theory.

Magnetism and superconductivity

Žiga Gosar, **Tina Arh**, **Andrej Zorko** and **Denis Arčon** investigated the quasi-one-dimensional superconductor $Rb_2Mo_3As_3$. In such systems, very unusual order parameters can be anticipated, and the possibility of triplet superconductivity is especially interesting. To address this open question, the authors used the muon spin relaxation method. The measurements were performed in weak transverse fields and the influence of the vortex lattice on the relaxation of the muon signal was observed. Surprisingly, they found that the temperature dependence of muon relaxation can also be described with a superconducting order parameter with p-symmetry. The work was published in the article by Ž. Gosar et al., The pairing symmetry in quasi-one-dimensional superconductor Rb2Mo3As3, J. Phys. Chem. Solids 181, 111478 (2023).

Functional materials

Matej Pregelj and **Denis Arčon**, with collaborators from the University of Nova Gorica and Bulgaria, reported on a facile one-step chemical method to synthesize reduced titanium dioxide (TiO_2) nanotube arrays (NTAs) with point defects. A treatment with $NaBH_4$ introduced oxygen vacancies (OVs) in the TiO_2 lattice. They found that the OV density can be significantly increased by changing the reduction time, leading to higher optical transmission of the TiO_2 NTAs and retarded carrier recombination in the photoelectrochemical process. Moreover, a cathodoluminescence study of reduced TiO_{2-x} NTAs revealed that OVs contribute significantly to the emission bands in the visible range, which is also reflected in X-ray photoelectron spectroscopy. Electron paramagnetic resonance spectra confirmed the presence of OVs in the TiO_{2-x} sample. The work was published in article M. Machreki et al., The Role of Lattice Defects on the Optical Properties of TiO2 Nanotube Arrays for Synergistic Water Splitting, ACS Omega 8, 33255 (2023).

Matej Pregelj, with collaborators from the Department of Thin Films and Surfaces, Department of Advanced Materials, Institute of Mathematics, Physics and Mechanic, and from Serbia, explored magnetic multilayers made of alternating crystalline Ni (nickel) and amorphous Si (silicon) layers. They found that perpendicular magnetic anisotropy, essential for, e.g., magnetic storage applications, can be maintained even if the thickness of an individual Ni layer exceeds 15 nm, i.e., beyond the current state of the art. The films produced by magnetron sputtering had a [a-Si/ Ni/a-Si] sandwich structure and [a-Si/Ni/a-Si]$_5$ multilayer structure, confirmed by scanning transmission electron microscopy. The magnetic properties were investigated with magnetization and electron magnetic resonance measurements, clearly indicating the presence of perpendicular magnetic anisotropy. The latter may stem from diffusion, a thermal expansion mismatch or intrinsic stresses during the growth process. These results could be important for applications in memory devices, sensors, logic chips, magneto-optic, magneto-electronic and spintronic devices. The work was published in article M. Tadić et al., Perpendicular magnetic anisotropy at room-temperature in sputtered a-Si/Ni/a-Si layered structure with thick Ni (nickel) layers, Ceram. Int. 49, 32068 (2023).

Together with **Yuri Tanuma**, a visiting postdoctoral researcher from Japan, and several colleagues from France and Germany, **Denis Arčon** investigated the magnetic and structural properties of azafullerene radicals C$_{59}$N. In the publication by Y. Tanuma et al., Noncontact Layer Stabilization of Azafullerene Radicals: Route toward High-Spin-Density Surfaces, ACS Nano 17, 25301–25310 (2023), the authors investigated the self-assembly of C$_{59}$N molecules on gold using low-temperature tunnelling microscopy. The most important result of this study is the discovery of the extraordinary stability of C$_{59}$N radicals in the second non-contact layer, which opens many possibilities for the manipulation of their spin (qubit) state. This interesting functional property of azafullerenes was then further investigated using electron paramagnetic resonance and it was shown that these radicals, when trapped in the so-called [10]CPP nanorings, have extremely long coherence times. The research was published in Y. Tanuma et al., Long Spin Coherence Times on C59N-C60 Heterodimer Radicals Entrapped in Cycloparaphenylene Rings, J. Phys. Chem. C 127, 13, 6552–6561 (2023).
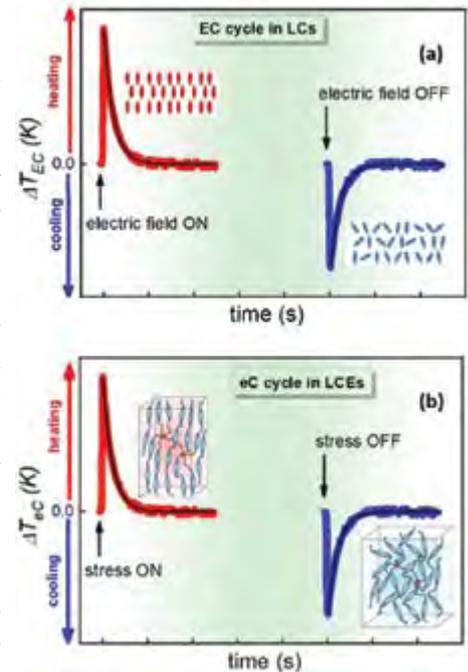

Figure 2: (a) Example of the electrocaloric temperature change as a function of time in liquid crystals after switching on or off the electric field. (b) The elastocaloric temperature change as a function of time in liquid crystal elastomers after applying or removing the stress field.
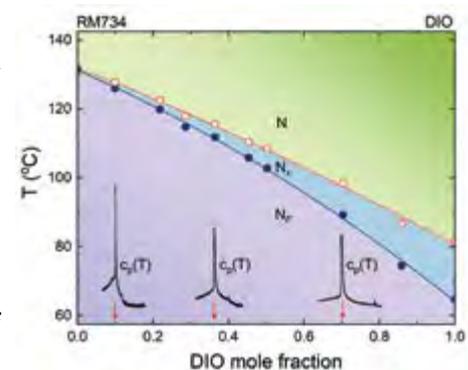
Dejvid Črešnnar, Nikita Derets, Maja Trček, Gregor Skačej, Andraž Rešetič, Marta Lavrič, Valentina Domenici, Boštjan Zalar, Samo Kralj, Zdravko Kutnjak and **Brigita Rožič** published an article, in which they presented the electrocaloric response in liquid crystal-based soft materials. Using high-resolution direct thermometry measurements, a large electrocaloric effect of 8K was demonstrated in smectic liquid crystal 14CB. The large electrocaloric effect was attributed to the significant latent heat released/absorbed during the first-order smectic A to isotropic phase transition. This proves that liquid crystals represent an interesting class of materials for cooling applications based on electrocaloric response. Further, it was demonstrated that by decreasing the crosslinker density in a main-chain liquid-crystal elastomer, the nature of the phase transition between the nematic and isotropic phases can be tuned from the supercritical to the first-order regime. As a result, an enhanced elastocaloric response in liquid crystal elastomers was presented together with elastocaloric responsivity that was about three orders of magnitude larger compared to shape memory alloys. The work was published in the article D. Črešnar et al., Caloric effects in liquid crystal-based soft materials, J. Phys. Energy 5, 045004 (2023).

George Cordoyiannis and collaborators from Belgium and the UK studied the phase transitions in a series of mixtures of liquid crystals RM734 and DIO exhibiting new types of ferroelectric nematic phases. RM734 exhibits a nematic (N) and a ferroelectric nematic (N$_F$) phase, whereas DIO has an intermediate phase (N$_x$) between N and N$_F$. Utilizing high-resolution calorimetry, a precise phase diagram was derived as a function of mixture composition, i.e., as a function of variable ferroelectric coupling. The phase diagram was consistent with the ideal mixture behavior, provided that the total enthalpy values were used in the analysis. The critical behavior of the N$_x$–N$_F$ phase transition exhibited by the mixtures showed a systematic trend of the critical exponent values from $\alpha = 0.88 \pm 0.10$ for DIO to $\alpha = 0.50 \pm 0.05$ (tricritical) when increasing the concentration of RM734. The work was published in the paper J. Thoen et al., Phase transitions study of the liquid crystal DIO with a ferroelectric nematic, a nematic and an intermediate phase and of mixture with the ferroelectric nematic compound RM734 by adiabatic scanning calorimetry, Phys. Rev. E 107, 014701 (2023).

Figure 3: Phase diagram of RM734 and DIO liquid crystal mixtures as a function of the mole fraction of DIO

Anna Razumnaya, Nikola Novak, Zdravko Kutnjak, and collaborators from Morocco, Czech Republic, France, and Ukraine studied the impact of a polymer precursor on the structural, microstructural, magnetic, and magnetocaloric properties in the ferromagnetic system La$_{0.8}$Sr$_{0.2}$MnO$_3$. Using XRD and SEM showed that the polymer precursor does not affect the crystal structure of the system, but it influences the microstructure by increasing the size of the synthesized nanoparticles. Magnetization measurements revealed that the samples prepared with a
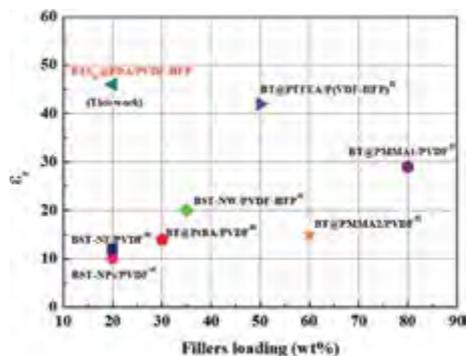
Figure 4: Comparison of dielectric permittivities among different ceramic/polymer-based nanocomposites shows a successful enhancement of dielectric response through surface treatment of ferroelectric nanoparticles.

polymer precursor exhibit a higher magnetization value compared to the samples prepared with auto-combustion. Using Maxwell's relations, the magnetocaloric response was calculated and it was demonstrated that it was two-fold higher than in the samples prepared with auto-combustion. The work was published in the paper A. Lakouader et al., Impact of polymeric precursor and auto-combustion on the structural, microstructural, magnetic, and magnetocaloric properties of $La_{0.8}Sr_{0.2}MnO_3$, J. Magn. Magn. Mater. 586, 171225 (2023).

Zdravko Kutnjak, together with collaborators from Morocco and France, investigated the dielectric properties and energy storage density properties of a ferroelectric/polymer nanocomposite. Ferroelectric $BaTi_{0.89}Sn_{0.11}O_3$ nanoparticles were hydroxylated to improve the interfacial interactions between the polymer PVDF-HFP matrix and ferroelectric nanoparticles. By improving the interface interactions in the nanocomposite, a five-time higher dielectric constant was achieved compared to the dielectric constant of the pure matrix. With the help of polarization hysteresis loops, the energy storage density of the prepared nanocomposite system was studied. It was found that the energy storage density was four times higher than that of the pure polymer matrix. The work was published in the paper M. Zahid et al., Dielectric and energy storage properties of surface-modified $BaTi_{0.89}Sn_{0.11}O_3$@polydopamine nanoparticles embedded in a PVDF-HFP matrix, *RSC Adv.* 13, 26041 (2023).

Anna Razumnaya, with collaborators from Germany, France, Ukraine and Russia, studied the topological polar states in lead titanate ferroelectrics. Using phase-field numerical modeling and analytical calculations it was demonstrated that the formation of stable vortex-like textures of polarization in noncylindrical ferroelectrics arises due to the competition of the elastic and electrostatic interactions. As a consequence, the orientation of the vortex core with respect to the cylinder axis is tuned by the geometrical parameters and temperature of the system. The work was published in the paper S. Kondovych et al., Vortex states in a $PbTiO_3$ ferroelectric cylinder, SciPost Phys. 14, 056 (2023).

At the Laboratory of **Vid Bobnar**, we addressed one of the major challenges in developing materials for energy storage systems – the realization of high energy density while maintaining low dielectric losses. The composite approach, where conductive particles are dispersed in a dielectric matrix, effectively increases the dielectric permittivity but also boosts the losses. An alternative approach is operation under high electric fields, i.e., increasing the electric breakdown strength (E_b) without increasing the dielectric permittivity. Phenyl groups are fundamental chain components of many high-temperature polymers and, depending on the polymer's molecular structure, delocalized electrons in these groups may exhibit a partially positive or negative charge. We prepared blends of polyetherimide (PEI) and polyimide (PI) with solution casting and performed their extensive dielectric characterization. We demonstrated a significant enhancement of E_b in the blends due to strong electrostatic interactions between different polymer chains; namely, PEI contains three negatively charged phenyls, while PI has two strong, positively charged phenyl groups. Electrostatic interactions (i) strongly reduce the number of space charges and (ii) lead to much higher chain packing density in blends. Since the breakdown is initiated by charges that are accelerated by an applied electric field in weak points, i.e., voids in the system, both features contribute to the enhancement of E_b. The blending of appropriately matched polymers thus turned out as an outstanding strategy for improving the dielectric properties of polymer systems. The study was published in V. Jurečič et al., Space charge contributions to the dielectric response and breakdown strength of high-temperature polyetherimide/polyimide blends, Macromolecules 56, 1097 (2023).
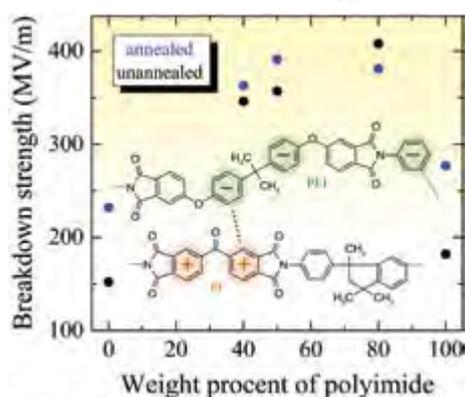

Figure 5: Electrostatic interactions between the phenyl groups of PEI and PI polymer chains reduce the number of space charges and lead to much higher chain packing density, thus strongly enhancing the dielectric breakdown strength of PEI/PI blends.

We investigated the influence of critical end points on the functional properties of antiferroelectric ceramics $Pb_{0.99}Nb_{0.02}[(Zr_{0.57}Sn_{0.43})_{0.92}Ti_{0.08}]_{0.98}O_3$. In the electric field–temperature phase diagram, the existence of two separate critical end points which terminate the lines of first-order phase transitions, the supercritical region above the critical end points, and the triple point, were shown. The exceptionally high dielectric tunability (221 %), measured at the temperature of the antiferroelectric-paraelectric critical end point, was attributed to the divergent nature of the dielectric permittivity at the paraelectric phase transition and the proximity of the triple point with degenerate phases. The maximum recoverable energy storage was obtained at the temperature of the ferroelectric-antiferroelectric critical end point due to the optimal ratio between the maximum polarization, critical electric field, and the slope of the polarization loop. The work was published in V. Jurečič et al., Synergetic boost of functional properties near critical end points in antiferroelectric systems, Physical Review Materials 7, 114407 (2023).

PMN-33PT epitaxial thin films were prepared with pulsed-laser deposition (PLD) using ceramic targets, enriched with PbO and MgO. The phase composition and crystal structure were analyzed with high-resolution X-ray diffraction. A precise chemical analysis of developed films was carried out using wavelength-dispersive X-ray spectroscopy,

which revealed that the target substrate material transfer was not fully stoichiometric. The largest deviations were found for the Pb and Mg content. Our results show that it is possible to effectively tune the stoichiometry of the films via the use of custom-made ceramic targets, emphasizing their advantage over single-crystal targets in the PLD growth of complex metal oxides. The functional response of the films, however, is the result of complex interactions between the crystal structure, microstructure, and chemical composition of the films. The study was published in U. Trstenjak et al., Non-stoichiometry and its implications for the properties of PMN-PT thin films, Journal of Materials Chemistry C 11, 1144 (2023).

Nikola Novak, in collaboration with Satyanarayan Patel (Indian Institute of Technology Indore) and Rahul Vaish (Indian Institute of Technology Mandi) published a chapter in a book entitled *The Electrocaloric Effect: Materials and Application* (Woodhead Publishing). The book summarizes the current state of the art in the field of electrocaloric effect: from fundamentals of electrocaloric effect, materials and their optimization, electrocaloric measurements and device applications. In the published chapter entitled Electrocaloric Devices Using Cantilever Structures, the authors present a comprehensive overview of various electrocaloric devices based on cantilever structures for solid-state cooling applications. Different approaches presented in the literature are examined, compared, and critically evaluated. Hence, the book offers a broad readership insight into the world of electrocaloric-based cooling, providing the basic knowledge about the electrocaloric effect, materials, and applications.
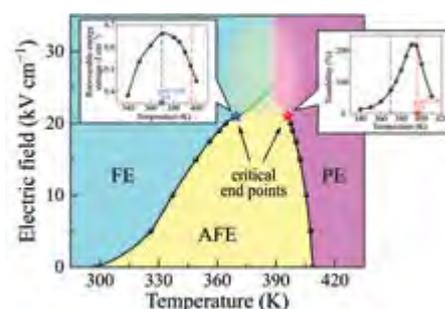

Figure 6: Electric field–temperature phase diagram of the antiferroelectric PNZST ceramics exhibits first-order FE-AFE and AFE-PE transition lines, terminated by critical end points marked with stars. The presence of critical end point enhances functional properties such as energy storage density and dielectric tunability.
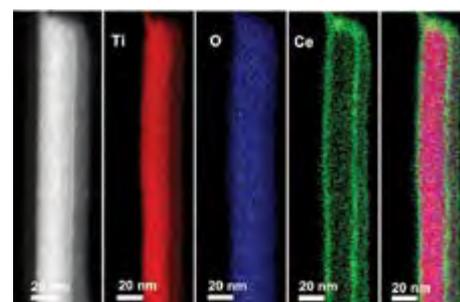
Polona Umek continued research on 1D TiO$_2$-based nanostructures, focusing on the preparation of hybrid nanostructures based on TiO$_2$ nanoribbons and CeO$_2$ nanoparticles. In this context, we also investigated the effect of the oxidation state of cerium on the conversion temperature of H$_2$Ti$_3$O$_7$ nanoribbons transforming to TiO$_2$-B nanoribbons, then to anatase and finally to rutile: CeO$_2$-TiO$_2$ is an important mixed oxide due to its catalytic properties, particularly in heterogeneous photocatalysis. As the precursor, we used H$_2$Ti$_3$O$_7$ nanoribbons that transform into TiO$_2$ upon heating (first to TiO$_2$-B, then to anatase and finally to rutil). Two cerium salts with an oxidation state of +3 and +4, Ce(SO$_4$)$_4$×4H$_2$O and Ce(NO$_3$)$_3$×6H$_2$O, were used as sources of cerium. Ce^{4+}-containing species homogenously covered the surface of H$_2$Ti$_3$O$_7$ nanoribbons (Figure 7) as confirmed by EELS mapping (Figure 7), while Ce^{3+} cerium ions intercalated partially between the titanate layers. The phase composition and morphology changes were monitored during the calcination between 620 and 960 °C. Thermal treatment led to the formation of CeO$_2$ nanoparticles on the surface of the TiO$_2$ nanoribbons, whose size increased with the calcination temperature. The use of Ce^{4+} raised the temperature required for converting H$_2$Ti$_3$O$_7$ into TiO$_2$-B by approximately 200 °C, and the temperature for the formation of anatase was also increased. For the Ce^{3+} batch, the presence of cerium inhibited the conversion into rutile. The analysis of cerium oxidation states revealed the existence of both +4 and +3 in all calcined samples, regardless of the initial cerium oxidation state. Our results were published in P. Umek et al., The Role of Cerium Valence in the Conversion Temperature of H2Ti3O7 Nanoribbons to TiO2-B and Anatase Nanoribbons, and Further to Rutile, Molecules 28, 1-14 (2023).

Figure 7: HAADF-STEM image of an individual H$_2$Ti$_3$O$_7$ nanoribbon coated with Ce^{4+}-containing species with corresponding elemental maps of Ti, O, and Ce (EELS). A comparison of the elemental maps (Ti, O, and Ce) reveals that the nanoribbon's surface is covered with a continuous, ~4-nm thick cerium-containing layer.
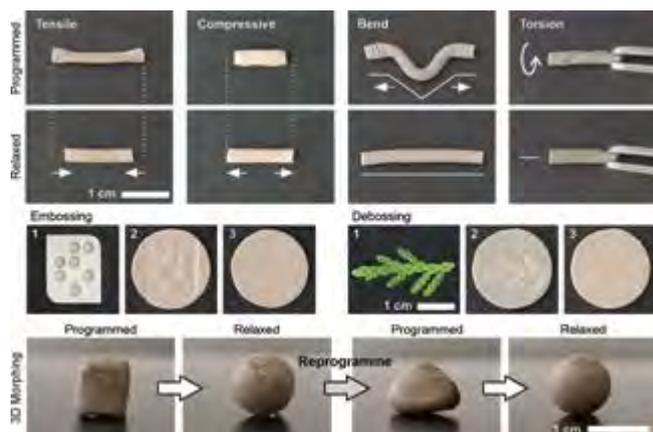
Programmable shape memory of polymer-dispersed liquid crystal elastomers

The current development of soft shape-memory materials is typically restricted to the synthesis of thin-walled samples, which greatly limits their practical application. Three-dimensional specimens can be produced using complex manufacturing methods, e.g., additive manufacturing, but these require specialized equipment, while the production output is usually very low. **M. Bobnar, N. Derets, S. Umerova, N. Novak, M. Lavrič, G. Cordoyiannis, B. Zalar** and **A. Rešetič**, together with V. Domenici from Italy, developed a new composite shape-memory material made from main-chain liquid-crystal elastomer microparticles (LCEs) dispersed in a silicone polymer matrix. The composite dispersions can be effortlessly moulded into arbitrary shapes or sizes, most significantly, into bulk-sized solids, which is challenging to achieve with conventional synthesis methods. Shape-memory capabilities result from temperature-dependent mechanical properties of LCE inclusions. These become significantly softer at higher temperatures, when the particles reach the isotropic phase, and harden while cooled back into the glassy phase. A composite material can thus be shape-programmed by deforming it at a higher temperature and cooling it into a new stable shape, fixed by the stiffened LCE inclusions. The new shape can then be reset by heating the material above the isotropic-phase temperature. LCE particles can be additionally magnetically ordered, providing for an additional thermomechanical reversible response. The newly developed composite material serves as a practical shape-morphing material for easy implementation into future applications, such as active elements in soft robotics. The results of this study were published in the paper M. Bobnar et al., Polymer-dispersed liquid crystal elastomers as moldable shape-programmable material, Nature Communications 14, 764 (2023).

Figure 8: Shape programmability of PDLCEs with various deformation modes
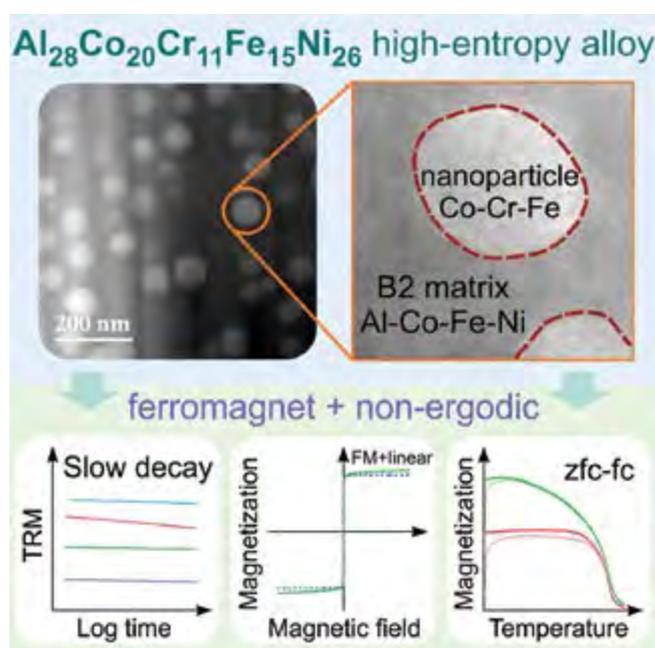

Figure 9: Nanostructure of high-entropy alloy $Al_{28}Co_{20}Cr_{11}Fe_{15}Ni_{26}$ determined with TEM (the upper two panels). Magnetic measurements – time-decay of thermoremanent magnetization (TRM), magnetization curve M(H) and temperature-dependent magnetization (lower panels).
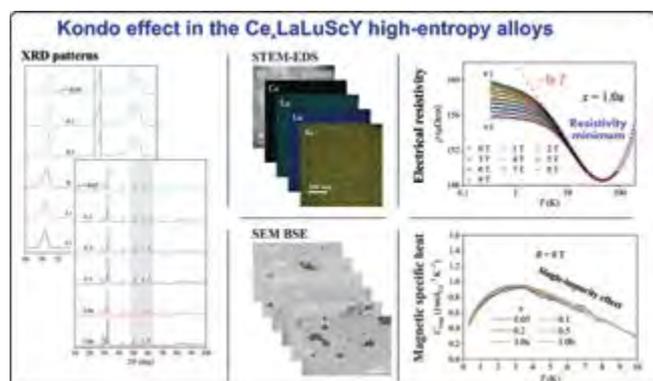

Figure 10: XRD profiles, EDS elemental maps, SEM backscattered-electron images, electrical resistivity and magnetic specific heat of the hexagonal high-entropy alloys $Ce_xLaLuScY$ (x = 0.05 – 1.0)

High-entropy alloys and intermetallic compounds

In 2023, the research group of the laboratory for electrical, magnetic and thermal measurements of materials from the Condensed Matter Physics Department (**Andreja Jelen, Julia Petrović, Magdalena Wencka, Jože Luzar, Primož Koželj, Stanislav Vrtnik, Peter Mihor and Janez Dolinšek**) investigated electrical, magnetic and thermal properties of high-entropy alloys, denoting crystalline solid solutions composed of five or more chemical elements in equiatomic concentrations.

In the paper P. Koželj et al., Complex magnetism of single-crystalline AlCoCrFeNi nanostructured high-entropy alloy, iScience 26, 106894 (2023), we investigated the magnetism of the $Al_{28}Co_{20}Cr_{11}Fe_{15}Ni_{26}$ single-crystalline high-entropy alloy. The material is nanostructured, composed of a B2 matrix with dispersed spherical A2 nanoparticles of an average diameter of 64 nm (Figure 9). The magnetism was studied from 2 to 400 K via direct-current magnetization, hysteresis curves, alternating-current magnetic susceptibility and thermoremanent magnetization time-decay, to determine the magnetic state that develops in this highly structurally and chemically inhomogeneous material (Figure 9). The results reveal that the Cr-free B2 matrix of composition $Al_{28}Co_{25}Fe_{15}Ni_{32}$ forms a disordered ferromagnetic (FM) state that undergoes a FM transition at $T_c \approx 390$ K. The Al- and Ni-free A2 nanoparticles with an average composition of $Co_{19}Cr_{56}Fe_{25}$ adopt a core-shell structure, where the shells, approximately 2 nm thick, are CoFe-enriched. While the shells are FM, the nanoparticle cores are asperomagnetic, classified within the broad class of spin glasses. Asperomagnetism develops below 15 K and exhibits broken-ergodicity phenomena, typical of magnetically frustrated systems.

In the paper J. Petrović et al., The Kondo Effect in CexLaLuScY (x = 0.05–1.0) High-Entropy Alloys, Materials 16, 7575 (2023), we were searching for electronic phenomena of high-entropy alloys (HEAs) that go beyond an independent-electron description, by synthesizing a series of hexagonal rare earth (RE)-based HEAs $Ce_xLaLuScY$ (x = 0.05–1.0). Measurements of electrical resistivity, magnetic susceptibility and specific heat showed that the $Ce_xLaLuScY$ HEAs exhibit a Kondo effect (Figure 10) of the single-impurity type across the entire range of employed Ce concentrations, although the alloys are classified as dense (concentrated) Kondo systems. A comparison with other known dense Kondo systems revealed that the Kondo effect in the $Ce_xLaLuScY$ HEAs behaves very differently from that in chemically ordered Kondo lattices, but quite similar to that in RE-containing magnetic metallic glasses and randomly chemically disordered Kondo lattices with the formula $RE1_xRE2_{1-x}M$ (where RE1 is magnetic and RE2 is nonmagnetic). The main reason for the similarity of HEAs to metallic glasses and chemically disordered Kondo lattices appears to be the absence of a periodic 4f sublattice in these systems, which prevents the formation of a coherent state between the 4f-scattering sites as $T \to 0$. This study broadens the classification of HEAs to correlated-electron systems.

Applications of magnetic resonance methods

As part of the research on pharmaceuticals, **Tomaž Apih** and his colleagues studied the Favipiravir drug, registered in Japan as Avigan and used for viral infections, including the coronavirus SARS-CoV-2. By combining fast-field-cycling cross-relaxation spectroscopy and nuclear quadrupole double resonance with solid-state computational modelling (density functional theory supplemented by the quantum theory of atoms in molecules, 3D Hirshfeld surfaces, and reduced density gradient), we were able to model the molecular environment of nitrogen atoms and characterize intermolecular interactions. A comparison of the binding modes of molecules (in crystal, precatalytic, and active form) with the RNA molecule might be useful in the design of more effective drugs against SARS-CoV-2. This study was published

in J.N. Latosińska et al., Elucidating the Role of Noncovalent Interactions in Favipiravir, a Drug Active against Various Human RNA Viruses; a 1H-14N NQDR/Periodic DFT/QTAIM/RDS/3D Hirshfeld Surfaces Combined Study, Molecules 28, 3308 (2023)

II. Research Programme: Physics of soft matter, surfaces, and nanostructures

Liquid crystals

Coarsening and refinement in active turbulence. **Miha Ravnik** and **Žiga Kos** published an article with Nika Kralj (University of Ljubljana) titled N. Kralj et al. Defect Line Coarsening and Refinement in Active Nematics, Phys. Rev. Lett. 130, 128101 (2023). Active nematic fluids are non-equilibrium systems characterized by a chaotic dynamic state known as active turbulence, which in three-dimensional active nematics is realized as a dynamic network of defect lines. The

Figure 11: Crystal structure of Favipiravir over the total 3D Hirshfeld surface

authors showed how active turbulence dynamically reacts to changes in material properties and external parameters, which leads to coarsening and refinement of defect line density. In the limit of passive nematic liquids, such a phenomenon describes the last stage of the Kibble-Zurek mechanism and appears in many physical systems, from cosmic strings to superfluid helium and liquid crystals. The authors show how such a process takes place in active matter, which leads to interesting parallels with cosmic string coarsening models.

We researched active nematic liquids, opened a new field of nematronics research and achieved important breakthroughs in the development and understanding of liquid-crystal waveguides. We studied chiral skyrmions in the blue phases, and topological defects in the nematic shells. Research on inorganic nanotubes has led to the discovery of a new generation of electron emission materials.

Nematronics

The coupling between ionic currents and nematic dynamics is called nematronics. **Miha Ravnik**, together with co-authors from UCLA and Polish Academy of Science published an article (C. Dao et al., Nematronics: Reciprocal Coupling between Ionic Currents and Nematic Dynamics, Phys. Rev. Lett. 130, 168102 (2023)) on a possible novel coupling mechanism between electric ion currents and nematic dynamics, motivated by a theoretical analogy with spintronics. Based on the principle of least dissipation of energy, the work derives the adiabatic "nematic torque" exerted by ionic currents on the nematic director field as well as the reciprocal motive force on ions due to the orientational dynamics of the director. Several examples of potential functionality of this coupling and possible experimental set-ups are proposed.

Figure 12: Electric field of resonant photonic eigenmodes with corresponding Q factors

Liquid crystal waveguides

We published a paper by J. Zaplotnik et al., Photonic eigenmodes and transmittance of finite-length 1D cholesteric liquid crystal resonators, Scientific Reports 13, 16868 (2023), presenting the results of experimental studies and numerical simulations of light propagation in cholesteric liquid crystals. We studied transmission spectra as a function of sample thickness and birefringence, as well as the effect of incident light's polarization and the shape of the beam. Numerical simulations provide additional insight into the electric field profile of the resonant modes within the material and an estimation of their Q factors. Overall, the study contributes to a better understanding of light propagation in cholesteric liquid crystals, which can potentially help fabricate optimal liquid crystal micro-lasers.

In the addition, we investigated the optical amplification and photobleaching in a wide range of optical gain materials, including fluorescent dyes, quantum dots and rods, organic and inorganic room-temperature polaritons, and nanodiamonds. We used amplified spontaneous emission (ASE) for each material to measure the optical gain. We showed that pyrromethene laser dyes are the best organic emitters in terms of low excitation energy and good optical gain, whereas solid-state polariton materials are better in terms of high optical gain and stability. We showed that nanodiamonds are a superior optical gain material due to their extremely long lifetime.

Figure 13: Schematic of nematronics: the coupling between electric ion current and nematic dynamics

We also demonstrated the fabrication of high-quality surface alignment layers on glass by direct laser writing using a 2-photon polymerization technique (*Liquid Crystals*, **50**, 1999 (2023)). We used commercially available photosensitive resins to print alignment layers by scanning the focal point of a femtosecond laser near the resin-glass interface. This resulted in thin alignment layers that provided good liquid-crystal planar anchoring with an azimuthal anchoring strength of around 5×10^{-6} J/m². The advantage of this new method is its flexibility, as we can demonstrate the printing of complex surface alignment patterns with an alignment layer thickness below 100 nm.
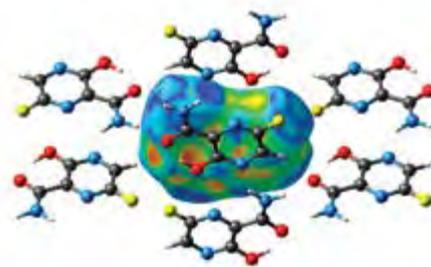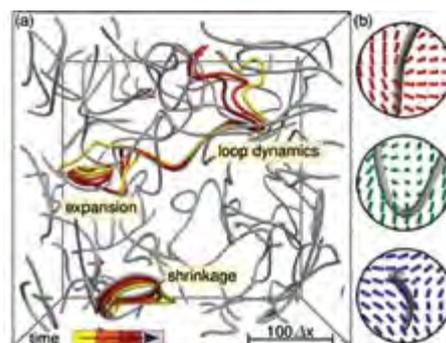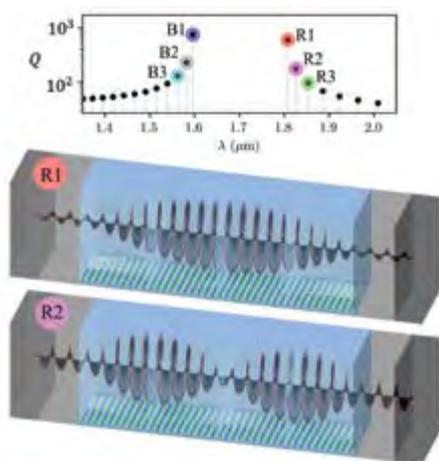
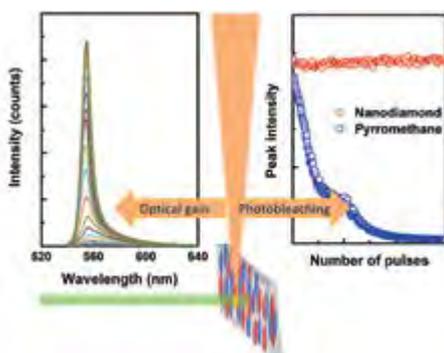*Figure 14: Electric field of resonant photonic eigenmodes with corresponding Q factors*

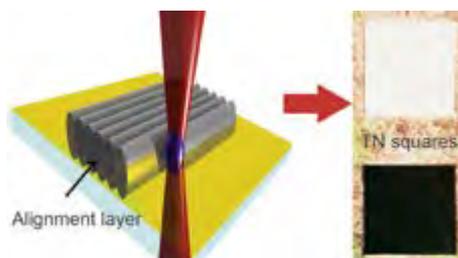*Figure 15: Optical gain and photobleaching measurements*

Figure 16: Direct laser writing ensures good liquid-crystal alignment
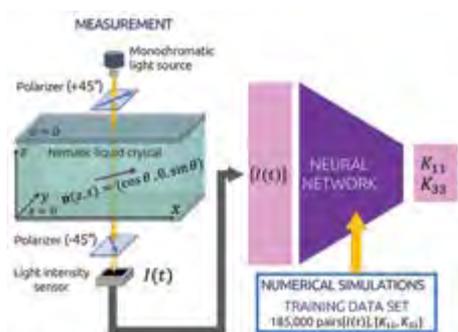

Figure 17: Method for determining elastic constants of nematic liquid crystals using neural networks

In the paper J. Zaplotnik et al., Neural networks determination of material elastic constants and structures in nematic complex fluids, Scientific Reports 13, 6028 (2023), we presented the use of supervised machine learning based on neural networks for the determination of the Frank nematic elastic constants. The relaxational dynamics of the liquid crystal from the non-equilibrium initial state, and the time dependence of transmitted light, both depend on them. By numerically simulating thousands of samples with random constants, one can train a neural network that can identify them from the time dependence of transmitted light. Eventually, the same neural network can be used to identify the unknown elastic constants of real samples from experimental measurements.

Blue phases and chiral skyrmions

Using a high-resolution microscope, we showed that both the static cubic (BPI) and dynamic amorphous (BPIII) blue phases consist of fractional skyrmion filaments that transform into the same quasi two-dimensional structure of 'baby' half-skyrmions upon confinement to layers below the thickness of about 200–300 nm. We described this experimental work, supported by extensive numerical simulations, in detail in a paper by Pišljar et. al. published in *Liquid Crystals*, **50**, 1406-1425 (2023). In a different study that was accepted for publication in *Physical Review Letters* we characterized the phase transition of a blue phase material confined to a thickness below 100 nm. Namely, the distinct first-order phase transition, typical of thicker layers, begins to exhibit extremely slowed-down transition fluctuations, consisting of half-skyrmion fragments. The types of fluctuations observed also include the dynamic formation and decay of half-skyrmions, which are non-trivial topological objects. The change in the phase transition appearance was linked to capillary condensation caused by strong surface effects in confinement, which effectively lowered the energetic boundary between the two phases.

Topological defects in nematic shells

In the collaboration with Universities of Ljubljana and Maribor we studied the impact of the intrinsic curvature of orientationally ordered, in-plane curved flexible nematic molecules attached to closed three-dimensional (3D) flexible shells (L. Mesec et al., Coupling of nematic in-plane orientational ordering and equilibrium shapes of closed flexible nematic shells, Scientific Reports 13, 10663 (2023)). A Helfrich-Landau-de Gennes-type mesoscopic approach was adopted, in which the flexible shell's curvature field and the nematic field are coupled and concomitantly determined during the process of free energy minimization. We demonstrated that this coupling has the potential to generate a rich diversity of qualitatively new shapes of closed 3D nematic shells and the corresponding specific in-plane orientational ordering textures.

In the collaboration with the University of Cleveland we analysed numerically the reconfiguration process of colliding $|m|=1/2$ strength disclinations in an achiral nematic liquid crystal (Crystals **13**, 904, (2023)). A Landau-de Gennes approach, using tensor nematic order parameters, was used. Initially, different pairs of parallel wedge disclinations connecting opposite substrates confining the NLC in a plane-parallel cell of thickness h were imposed. Collisions were enforced by the relative rotation of one confining substrate, which strongly pinned the defect endpoints.

Electrocaloric response in nematic liquid crystals

In a collaboration with the University of Maribor we numerically analysed an active EC regenerator. In modelling, we used the Landau-de Gennes mesoscopic approach, focusing on the temperature regime where the isotropic (paranematic) and nematic phase orders compete. We established a temperature span across the regenerator by commuting a liquid crystalline (LC) unit between regions with and without an external electric field.

Inorganic nanotubes

Molybdenum disulfide (MoS_2) nanoribbons and nanotubes are quasi-1D semiconductors with strong spin-orbit interactions, making them essential nanomaterials for quantum electronic applications. In cooperation with OTH Regensburg, we proved that an additional layer of bismuth between the contact metal and MoS_2 enhances electron transport and prevents the formation of additional electronic states, which would otherwise complicate the observation of quantum phenomena. At low temperatures (T < 100 mK), the Coulomb blockade is clearly visible, causing the quantum transport of electrons in individual nanotubes or nanoribbons of MoS_2. This finding will enable researchers to discover new phenomena in MoS_2 nanotubes in the quantum regime.

(R. T. Schock et al., Non-Destructive Low-Temperature Contacts to MoS2 Nanoribbon and Nanotube Quantum Dots, Advanced Materials 35, 2209333 (2023)).

Next, we synthesized the first $Mo_xW_{1-x}S_2$ nanotubes, in which two different metals were embedded, which were homogeneously distributed in the structure. These nanotubes exhibit a low density of structural defects and excellent crystallinity. They have a lower work function compared to nanotubes containing only one type of metal atom, which influences their use as electron sources. With colleagues from OTH Regensburg, we tested the field emission of electrons from these nanotubes and the temporal stability of the emission current. Individual nanotubes as a source of electrons are useful in a new generation of field-emission devices in electron microscopes, in the generation of X-rays, and in space, where they are used to neutralize spacecraft (L. Pirker et al., MoxWx–1S2 Nanotubes for Advanced Field Emission Application, Adv. Funct. Mater. 33, 2213869 (2023)).

In collaboration with the Ioffe Institute in St. Petersburg, we studied micro-photoluminescence spectra measured along individual MoS_2 nanotubes with partially or completely flattened cross-sections rotating along the tube axis. It was established that the splitting value of the whispering gallery modes depends exponentially on the aspect ratio of the cross-section, while the relative intensity of the modes in a pair is determined by the angle of rotation of the cross-section. These results open up the possibility of creating multifunctional tubular nanodevices based on transition-metal dichalcogenides that provide resonant amplification of self-emitting light at adjustable frequencies (*Adv. Optical Mater.* **11**, 2202782 (2023)). **Abdou Hassanien**, in collaboration with researchers from the Zewail University, Karslruhe Institute of Technology, and National Institute of Chemistry, Ljubljana, published an article in *ACS Applied Nano Materials* titled Engineering of Molybdenum Sulfide Nanobunches on MWCNTs. The paper describes a facile method to synthesize durable mixed-valence MoS_x catalysts on multiwall nanotubes for an efficient hydrogen evolution reaction. The oxidation state of the catalysts is inherently preserved through defect engineering within the amorphous mixed-valence phase, preventing the formation of fully reduced MoS_2 phases. High-resolution structural data and elemental analysis show that the origin of the efficient reaction is related to the combined effect of the reactive oxidation state and the highly conducting pathways provided by MWCNTs.

Active fluids

Andrej Vilfan, in collaboration with MPI Göttingen, derived a general theorem for the minimum dissipation needed by a microswimmer in a viscous fluid, considering both external and internal dissipation (Abdallah Daddi-Moussa-Ider et al., Minimum entropy production by microswimmers with internal dissipation, Nat. Commun. 14, 6060 (2023)). The theorem allows us to express a lower bound on dissipation with the drag coefficients of two bodies of the same shape as the swimmer, but with different boundary conditions. Our results show that entropy production by active microswimmers is subject to different fundamental limits compared to entropy production by externally driven particles.

Also, in the collaboration with MPI Göttingen, **Andrej Vilfan** used a minimal model of a ciliary carpet, which accounts for near-field hydrodynamic coupling between cilia, and showed that the interaction between cilia can be nonreciprocal (*Proc. Natl. Acad. Sci.* USA 120, e2307279120 (2023)). The collective dynamics of an array of cilia is therefore characterized by three different velocities and their directions: the direction of fluid transport, the direction of metachronal waves (phase velocity), and the direction of order propagation (group velocity). The last one determines the time scale of synchronization. Near-field nonreciprocal interactions can therefore give rise to a rapid emergence of metachronal waves.

Within the same collaboration we studied the Lorentz reciprocal theorem in fluids with odd viscosity (Y. Hosaka et al., Lorentz Reciprocal Theorem in Fluids with Odd Viscosity, Phys. Rev. Lett. 131, 178303 (2023)). The Lorentz reciprocal theorem is a versatile statement that can be used to solve problems in low Reynolds number hydrodynamics by connecting them to auxiliary problems with known solutions. Active fluids with odd viscosity break the time reversal symmetry and consequently the Lorentz reciprocal theorem does not hold. We showed that its validity can be restored if the auxiliary problem has odd viscosity with the opposite sign. We demonstrated how it can be applied to predict the motion of active particles in such a fluid.

Respiratory masks reduce the amount of pollutants we inhale and protect us from airborne diseases. In order to reduce the burden on the environment caused by hard-to-degrade respiratory masks, we applied polyvinylidene fluoride (PVDF) fibres to five natural materials (cotton, wool, linen, silk, muslin) using the electrospinning method.

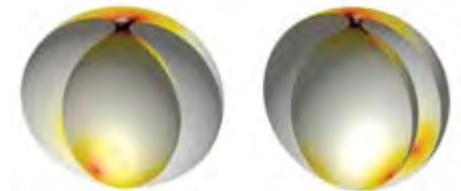*Figure 18: Phase-transition appearance change with confining thickness d*

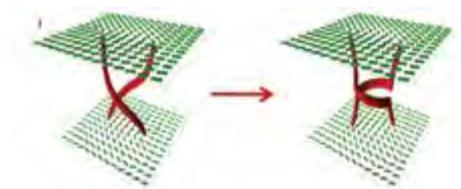*Figure 19: Topological defects in nematic shells*

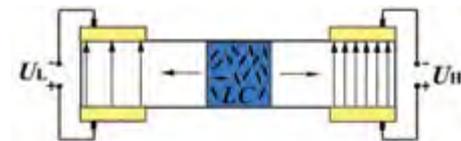*Figure 20: Reconfiguration of disclinations*

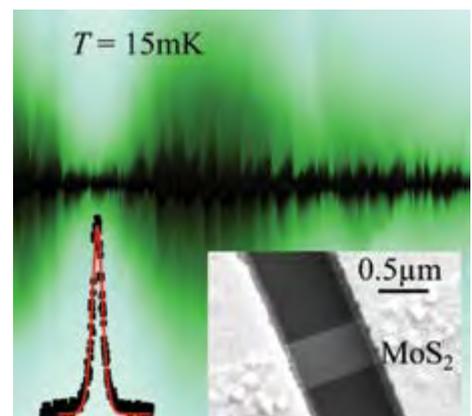*Figure 21: Schematic presentation of an active EC regenerator*

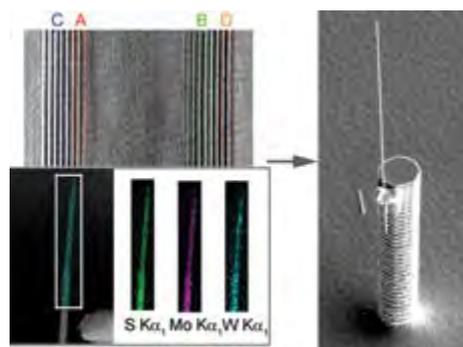*Figure 22: Discrete quantum states in MoS2 nanotubes and nanoribbons*

Figure 23: $Mo_xW_{1-x}S_2$ nanotubes used as a field emitter of electrons

Figure 24: Cover of ACS Applied Nanomaterials schematically depicts nanoclusters of MWCNTs with MoS_x

Figure 25: Using the minimum dissipation theorem, we determined the theoretically optimal shapes of microswimmers.

Figure 26: Synchronization of biological cilia in a finite group

These spontaneously polarized fibres increased the filtration efficiency for particles between 100 and 300 nm in diameter by electrostatic attraction, but did not significantly increase the pressure drop. We demonstrated excellent filtration efficiency using a minimal amount of the polymer, which did not exceed 3 mg/m² (*Materials* 16, 2314 (2023)). We also demonstrated optimization changes in a simple design of filtration masks to increase filtration efficiency by combining experiments and numerical modelling (*ACS Appl. Nano Mater.* 6, 17, 15807 (2023)).

Microcavity- and microlaser-based optical barcoding

Abdur Rehman Anwar, **Maruša Mur**, and **Matjaž Humar** published a review paper on the encoding techniques and applications of microcavity- and microlaser-based barcodes (Abdur Rehman Anwar et al., Microcavity- and Microlaser-Based Optical Barcoding: A Review of Encoding Techniques and Applications, ACS Photonics 10, 5, 1202-1224 (2023)). In the paper they reviewed the potential of microcavity- and microlaser-based barcodes for a broad range of applications such as cell tracking, anticounterfeiting, and product labelling. In microcavity-based barcodes the information is encoded in various ways in the properties of the emitted light, most frequently in the spectrum. Spectra of microcavity- and microlaser-based barcodes contain very narrow spectral lines and depend on the properties of the microcavity, such as size, shape, and gain material, therefore enabling the generation of millions of unique barcodes. Microcavity- and microlaser-based barcoding is a very powerful tool, which holds great promise. By developing new kinds of microcavities together with optical systems for their detection, they could become valuable tools in research and be useful for labelling products in everyday life.
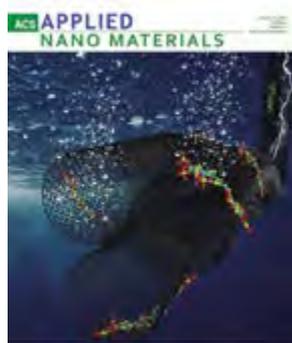
III. Research Programme: Experimental biophysics of complex systems and imaging in biomedicine

Research group for **Experimental biophysics of complex systems and imaging in biomedicine** combines the study of processes and structures in biological systems with the development of advanced experimental techniques, uncluding super-resolution microscopies, microspectroscopies and nanoscopies as well as new imaging techniques. Our research is mainly focused on the response of molecular and supramolecular structures to interactions between materials and living cells, as well as between light and living cells. We are interested in molecular events and physical mechanisms, with which these events are causally connected, time scales, conditions and applied values of the investigated mechanisms, especially for their use in medicine and in the field of health care in general. With the development of new coupled super-resolution and spectroscopic techniques we want to open new possibilities to investigate biological systems and, from there onwards, open new possibilities for designing medical materials and devices for diagnostics, therapy and tissue regeneration, which are the key challenges due to the population aging.
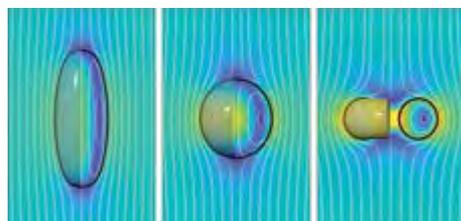
The investment into the new super-resolution STED system opened a variety of fluorescence microscopy approaches: STED microscopy and two-photon (2PE) microscopy, multichannel spectrally resolved fluorescence lifetime imaging (spFLIM), and fluorescence microspectroscopy (FMS). These, coupled with optical tweezers, can be used to examine interactions between materials, nanomaterials and cell lines and the phenomena involved such as lipid wrapping and nanomaterial passivation, membrane disintegration, and cellular membrane translocation bypassing conventional signalling pathways. We also introduced a method for monitoring the electric field in tumours in the treatment of cancer with electroporation, and further developed a method of multiparametric magnetic resonance imaging for the characterization of food, medicines and various industrial processes. High-resolution magnetic resonance imaging can monitor the effectiveness of surface treatments, track the formation and dissolution of gels and measure diffusion in confined geometries using modulated gradients.
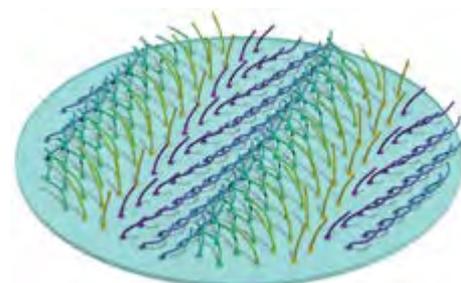
Mechanisms and prediction of diseases related to exposure to particulate matter

We started to coordinate the Horizon Europe Research and Innovation Action project *nanoPASS* (Bridging the gaps in nanosafety for animal-free prediction of adverse outcomes, ID: 101092741), involving nine partners from seven EU countries. The main aim of the project is to develop in vitro/in silico tests of four outcomes related to inhalation of particulate matter (chronic lung inflammation with fibrosis, reduced lung function, cardiovascular disease, and neurodegeneration) and validate the predictions on diverse families of real-world materials (used in construction, medicine, consumer and high-tech products, or released during waste treatment and recycling). Together with the spin-out company Infinite Biotech, we are involved in the development of the in vitro models (cell types) and observables, acquisition and analysis of live-cell microscopy data, and development and validation of in silico models to predict the time course of disease symptoms. A manuscript

on quantitative prediction of chronic lung inflammation is in preparation. We have presented the work at several scientific conferences, including the two main toxicology events (NanoSafe 2023, Eurotox2023) and at an invited lecture at a biophysical congress (Izmir, 2023).

Using high-throughput live-cell microscopy, we have discovered that environmental particulate matter (e.g., diesel exhaust nanoparticles) can trigger several major hallmarks of Alzheimer's disease in an in vitro model: shortening of axons, loss of connections between neuron-like cells, and build-up of amyloid-β and Tau-containing plaques (Figure 1). The manuscript, currently in the second revision stage at the journal *Nanotoxicology,* has been made available as a preprint (Sebastijanović, *bioRxiv*, 2024).

In the scope of the ongoing national research project "Concept development for mechanistic prediction of material-induced fibrosis and blood coagulation initiation (uCellnNet)", we are exploring early molecular/cellular events originating from lung epithelium that might be important for triggering fibrosis. We were invited to present our preliminary findings at the Department of Genetics at Louisiana State University (LSU) Health, School of Medicine, USA.

Together with Infinite Biotech, we are discovering early events related to the initiation and progression of cancer after exposure to nanoparticles. Particularly, we have focused on irregularities in cell division, such as prolongation of the time of mitosis and formation of binucleate cells, which could originate from a disrupted network of microtubules, observed after exposure to nanoparticles (Podlipec, *bioRxiv*, 2024).

Figure 27: Lorentz reciprocal theorem allows us to solve the main problem (self-propelled microswimmer, left) by connecting it to one of the auxiliary problems (with no-slip boundary, centre, or perfect-slip boundary, right).

Figure 28: Microlasers and microcavities can be employed for barcoding products and tracking live cells.

Development and application of advanced microscopy methods

In the newly established Center of Advanced Optical Microscopies (CNOM), which operates within the Center for Electron Microscopy and Microanalysis (CEMM), we reached several milestones in building a cutting-edge system combining high-throughput fluorescence structured illumination microscopy (SIM) and 2.5D microscopy. We successfully implemented the SIM modality and achieved successful reconstruction with the expected 1.75 resolution improvement over confocal microscopy. We were also successful in coupling 2.5D and SIM detection lines to enable fast switching between the modalities. To expand the capabilities of the system we plan to add a label-free quantitative phase imaging (QPI) modality to our experimental set-up. Our goal is to complete the system, including all three modalities, by the end of September 2024, with a hands-on demonstration to the wider community at the Jožef Stefan Institute.

We are now using the algorithms developed within the projects on autonomous microscopy (projects ARIS J7-2596, N1-0240, in collaboration with the Visual Cognitive Systems Laboratory, Faculty of Computer and Information Science, University of Ljubljana) for the characterization of sparse nuclear RNA-protein condensates, which appear to be crucial in the regulation of embryonic development (ARIS J4-50145 in collaboration with the group of dr. Miha Modic/prof. Jernej Ule, National Institute of Chemistry, Ljubljana, and Francis Crick Institute, London, UK).

We tested and characterized several novel fluorescent probes and intracellular sensors for advanced microscopy and microspectroscopy techniques, which were synthesized at the Faculty of Pharmacy, University of Ljubljana (Kokot, under review by *Bioorganic Chemistry*). In collaboration with the GlycoFluoNano laboratory from the University of Florence, Italy, we determined the photo-physical properties of their modular bio-compatible glyconanomaterials (G. Biagiotti et al., Simple engineering of hybrid cellulose nanocrystal-gold nanoparticles results in a functional glyconanomaterial with biomolecular recognition properties, Nanoscale Horizons 8, 776–782 (2023)).

With collaborators from the University of Oxford (prof. C. Eggeling, now at the University of Jena, Germany, and prof. E. Sezgin, now at the Karolinska Institute, Sweden), we were invited to write a News & Views article on investigating molecular mechanisms of the activation of B-cells, a part of our immune response, with super-resolution fluorescence microscopy (I. Urbančič et al., Do lipids tune B cell signaling?, Nature Chemical Biology 19, 669–670 (2023)).

The Laboratory for Biophysics and its spin-out company Infinite d.o.o. started to coordinate a new four-year EU project nanoPASS, focused on the development and validation of novel animal-free predictive technologies for long-term safety assessment. The international consortium comprises highly renowned research, industrial and regulatory partners from seven EU countries.

Figure 29: High spatial resolution fluorescence image (stimulated emission depletion STED) of synapse damage and early plaque formation (white arrows) at the sites of damaged synapses (green, MEMBRANE) caused by anatase TiO_2 nanotubes (red, NANO) containing amyloid β (blue, Aβ)

Monitoring plant tissue processing with electric field pulses using magnetic resonance imaging

The change in the cell membrane permeability upon exposure of plant tissues to pulsed electric fields (PEF) is associated with physical changes in cellular and subcellular structures. The aim of our research was to investigate possible heterogeneities in PEF treatment due to the structural heterogeneity of plant tissues. We tested the use of PEF on the following plant tissues: apples, potatoes and carrots. We measured the spatial distribution of T_2 NMR
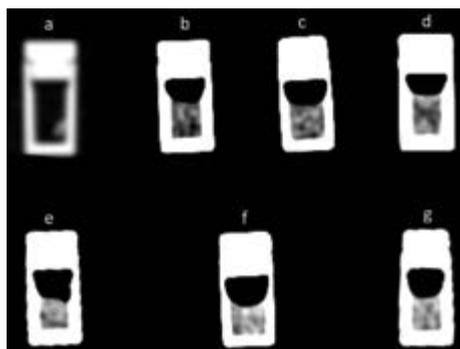
Figure 30: Computed tomography (CT) images in dual-energy (80 kV) mode of all seven different thrombus models taken five hours after the initiation of their clotting: platelet thrombus (a), pure plasma thrombus (b), 20% red blood cell (RBC) thrombus (c), 40% RBC thrombus (d), 60% RBC thrombus (e), 80% RBC thrombus (f) and 100% RBC thrombus (g). In images (b–g), presented in the same window width (WW) and window centre (WC), it is clearly seen how image brightness increases with increasing HT. The platelet thrombus in image (a) is displayed with different WW and WC, which is optimal for its presentation.
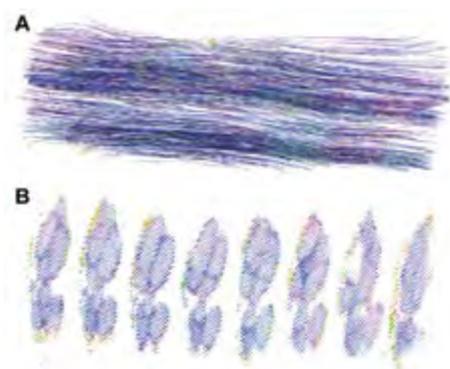

Figure 31: DT tractography and diffusion ellipsoids of a nerve sample. (A) Three-dimensional representation of nerve fibres in an approximately 9 mm long segment of the median nerve. By convention, the red colour represents the x-direction, green represents the y-direction, and blue is the z-direction; in our case, the nerve was oriented along the z-axis. (B) Diffusion ellipsoid display of the subsequent slices. The dimensions and orientations of the ellipsoids correspond to the eigenvalues and eigenvectors, while their colour scheme is orientation-dependent and determined by the same principle as the colours in the tractography image.

relaxation using magnetic resonance imaging as a function of the local electric field during PEF treatment, which was assessed with magnetic resonance electrical impedance tomography. The results showed increasing heterogeneity of the distribution of T_2 relaxation times with the increasing complexity of the tissue structure (carrot > potato > apple) (J. Genovese et al., PEF treatment effect on plant tissues of heterogeneous structure no longer an enigma: MRI insights beyond the naked eye, Food chemistry 405, 134892 (2023)).

Comparison of CT and MR properties of artificial cerebral thrombi

With this research, we wanted to answer the question of whether and to what extent it is possible to assess the structure and composition of thrombi using NMR and CT measurements. For this purpose, we made seven different thrombus models: six erythrocyte thrombi with hematocrit (HT) levels of 0, 20, 40, 60, 80 and 100% and one platelet thrombus model. These clots were analysed with proton NMR at 100 and 400 MHz using T1 and T2 NMR relaxation time measurements and apparent diffusion coefficient (ADC) measurements. In addition, the thrombus models were also imaged with CT in the dual-energy mode (80 and 140 kV) and in the single-energy mode (80 kV) to determine their X-ray absorption in Hounsfield units from the images (Figure 30). The results confirmed that erythrocyte thrombi can be distinguished from platelet thrombi with ADC and CT count measurements in all three settings, whereas they cannot be distinguished with T1 and T2 measurements. All measured parameters allowed the differentiation of erythrocyte thrombi according to their HT values, but the best sensitivity to HT was achieved with the ADC and single-energy CT measurements. The results could be applied to the characterization of actual thrombi in vivo (R. Viltužnik et al., Comparing CT and MR properties of artificial thrombi according to their composition, Diagnostics 13, 1802 (2023)).

Diffusion tensor imaging of peripheral nerves by magnetic resonance microscopy

Understanding the microanatomy of nerves is important because various neuropathies and some nerve neoplasms are accompanied by fascicle enlargement. The aim of our study was to obtain clinically oriented knowledge of the fascicular anatomy of the nerve using different anatomical imaging methods. These also included imaging with the help of magnetic resonance microscopy, which we perform on a superconducting magnet with a magnetic field density of 9.4 T. Recently, we also developed a new diffusion tensor imaging (DTI) method, which we were able to use in this study for imaging sections of the median and ulnar nerves. This method was used to study the diffusion properties and fractional anisotropy of different anatomical structures of the nerve (Figure 31). The high spatial resolution of the imaging, which was 35 micrometres, made this study, one of the first of its kind in the world, a particular challenge (L. Pušnik et al., Correlation between diffusion tensor indices and fascicular morphometric parameters of peripheral nerve, Frontiers in Physiology 14, 1 (2023)).

IV. Research Programme: Physics of quantum technologies

Suppression of dark-state polariton collapses in a cold-atom quantum memory

We experimentally observed dark-state polariton collapses and revivals in a quantum memory based on electromagnetically induced transparency in a cloud of cold cesium atoms in a magnetic field. We suppressed the dark-state polariton collapses by polarizing the atoms towards one of the stretched Zeeman states and optimizing the frequency detuning of the control beam. In this way, we demonstrated a quantum memory with only partial dark-state polariton collapses, making the memory usable at any storage time, not only at discretized times of revivals. We obtained a storage time of more than 400 μs, which is ten times longer than what we can achieve by trying to annul the magnetic field. (K. Gosar et al., Suppression of dark-state polariton collapses in a cold-atom quantum memory, Phys. Rev. A 108, 032618 (2023)).

ERC projects

1. H2020 - Cell-Lasers; Intracellular Lasers: Coupling of Optical Resonances with Biological Processes
   Asst. Prof. Matjaž Humar
   European Commission

2. H2020 - LOGOS; Light-Operated Logic Circuits from Photonic Soft-Matter
   Prof. Igor Muševič
   European Commission

Some outstanding publications in 2023

1. J. Kathua et al., Experimental signatures of quantum and topological states in frustrated magnetism, Phys. Rep. 1041, 1 (2023).
2. M. Gomilšek et al., Many-body quantum muon effects and quadrupolar coupling in solids, Commun. Phys. 6, 142 (2023).
3. Y. Tanuma et al., Noncontact Layer Stabilization of Azafullerene Radicals: Route toward High-Spin-Density Surfaces, ACS Nano 17, 25301–25310 (2023).
4. Bobnar, M., Derets, N., Umerova, S. et al., Polymer-dispersed liquid crystal elastomers as moldable shape-programmable material, Nat. Commun. 14, 764 (2023).
5. N. Kralj et al., Defect Line Coarsening and Refinement in Active Nematics, Phys. Rev. Lett. 130, 128101 (2023).
6. C. Dao et al., Nematronics: Reciprocal Coupling between Ionic Currents and Nematic Dynamics, Phys. Rev. Lett. 130, 168102 (2023).
7. Abdallah Daddi-Moussa-Ider et al., Minimum entropy production by microswimmers with internal dissipation, Nat. Commun. 14, 6060 (2023).
8. Y. Hosaka et al., Lorentz Reciprocal Theorem in Fluids with Odd Viscosity, Phys. Rev. Lett. 131, 178303 (2023).
9. L. Pirker et al., $MoxWx-1S2$ Nanotubes for Advanced Field Emission Application, Adv. Funct. Mater. 33, 2213869 (2023).
10. Abdur Rehman Anwar et al., Microcavity- and Microlaser-Based Optical Barcoding: A Review of Encoding Techniques and Applications, ACS Photonics 10, 5, 1202–1224 (2023).
11. I. Urbančič et al., Do lipids tune B cell signaling?, Nature Chemical Biology 19, 669–670 (2023)).
12. K. Gosar et al., Suppression of dark-state polariton collapses in a cold-atom quantum memory, Phys. Rev. A 108, 032618 (2023).
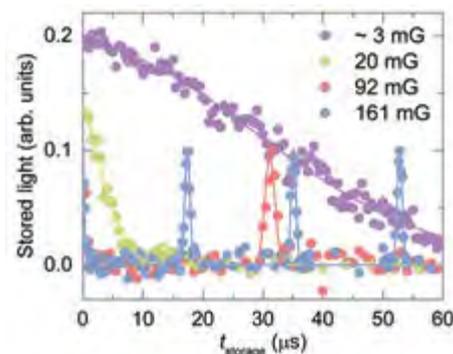

Figure 32: Efficiency of the quantum memory retrieval as a function of the storage time for different amplitudes of the magnetic field

Some outstanding publications in 2022

1. T. Arh et al., The Ising triangular-lattice antiferromagnet neodymium heptatantalate as a quantum spin liquid candidate, Nat. Mater. 21, 416 (2022).
2. J. Luzar, P. Priputen, M. Drienovský, S. Vrtnik, P. Koželj, A. Jelen, M. Wencka, D. Gačnik, P. Mihor, B. Ambrožič, G. Dražić, A. Meden, J. Dolinšek, Zero-Magnetostriction Magnetically Soft High-Entropy Alloys in the Al-CoFeNiCux (x = 0.6 – 3.0) System for Supersilent Applications, Adv. Mater. Interfaces 9, 2201535 (2022).
3. Z. Hananai, Z. Kutnjak et al., Nanoscale Adv. 4, 4658–4668 (2022).
4. T. Yao, Ž. Kos, Qi Xing Zhang, Yimin Luo, E. B. Steager, M. Ravnik, K. J. Stebe, Topological defect-propelled swimming of nematic colloids, Sci. Adv. 8, eabn8176 (2022).
5. Ž. Kos, J. Dunkel, Nematic bits and universal logic gates, Sci. Adv. 8, eabp8371 (2022).
6. J. Pišljar, S. Ghosh, S. Turlapati, N. V. S. Rao, M. Škarabot, A. Mertelj, A. Petelin, A. Nych, M. Marinčič, A. Pusovnik, M. Ravnik, I. Muševič, Blue Phase III: Topological Fluid of Skyrmions, Phys. Rev. X 12, 011003 (2022).
7. G. Poy, A. J. Hess, A. J. Seracuse, M. Paul, S. Žumer, I. I. Smalyukh, Nature Photonics 16, 454–461 (2022).
8. Galiani, Silvia, Reglinski, K., Carravilla, P., Barbotin, Aurélien, Urbančič, Iztok, Ott, J., Sehr, J., Sezgin, Erdinc, Schneider, F., Waithe, Dominic, Hublitz, P., Schliebs, W., Erdmann, R., Eggeling, Christian, Diffusion and interaction dynamics of the cytosolic peroxisomal import receptor PEX5, Biophysical Reports 2, 1–15 (2022).
9. M. Leroux, B. Kokot, H. Kokot, T. Koklič, J. Štrancar et al., Aerosol–cell exposure system applied to semi-adherent cells for aerosolization of lung surfactant and nanoparticles followed by high quality RNA extraction, Nanomaterials 12, 1362 (2022).
10. I. Serša, Electric current detection based on the MR signal magnitude decay, Magnetic Resonance in Medicine 88, 1282–1291 (2022).
11. K. Gosar et al., Preparation of ultracold atomic-ensemble arrays using time-multiplexed optical tweezers, Phys. Rev. A 106, 022604 (2022).

Some outstanding publications in 2021

1. Schymura, Stefan, Drev, Sandra, Podlipec, Rok, Rijavec, Tomaž, Lapanje, Aleš, Štrok, Marko, et al., Dissolution-based uptake of CeO2 nanoparticles by freshwater shrimp – a dual-radiolabelling study of the fate of anthropogenic cerium in water organisms, *Environmental Science: Nano,* 2021, **8**, 7, 1934–1944

2. Everts, J. C., Ravnik, M., Ionically charged topological defects in nematic fluids, *Phys. Rev. X*, 2021, **11**, 1, 011054

3. Papič, M., Mur, U., Zuhail, K. P., Ravnik, M., Muševič, I., Humar, M., Topological liquid crystal superstructures as structured light lasers, *Proc. Natl. Acad. Sci. U.S.A.*, 2021, **118**, 49, e2110839118

4. Peddireddy, K., Čopar, S., Le, V.K., Muševič, I., Bahr, C., Jampani, V.S.R., Self-shaping liquid crystal droplets by balancing bulk elasticity and interfacial tension, *Proc. Natl. Acad. Sci. U.S.A.*, 2021, **118**, 14, e2011174118

5. Pirker, L., Pogačnik Krajnc, A., Malec, J., Radulović, V., Gradišek, A., Jelen, A., Remškar, M., Mekjavić, I. B., Kovač, J., Mozetič, M., Snoj, L., Sterilization of polypropylene membranes of facepiece respirators by ionizing radiation, *J. Membr. Sci.*, 2021, **619**, 118756

6. Del Pupo, S., Zupanič, E., et al., Tuning graphene doping by carbon monoxide intercalation at the Ni(111) interface, *Carbon*, 2021, **176**, 253–261

7. Nasour, B., Vilfan, A., Golestanian, R., Minimum dissipation theorem for microswimmers, *Phys. Rev. Lett.*, 2021, **126**, 3, 034503

8. Hickey, D., Vilfan, A., Golestanian, R., Ciliary chemosensitivity is enhanced by cilium geometry and motility, *eLife*, 2021, **10**, e66322

9. M. Klanjšek, Singlets singled out, *Nature Physics*, 2021, **17**, 1081–1082

10. X. Chen, T. Yang, Q. Zhang, L. Q. Chen, V. Bobnar, C. Rahn, Q. M. Zhang, Topological structure enhanced nanostructure of high temperature polymer exhibiting more than ten times enhancement of dipolar response, *Nano Energy*, 2021, **88**, 106225

11. Y. Tanama et al., Robust coherent spin centers from stable azafullerene radicals entrapped in cycloparaphenylene rings, *Nanoscale*, 2021, **13**, 47, 19946–19955

Awards and Appointments

1. Prof. Dr Andrej Zorko: Robert E. Marshak Lectureship Award, American Physical Society, United States of America

2. Dr Peter Jeglič and Prof. Dr Erik Zupanič: Special Prize for Innovations for the Economy, 16th International Technology Transfer Conference (ITTC16), Ljubljana, Slovenia

3. Prof. Dr Miha Ravnik: Golden Plaque for Outstanding Contribution to the Development of Scientific, Pedagogical, or Artistic Creation and for Strengthening the Reputation of the University of Ljubljana, Slovenia

4. Dr Tilen Knaflič: Award for the poster presentation with the title: Spin-dimer ground state in the mixed-valence compound Rb4O6 as revealed by electron spin resonance, received at the international workshop Magnetic Resonance of Correlated Electron Materials, Dresden, Germany

Organization of Conferences, Congresses and Meetings

1. NanoSpace – 1st Scientific Meeting, JSI, Ljubljana, 9–11 November 2023

Patents Granted

1. Matjaž Lukač, Franci Bajd, Marko Kazič, Zdenko Vižintin, Tadej Perhavec, Apparatus and method for tissue regeneration, US 11,648,417 B2, US Patent Office, 16. 5. 2023

2. Aswathy Vasudevan, Gregor Filipič, Janez Zavašnik, Uroš Cvelbar, Method for in-situ synthesis and deposition of metal oxide nanoparticles with atmospheric pressure plasma, EP 3 960 703 B1, European Patent Office, 7. 6. 2023

INTERNATIONAL PROJECTS

1. ERC H2020 - Cell-Lasers; Intracellular Lasers: Coupling of Optical Resonances with Biological Processes
   Asst. Prof. Matjaž Humar
   European Commission

2. ERC H2020 - LOGOS; Light-Operated Logic Circuits from Photonic Soft-Matter
   Prof. Igor Muševič
   European Commission

3. P-LAYER - JSI; Equipment Rental in C027 and Sale of a „Device for Orienting Liquid Crystals"
   Prof. Igor Muševič
   P-layer

4. COST CA9108; HiSCALE - High-Temperature SuperConductivity for AcceLerating the Energy Transition
   Dr. Abdelrahim Ibrahim Hassanien
   COST Association Aisbl

5. BIO-OPT-COMM; A Living Optically-Communicating Neural Network
   Asst. Prof. Matjaž Humar
   Hfspo- International Human Frontier
6. H2020 - ENGIMA; Engineering of Nanostructures with Giant Magneto-Piezoelectric and Multicaloric Functionalities
   Prof. Zdravko Kutnjak
   European Commission
7. H2020 - ATHENA; Implementing Gender Equality Plans to Unlock Research Potential of RPOs and RFOs in Europe
   Prof. Maja Remškar
   European Commission
8. H2020 - FoodTraNet; Advanced Research and Training Network in Food Quality, Safety and Security
   Asst. Prof. Matjaž Humar
   European Commission
9. H2020 - QMatCh; Towards Quantum States of Matter via Chemistry under Extreme Conditions
   Prof. Denis Arčon
   European Commission
10. Tunable Memristive Switching in Carbon Nanotube Network for Neuromorphic Computing
    Dr. Abdelrahim Ibrahim Hassanien
    Slovenian Research Agency
11. High-Temperature Polymer Blends with Greatly Enhanced Electrical Breakdown Strength
    Prof. Zdravko Kutnjak
    Slovenian Research Agency
12. Novel Quantum Materials from a Local-Probe Perspective
    Prof. Andrej Zorko
    Slovenian Research Agency
13. 3D Printed Internals for Optimized Water Electrolysis
    Prof. Janez Dolinšek
    Slovenian Research Agency
14. Topological Excitations and Quasi-Particles in Nematic Liquid Crystals
    Prof. Samo Kralj
    Slovenian Research Agency
15. Initiation of Coagulation by Lung Epithelium Exposed Nanoparticle in Vitro
    Dr. Tilen Koklič
    Slovenian Research Agency
16. Layered Hybrid Metal-Organic Perovskites: Structure - Magnetism Correlation
    Prof. Andrej Zorko
    Slovenian Research Agency
17. HE - FerroChiral; Tunable Topological Chirality in Ferroelectric Nanomaterials
    Prof. Zdravko Kutnjak
    European Commission
18. HE - nanoPASS; Bridging the Gaps in Nanosafety for Animal-Free Prediction of Adverse Outcomes
    Asst. Prof. Iztok Urbančič
    European Commission
19. HE - LibMOF; High-Throughput Synthesis and Characterisation of Metal-Organic Framework Thin Films for Volatile Compound Sensing
    Prof. Zdravko Kutnjak
    European Commission
20. DIGITAL EU; SiQUID - Slovenian Quantum Communication Infrastructure Demonstration
    Dr. Peter Jeglič
    European Commission
21. COST CA21126; NanoSpace - Carbon Molecular Nanostructures in Space; Scientific Meeting of the Nanospace Project
    Prof. Denis Arčon
    COST Association Aisbl
22. COST CA21144; Superconducting Nanodevices and Quantum Materials for Coherent Manipulation
    Dr. Abdelrahim Ibrahim Hassanien
    COST Association Aisbl
23. NATO - FRAPCOM; Flexible Nano-Ferroelectrics for Rapid Cooling of Combat Electronic
    Prof. Zdravko Kutnjak
    Nato - North Atlantic Treaty Organisation
24. COST CA22105; BeSafeBeeHoney - BEekeeping products valorization and biomonitoring for the SAFEty of BEEs and HONEY
    Asst. Prof. Anton Gradišek
    COST Association Aisbl

RESEARCH PROGRAMMES

1. Physics of quantum and functional materials
   Prof. Denis Arčon
2. Physics of Soft Matter, Surfaces and Nanostructures
   Prof. Miha Ravnik

3. Experimental Biophysics of Complex Systems
   Prof. Janez Štrancar
4. Nonequilibrium Quantum System Dynamics
   Prof. Denis Arčon
5. Physics of quantum technologies
   Dr. Peter Jeglič
6. R&D grants and contracts
7. Phase transitions towards coordination in multilayer networks
   Dr. Uroš Jagodič
8. Development of building blocks for new European quantum communication network
   Dr. Peter Jeglič
9. Development of high-performance piezoelectric coatings for self-powering of nonwovens used in e-mobility
   Prof. Vid Bobnar
10. Cell membrane uptake of bacteria, virions and anorganic particles controlled by membrane mechanics and topology
    Georgios Kordogiannis
11. Non-equilibrium colloidal topological soft matter
    Asst. Prof. Žiga Kos
12. Programming of protein-RNA condensation during mammalian development
    Asst. Prof. Iztok Urbančič
13. Two-dimensional materials-based piezophotonic composites for tailor-made ultrasounds in biological systems (2D-UltraS)
    Asst. Prof. Matjaž Humar
14. Stabilization and destabilisation of spin liquids by perturbations
    Prof. Andrej Zorko
15. Physics of Majorana fermions in Kitaev magnets
    Asst. Prof. Martin Klanjšek
16. Novel experimental approach for determination of quantum spin liquids
    Prof. Andrej Zorko
17. Topological turbulence in confined chiral nematic fields
    Prof. Miha Ravnik
18. Controllable broadband electromagnetic-radiation shielding
    Asst. Prof. Matej Pregelj
19. Intelligent Content-Aware Nanospectroscopy (iCAN) of molecular events in nanoparticles-induced neurodegeneration
    Asst. Prof. Iztok Urbančič
20. Self-assembly of Photon-Enabled Circuits using Topologically Reconfigurable Anisotropic Liquids
    Dr. Venkata Subba Rao Jampani
21. Advanced optical magnetometry of vortices in unconventional superconductors
    Prof. Denis Arčon
22. Diamond-assisted quantum processing of fullerene qubits
    Prof. Denis Arčon
23. Coulombic subgap states in superconducting quantum devices
    Prof. Denis Arčon
24. Single-flux-quantum controlled charge configurational memory (CCM) devices
    Prof. Andrej Zorko
25. Solving the Early Eventome of Cellular Responses by Intelligent Content-Aware nanoscopy
    Asst. Prof. Iztok Urbančič
26. Changes of neuro-musculo-fascial system in diabetes analyzed by 3D microscopy and biomechanic tests
    Prof. Igor Serša
27. Plasma activated nanobubbles: A new approach for high-level disinfection of flexible endoscopes
    Dr. Gregor Filipič
28. Antiferroelectric materials for cooling and high power electronic applications
    Dr. Nikola Novak
29. Exploring the biofilm phenotype and surfactome of Listeria monocytogenes to predict its persistence and pathogenicity potential using machine learning
    Dr. Boštjan Kokot
30. Anisotropic quantum magnetism in novel rare-earth materials
    Prof. Andrej Zorko
31. Entangled and delocalized states of muons and nuclei
    Asst. Prof. Matjaž Gomilšek
32. Magnetic, electric and stress – field programming of shape response in polymer-dispersed liquid crystal elastomers – based actuators
    Asst. Prof. Andraž Rešetič
33. Development of integrated multi-channel artificial nose for detection of cancer
    Prof. Igor Muševič
34. Concept development for mechanistic prediction of material-induced fibrosis and blood coagulation initiation (uCellnNet)
    Dr. Tilen Koklič
35. Cryptographically secure random number generator
    Dr. Peter Jeglič
36. Ultrafine particles in urban environment
    Prof. Maja Remškar
37. SiMBION – EuBI
    Prof. Igor Serša
    Slovenian Research Agency

38. Slovenian Quantum Communication Infrastructure Demonstration
Dr. Peter Jeglič
Government Information Security Office
39. Cryptographically secure random number generator
Dr. Peter Jeglič
Government Office for the Protection of Classified Information
40. Physics of quantum technologies
Dr. Peter Jeglič
Slovenian Research Agency
41. Ultrafine particles in urban environment
Prof. Maja Remškar
Ministry of the Environment, Climate and Energy
42. CROSSING - Crossing Borders and Scales - An Interdisciplinary Approach
Prof. Janez Štrancar
Helmholtz-Zentrum Dresden-Rossendorf E.V.
43. ECMetAC Days 2023
Prof. Janez Dolinšek
European Cmetac

NEW CONTRACTS

1. Development and maintenance of PHP and MS SQL Server
Prof. Igor Muševič
SRC d. o. o.
2. Magnetic, electric and stress - field programming of shape response in polymer-dispersed liquid crystal elastomers - based actuators
Asst. Prof. Andraž Rešetič
KMZ - Zalar Miran S.p.
3. Research and analysis of new molecular events and their causal connections in vitro
Prof. Janez Štrancar
Infinite d. o. o.
4. Magnetic resonance imaging of tablets in various media
Prof. Igor Serša
Lek d. d.
5. Mechanistic prediction of material-induced fibrosis and blood coagulation initiation (uCellnNet)
Dr. Tilen Koklič
Infinite d. o. o.
6. Development of integrated multi-channel artificial nose for detection of cancer
Prof. Igor Muševič
RLS merilna tehnika d. o. o.

VISITORS FROM ABROAD

1. Dr Bar Laure, Universite Libré de Bruxelles, Brussels, Belgium, 2–10 September 2023
2. Bastien Anezo, University of Nantes, France, 3–12 July and 5–23 December 2023
3. Dr Carla Bittencourt, University of Mons, Belgium, 15–27 June 2023
4. Prof. dr. Diego Rubbi, National Scientific and Technical Research Council (CONICT) and National Atomic Energy Commission (CNEA), Bariloche, Argentina, 19–26 November 2023
5. Prof. dr Valentina Domenici, Department of Chemistry and Industrial Chemistry, University of Pisa, Italy, 20 July to 6 August 2023
6. Prof. Mimoun El Marssi, University of Picardie Jules Verne, LPMC, Amiens, France, 27–29 December 2023
7. Fabian Hotz, University of Zürich, Switzerland, 9–27 January 2023
8. Fabian Hotz, University of Zürich, Switzerland, 16–27 October 2023
9. Valentine Jauquet, University of Mons, Belgium, 6 March to 7 April 2023
10. Said Khardazi, University Cadi Ayyad, Marrakesh, Morocco, 7 December 2022 to 6 January 2023
11. Martin Klaczak, University of Jagiellonian in Krakow and University of Gdansk, 24–30 September 2023
12. Lahoucine Hajji, University Cadi Ayyad, Marrakesh, Morocco, 7 December 2022 to 9 January 2023
13. Afaak Lakouader, University Cadi Ayyad, Marrakesh, Morocco, 4 February to 28 April 2023
14. Jasmina Lazarević, Nenad Lazarević, Institute of Physics Belgrade, Serbia, 27–30 November 2023
15. Ionis Lelidis, University of Athens, Greece, 19–21 September 2023
16. Lev Bohdan, Bogolyubov Institute for Theoretical Physics, NAS Ukraine and Institute of Physics, NAS Ukraine, 13 December 2022 to 31 August 2023
17. Eduardo Llobet, University of Tarragona, Spain, 20–26 February 2023
18. Amjoud M'Barek, University Cadi Ayyad, Marrakesh, Morocco, 6–13 March 2023
19. Daoud Mezzane, University Cadi Ayyad, Marrakesh, Morocco, 6–13 March 2023
20. Mariusz Mrozek, Jagielloninan University, Krakow, Poland, 10–17 December 2023
21. Mutsuo Igarashi, Department of Applied Physics, Gunma National College of Technology, Maebashi, Japan, 30 May to 10 June 2023
22. Pajić, Mirta Rubčić and Barišić, Faculty of Natural Sciences, University of Zagreb, Croatia, 6 June 2023
23. Pavol Pripoten, Slovak University of Technology in Bratislava, Faculty of Materials Science and Technology in Trnava, Slovakia, 24–28 April 2023
24. Anna Ryzhkova, ASML Netherlands B.V., 1–16 April 2023
25. Sebastiao Pedro, Instituto Superior Tecnico, University of Lisbon, Portugal, 28 May to 3 June 2023
26. Radoslaw Strzalka, AGH University of Krakow, Poland, 3 June to 2 August 2023
27. Szymon Starzonek, Institute of High Pressure Physics of the Polish Academy of Sciences, Warsaw, Poland, 5–14 January 2023
28. Stefan Šćepanović, University of Montenegro, Podgorica, 2–30 October 2023
29. Stefan Šćepanović, University of Montenegro, Podgorica, 11–20 December 2023
30. Dr Pavla Šenjug, Department of Physics, Faculty of Science, University of Zagreb, 13–31 March 2023
31. Prof. Torben R. Jensen, Aarhus University, Denmark; Prof. Yaroslav Filinchuk, Université Catholique de Louvain, Belgium; prof. Marek Polanski, Military University of Technology, Warsaw, Poland, 14 December 2023
32. Bojana Višić, Institute of Physics Belgrade, Serbia, 27 November to 3 December 2023
33. dr Magdalena Wencka, Polish Academy of Sciences, Institute of Molecular Physics, Poznan, Poland, 15 January 2022 to 31 December 2023
34. Yoshiko Takenaka, Research Institute for Sustainable Chemistry, AIST, Japan, 12 February to March 2023
35. Zahid Marwa, Cadi Ayyad University, Marrakesh, Morocco, 18 January to 22 February 2023
36. Prof. Qiwen Zhan, University of Shanghai for Science and Technology, Shanghai, China, 18–20 September 2023
37. Maha Zid, Tunisia, from 2 February 2023

STAFF

Researchers
1. Prof. Tomaž Apih
2. **Prof. Denis Arčon, Head**
3. *Prof. Denis Arčon*, Head, left 01.10.23*
4. Prof. Vid Bobnar
5. Prof. Janez Dolinšek*
6. Dr. Gregor Filipič
7. Asst. Prof. Matjaž Gomilšek
8. Asst. Prof. Anton Gradišek
9. Dr. Alan Gregorovič
10. Dr. Abdelrahim Ibrahim Hassanien
11. Asst. Prof. Matjaž Humar
12. DR. Venkata Subba Rao Jampani
13. Dr. Peter Jeglič
14. Dr. Andreja Jelen
15. Asst. Prof. Martin Klanjšek
16. Dr. Tilen Koklič
17. Dr. Georgios Kordogiannis
18. Asst. Prof. Žiga Kos*
19. Asst. Prof. Primož Koželj
20. Prof. Samo Kralj*
21. Prof. Zdravko Kutnjak
22. Dr. Aleksander Matavž
23. Dr. Mojca Urška Mikac
24. Asst. Prof. Aleš Mohorič*
25. Prof. Igor Muševič*
26. Dr. Nikola Novak
27. Dr. Andriy Nych
28. Asst. Prof. Dušan Ponikvar*
29. Dr. Matej Pregelj
30. Prof. Miha Ravnik*
31. Dr. Anna Razumnaya
32. Prof. Maja Remškar
33. Asst. Prof. Andraž Rešetič
34. Asst. Prof. Brigita Rožič
35. Dr. Anna Ryzhkova

36. Prof. Igor Serša
37. *Dr. Vandna Sharma, left 21.11.23*
38. Prof. Miha Škarabot
39. Prof. Janez Štrancar*
40. Prof. Uroš Tkalec*
41. Dr. Polona Umek
42. Asst. Prof. Iztok Urbančič
43. Dr. Herman Josef Petrus Van Midden
44. Dr. Mahendran Vellaichamy
45. *Asst. Prof. Jernej Vidmar*, left 01.07.23*
46. *Asst. Prof. Andrej Vilfan, left 02.09.23*
47. Dr. Bojana Višić
48. Dr. Stanislav Vrtnik
49. Prof. Aleksander Zidanšek
50. Prof. Andrej Zorko
51. Asst. Prof. Erik Zupanič
52. Prof. Slobodan Žumer

Postdoctoral associates
53. Dr. Franci Bajd*
54. Dr. Izidor Benedičič
55. *Dr. Apparao Gudimalla, left 01.04.23*
56. Dr. Uroš Jagodič
57. Dr. Tilen Knaflič
58. Dr. Hana Kokot
59. Dr. Boštjan Kokot
60. *Dr. Zuhail Kottoli Poyil, left 01.03.23*
61. Dr. Marta Lavrič
62. Dr. Jože Luzar
63. Dr. Deepshika Malkar
64. Dr. Tadej Mežnaršič
65. Dr. Maruša Mur
66. Dr. Mimoza Naseska
67. Dr. Andrej Petelin*
68. Dr. Luka Pirker
69. Dr. Jaka Pišljar
70. Dr. Rok Podlipec
71. Dr. Yuliia Shyshkina
72. Dr. Marion Antonia Van Midden Mavrič

Postgraduates
73. Abdur Rehman Anwar, M. Sc.
74. Tina Arh, B. Sc.
75. Dr. Dejvid Črešnar
76. *Nikita Derets, left 01.09.23*
77. Dr. Darja Gačnik
78. Žiga Gosar, B. Sc.
79. Katja Gosar, B. Sc.

80. Anton Hromov, M. Sc.
81. Vida Jurečič, B. Sc.
82. Aljaž Kavčič, B. Sc.
83. Zala Korenjak, B. Sc.
84. Benjamin Korošević Koser, B. Sc.
85. *Darin Lah, B. Sc., left 01.10.23*
86. Matjaž Malok, B. Sc.
87. Bojan Marin*, M. Sc.
88. Matevž Marinčič, B. Sc.
89. Maj Mejak, B. Sc.
90. Matic Morgan, B. Sc.
91. Arkalekha Neogi, M. Sc.
92. Rok Peklar, B. Sc.
93. Julia Petrović, M. Sc.
94. Jure Pirman, B. Sc.
95. Gregor Pirnat, B. Sc.
96. Anja Pogačnik Krajnc, B. Sc.
97. Linsy Jane Selvin Robert, M. Sc.
98. Dr. Rebeka Viltužnik
99. Maha Zid, M. Sc.

Technical officers
100. Petra Čotar, B. Sc.
101. Urška Gazdag, B. Sc.
102. Maša Kavčič, B. Sc.
103. Ana Krišelj, B. Sc.
104. Ivan Kvasić, B. Sc.
105. *Blaž Mencinger, M. Sc., left 05.05.23*
106. Jaka Močivnik, B. Sc.
107. *Govindanunni Padmakumar, M. Sc., left 01.10.23*
108. Peter Ropač*, B. Sc.
109. Cody Frank Tripp, M. Sc.
110. Jaka Zaplotnik*, B. Sc.

Technical and administrative staff
111. Dražen Ivanov
112. Janez Jelenc, B. Sc.
113. *Davorin Kotnik, retired 01.07.23*
114. Vesna Lopatič, B. Sc.
115. Silvano Mendizza
116. Peter Mihor
117. Janja Milivojević
118. Ana Sepe, B. Sc.
119. Marjetka Tršinar

Note:
* part-time JSI member

LABORATORY OF GASEOUS ELECTRONICS

F-6

The research activities within the Department of Gaseous Electronics cover various research areas, ranging from the science of gases and gaseous discharges, plasma nanoscience, plasma biology and biomedicine, advanced sensors, surface electronics, and crystals to advanced vacuum science and technology. Within this scope, we are exploring different gaseous and plasma systems and their use in various fields important for the progress of humanity. The research activities are, therefore, quite diverse. The most important achievements and progress beyond the existing state of the art are communicated in the paragraphs below.

Head:
Prof. Uroš Cvelbar

The major activities of the department encompass interconnected fields of research such as the science of gases and gaseous discharges, plasma nanoscience, processing and synthesis of nanomaterials, plasma chemistry, plasma electrochemistry and catalysis, plasma biomedicine and biotechnology, gas sensors, research on field emission in nanostructured materials, optoelectronics, vacuum science, design of vacuum systems, vacuum thermal insulation, and other emerging topics relevant to the manipulation of atoms and electrons. These topics of research are brought together to solve different problems, tackle grand challenges in science and technology and support new emerging fields of research. Some of the recent activities and highlighted challenges of the past year are listed in the paragraphs below.

Biofilm deactivation with facile plasma-activated water (PAW) disinfection. Flexible endoscopes, integral to modern medical practices for diagnosing and addressing various gastrointestinal conditions, possess inner channels conducive to biofilm development. The risk of cross-contamination arises when endoscope reprocessing is incomplete or ineffective, underscoring the imperative for novel disinfection approaches. For this reason, we explored the antibiofilm efficacy of a two-step disinfection method utilising cold atmospheric pressure plasma and plasma-activated water. Our results indicated that this combined approach achieved a substantial 5.72 log reduction in clinically relevant mixed-species biofilms within the narrow lumens of a standard endoscope. XPS, FTIR, and AFM were employed to assess potential surface damage resulting from the decontamination process, revealing minimal alterations in the surface composition or morphology even after multiple disinfection cycles. Furthermore, the ability of bacteria to adhere to the surface remained unenhanced. Our presentation of efficient endoscope inner channel surface disinfection using a two-step atmospheric-pressure plasma treatment was published in *Applied Surface Science*, *623*, 156936 (2023).

Development of a wide-range pH sensor with azo-dyed textiles. Textiles play a crucial role in the development of lightweight and flexible displays, which are essential for smart materials. In particular, halochromic textiles, characterised by changing colour depending on pH, are based on pH-sensitive dye molecules. Recently, a new class of 2-aminoimidazole azo dyes with particular substituent patterns has been introduced. A silk fabric was functionalised for the first time by exhaustion with a dye (AzoIz.Pip). The halochromic properties were evaluated both in an aqueous solution and after silk functionalisation. Thorough analyses were performed using UV-Vis spectra, the colour strength (K/S), the colour difference (ΔE), CIE-Lab* coordinates and the UV protection factor (UPF) on solutions and fabrics. The dyeing process was optimised, and the halochromic properties and reversibility were evaluated in universal Britton–Robinson buffers (with a pH of 3–12) and artificial body fluids. In buffered aqueous solutions, AzoIz.Pip exhibited bright colours and appealing halochromic properties with a hypsochromic shift from blue (557 nm) to magenta (536 nm). Similarly, with increasing pH, the functionalised silk showed a wavelength shift in the maximum K/S value from 590 nm to 560 nm. The silk fabric exhibited a high affinity for AzoIz.Pip, which provided additional colour stabilisation and prevented the colour loss observed in the dye solution at alkaline pH after 24 hours. Colour reversibility was maintained until the fourth cycle, and fastness tests showed favourable results, except for the wash fastness. Evaluation of the cytotoxicity of a silk fabric extract revealed that the viability of HaCaT cells was reduced to < 70% only at dye concentrations of 64 μg-mL–1 or higher. However, lower concentrations proved to be very effective for the halochromic properties of silk. The studied materials are valuable tools for the development of sensors in various fields, such as biomedicine, packaging, filtration, agriculture, protective clothing, sports, camouflage, architecture and design. The results of this study were published in *Polymers 15(7),* 1730 (2023).

Novel nanophotocatalyst for remediation of organic pollutants. To perform remediation of organic pollutants, nanocomposites of titanium dioxide and reduced graphene oxide (TiO_2@rGO) with different weight percentages

of rGO (4, 8 and 16 wt%) were synthesised with the hydrothermal/solvothermal method and subjected to thermal treatment at 300 °C. These nanocomposites were evaluated for their efficiency in removing methylene blue (MB) dye under simulated solar illumination and natural sunlight. The structural, morphological, chemical and optical properties of the synthesised TiO_2@rGO nanocomposites were investigated in detail. The results of the graphene-based nanocomposite materials showed the presence of interactions, especially Ti–O–C bonding, confirming a successful integration of TiO_2 and rGO to form the TiO_2@rGO nanocomposites. The incorporation of rGO led to an increase in the specific surface area, a decrease in the band gap energy and an improvement in the photocatalytic degradation efficiency of MB from water compared to TiO_2 nanoparticles. The photocatalytic activity results show that the amount of rGO in the TiO_2@rGO nanocomposites plays an essential role regarding various photocatalytic parameters, including the initial dye concentration, catalyst concentration, water environment, and illumination source. Our results show that enhancing the nanocomposite with 8 wt% rGO resulted in optimal photocatalytic performance for MB degradation (10 mg·L^{-1}), with a degradation percentage of 99.20 achieved after 2 hours. Furthermore, the study shows that the TiO2@rGO_8 wt% nanocomposite maintains a photocatalytic activity of over 90% for three consecutive cycles. The results were a joint endeavour of several JSI departments, and they were published in the journal *Molecules, 28(21),* 7326 (2023).

Degradation of water pollutants using atmospheric pressure plasma. In 2023 we continued the research of the potential to use the atmospheric pressure plasma technology for water cleaning treatment strategies. Bisphenols, known for their toxicity and potential threats to the environment and public health, were targeted for removal from aqueous systems using cold atmospheric pressure plasma (CAP). In this study, bisphenol A (BPA) and bisphenol S (BPS) were treated with CAP, along with the addition of methanol to simulate environmental conditions. After a 480-second plasma treatment, BPA exhibited faster removal (15–25% remaining) compared to BPS (>80% remaining). The plasma species analysis revealed that the presence of a radical scavenger impacted the formation of reactive oxygen and nitrogen species. Notably, the in vitro toxicological assessment using the HepG2 cell model indicated that the mixture of transformation products resulting from CAP was less toxic than the original BPA and BPS. This suggests that CAP effectively degrades bisphenols in a safe manner. The study also identified transformation pathways for both compounds, providing insights into the environmentally friendly degradation of bisphenols

Figure 1: CAP degradation and toxicity testing of bisphenol transformation products

Figure 2: SPR sensor design for biofilm formation monitoring

through CAP. The study was done in collaboration with researchers from F6 and O2 departments of the IJS, National Biology Institute, Ljubljana, partners from Greece including International Hellenic University, Aristotle University of Thessaloniki and Center for Interdisciplinary Research and Innovation (CIRI-AUTh), and York Plasma Institute, UK. The results of the study were published in *Journal of Hazardous Materials, 454,* 131478 (2023).

Surface plasmon resonance (SPR) sensor design. With partners from Israel, we collaborated on surface plasmon resonance (SPR) sensors to monitor biofilm development. Biofilms, a common issue in various industries dealing with moisture, pose challenges in areas such as food production, surgical devices, marine applications, and wastewater treatment plants. Recent advancements in label-free sensors, specifically localised and extended surface plasmon resonance (SPR), have shown promise for monitoring biofilm formation. However, traditional noble metal SPR substrates face limitations in detecting large entities like biofilms that can grow to a micrometre-scale thickness. This study introduces a novel plasmonic insulator-metal-insulator (IMI) structure (SiO_2–Ag–SiO_2) with an enhanced penetration depth, employed in a portable SPR device using a diverging beam single wavelength format of the Kretschmann configuration. A dedicated SPR line detection algorithm enables real-time monitoring of changes in the refractive index and biofilm accumulation with a precision down to 10^{-7} RIU. The optimised IMI structure exhibits a wavelength and incidence angle-dependent penetration, achieving a penetration depth of over 4 µm at 635 nm, in contrast to the ~200 nm depth of a thin gold film substrate.

The proposed graded index biofilm structure, characterised by a decreasing refractive index with distance from the interface, explains the observed saturation thickness of the biofilm at 6-7 µm after 24 hours of growth, with an approximately 63% live cell volume. In the context of plasma-assisted biofilm degradation, the IMI substrate demonstrated resilience compared to the gold substrate in a semi-real-time study. Variances in growth rates over SiO_2 and gold surfaces were attributed to differences in surface charge effects, where the absence of excited plasmon-induced electron oscillation on the SiO2 surface played a role. This methodology provides improved signal reliability for detecting and characterising biofilms, considering factors such as concentration and size dependence. The results were published in *Biosensors and Bioelectronics, 228,* 115204 (2023).

Solving the problem of atmospheric plasma signal in FTIR gas cells. During the exposure of FTIR glass cells to generated plasma species, strange peaks appear in the obtained IR spectra, which can lead to a misinterpreta-
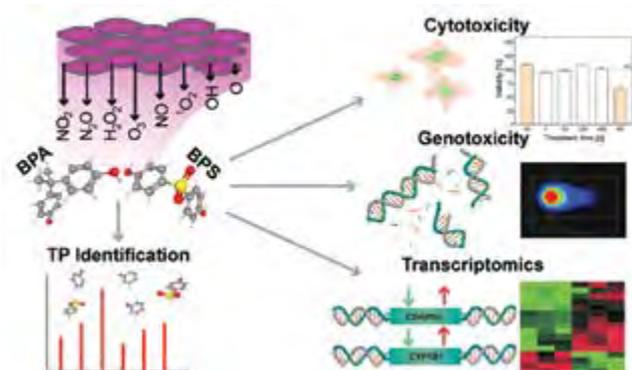
tion of the readout data. For this reason, we investigated interfacial processes arising from the interaction between reactive oxygen and nitrogen species generated by a non-equilibrium air plasma, and the metal halide windows of an FTIR gas cell. This interaction results in interfering absorption peaks forming and progressing within the 1400–1300 cm^{-1} range, introducing complexity to spectral interpretation. Using classical KBr as an illustrative example, the results indicate that plasma-exposed KBr exhibits a lower atomic fraction of Br, replaced by the NO_3 nitrate group. The primary absorption peak of NO_3 undergoes a gradual development with the plasma exposure, impacting the transparency of the window in the corresponding FTIR region. A correlation is established between the formation of KNO_3, plasma power and exposure time, leading to growth and changes in molecular vibrational energies associated with the asymmetric NO_3 stretching vibrations in the KNO_3 structure. This study was published, as a journal article, in the *Journal of Analysis and Testing* (2023) 7:392–404.
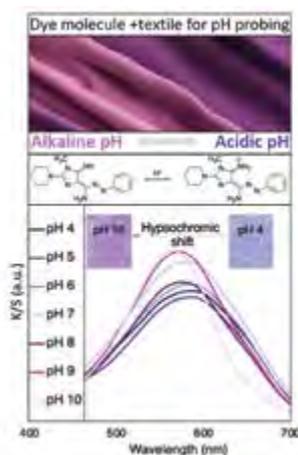
Hydrogen permeability through FeAl alloys. Intermetallic alloys of Fe and Al have many exceptional properties depending on the Fe:Al ratio. At some specific ratios, resistance to oxidation makes them competitive with steels, representing a significant group of technical alloys. Unfortunately, even a tiny amount of hydrogen is critical to induce brittleness. Consequently, over decades, an extensive database on hydrogen interactions with steels was collected. The stoichiometry for the optimised mechanical performance of a particular steel is set by the pure metal ratio (Cr, Ni, Fe). The parameters that play an essential role when hydrogen influences the brittleness are effective diffusivity, solubility and density of hydrogen traps. The formalism applied in hydrogen-metal interaction studies is well known today. So far, a similar comparison of published FeAl alloy data on hydrogen interaction cannot be made yet as they have rarely been studied. The main reason for it might be that these alloys have not yet been recognised as exceptional in some particular environments. They are well resistant to oxidation as their surfaces are immediately protected by a thin aluminium oxide film, preventing hydrogen from penetrating the alloy. All published data on diffusivity have been determined with the electro-chemical method in a narrow range from room temperature to 70 °C. **Moreover**, no data on permeability exist as the same evaluation method is inadequate for this characterisation. Using the gaseous technique, we studied the bulk hydrogen permeability and diffusivity of Fe35Al alloy from 200 to 500 °C. **In addition**, we examined the impact of an *in-situ* grown oxide film on hydrogen permeability. This film consists mainly of aluminium oxide formed due to controlled exposure of the upstream side of the membrane to pure oxygen at 400 °C. A complementary characterisation of the alloy and film was done using XPS, SEM, TEM and EDS. The main finding is that only a 10-nm-thick aluminium oxide suppresses the hydrogen permeation rate by three orders of magnitude compared to reference samples before oxidation.

Figure 3: FTIR windows are changed during plasma species monitoring

Growing metal oxide nanowires and understanding the processes. One of the department's research areas deals with the fabrication of transition-metal oxide nanostructures, which can be used for different applications. In particular, transition metal oxide nanowires (NWs) play an important role in gas sensing, catalysis, energy storage, and solar cells. One of the simplest methods for their synthesis is thermal oxidation, where a metallic copper substrate is exposed to oxygen at elevated temperatures. Understanding the relationship between experimental conditions and NW parameters and identifying limiting growth conditions are essential for the controlled synthesis of NWs. In applications requiring a high surface area, it is imperative for NWs to be as thin as possible. Addressing this concern, our research focused on determining the minimum achievable NW diameter of thermally grown copper oxide (CuO) NWs. Temperature was found to be the primary factor influencing CuO NW diameters, with higher temperatures resulting in thicker NWs and vice versa. Therefore, the minimum temperature where NWs still grow was investigated. To identify the limiting NW growth temperature and diameter, the temperature was systematically decreased until no NWs were grown. We observed that the NW growth ceased just below 190 °C, and the thinnest NW diameters were between 3 and 4 nm. The explanation for these dimensions involved a simple theoretical model of NW nucleation and a calculation of the temperature dependence of the critical NW nucleus size and free energy of NW nucleation. The results were published in *Applied Physics Letters* 623, 156936 (2023).

Additionally, we also proposed a strategy to enhance the aspect ratio of NWs by delaying saturation in their growth. As CuO NWs lengthen, copper is supplied from the bottom to the top through side surface diffusion and the central twin boundary within the NW. However, as the NW length increases, the travel distance for copper atoms to reach the top also increases, leading to a decrease and eventual saturation in the NW growth rate. Additionally, the reaction with oxygen consumes diffusing copper on the NW side, further contributing to the decline in the NW elongation rate. To eliminate this factor, our strategy involved depositing an inert metal, such as gold, on the NW surface during multiple growth steps. Gold effectively prevents the
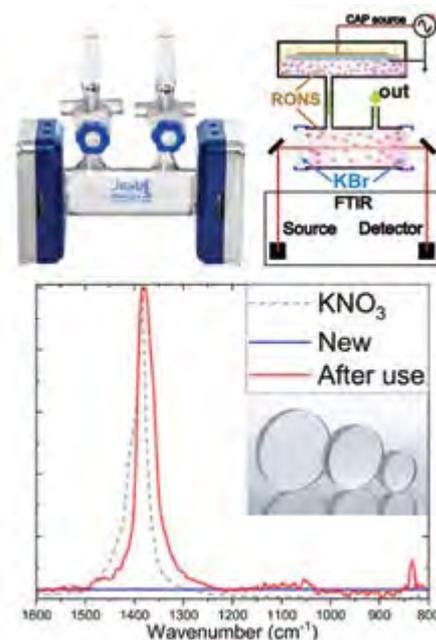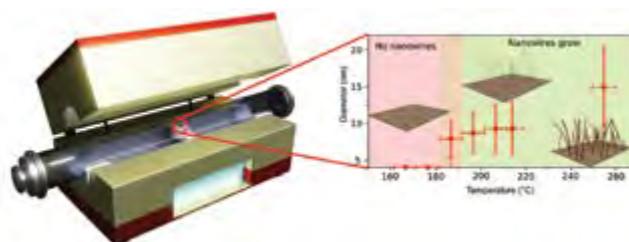

Figure 4: Thermal growth of CuO NWs and determination of the minimum NW diameters
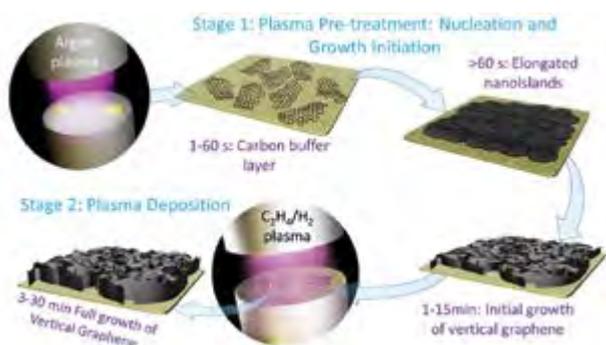
Figure 5: Two-stage plasma enabled low-temperature growth of vertical graphene
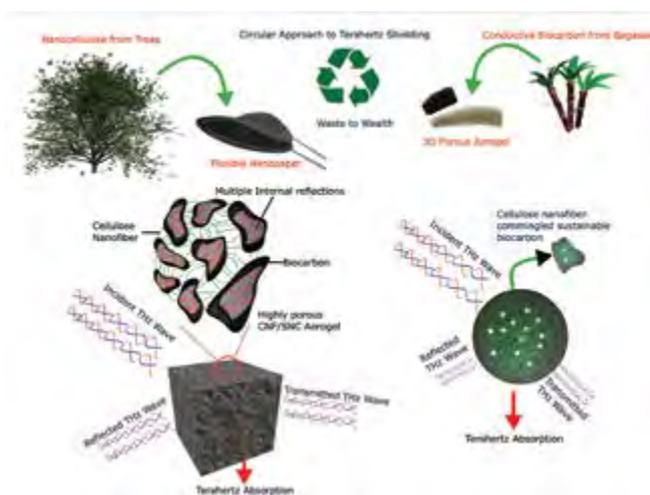

Figure 6: Plausible THz shielding mechanism of CNF/SBC aerogel and CNF/SBC paper

Figure 7: Dr Neelakandan M. Santhosh recived the Jožef Stefan Golden Emblem Prize for his PhD thesis.
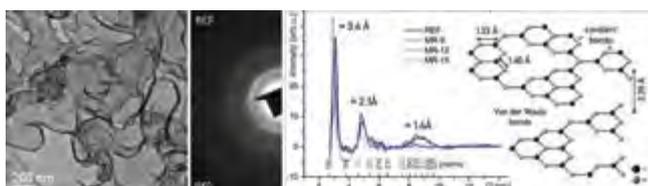

Figure 8: TEM micrograph and corresponding selected-area electron diffraction pattern, compared to reference samples. The SAEDs were enumerated and correlated with the prototype structure.

contact between diffusing copper atoms and oxygen, increasing the portion of copper atoms, reaching the NW top and thereby delaying saturation in the NW growth. This process, together with detailed theoretical modelling, was described in *Advanced Theory and Simulations* 10 (1), 2201739 (2023).

Plasma-enabled growth of 2D vertical graphene. Considering the importance of 2D vertical graphene (VG) structures, the researchers at F6, in collaboration with the researchers from GREMI, France, developed a low-temperature plasma-assisted growth mechanism of VG. To explore the unattended areas of plasma growth of VG, such as the initial nanowall growth mechanism and the condition of the plasma chamber, the team studied the VG growth in two stages: during the pre-treatment of the plasma chamber and the deposition. Using low-pressure radio-frequency plasma as a green approach, the team demonstrated the VG growth at a low-power Ar plasma pre-treatment, revealing that the carbon contaminants in the plasma chamber play a critical role during the initial growth phases. Nanowall growth is initiated from the carbon contaminants etched from the plasma chamber wall and deposited to the substrate as the carbon precursor. The materials analysed from the chamber wall indicate that they have amorphous-type features, deposited on the substrate as a graphene-like material, i.e., the product of plasma pre-treatment. Later, plasma deposition using the carbon precursors promotes the fast growth of VG. An illustration of the developed plasma method used for the growth of VG is presented in *Figure 7*. To make nanowalls an industrial product, upscaling the plasma systems to enable deposition on large surfaces is essential, and understanding the chamber influence is critical during the upscaling process. The findings on the importance of plasma chambers during the growth process will guide future research to consider the chamber condition as an influential factor, besides other plasma conditions, in the upscaling technology process. The exciting findings of this research were published in *Applied Surface Science* 643, 158716 (2024).

Biocarbon-based nanoconstructs for advanced broadband shielding applications. The researchers from F6 participated in a research collaboration with the Mahatma Gandhi University, India and Lancaster University, UK, to develop functional carbon-based nanostructures for terahertz shielding applications. The significance of this research is based on the alarmingly increasing electromagnetic pollution, caused by the intermixing of electromagnetic signals produced by many miniature electronic devices. During this research a high-performance THz absorber was developed, fully derived from a biomass for sustainable development by considering biomass waste management, which is also a critical challenge nowadays. In this collaborative research, biowaste sugarcane bagasse is successfully converted to highly conductive sustainable biocarbon (SBC) and composite with cellulose nanofibers (CNF) for THz absorption. The THz shielding effectiveness of a 600 µm nanopaper and 3.00 mm aerogel was found to be 46 dB and 70 dB, respectively, displaying superior THz absorption with a trivial reflection of THz signals.

Moreover, these sustainable absorbers exhibit a THz shielding performance comparable to that of a graphene foam (74 dB, one of the best performances reported so far), demonstrating their enormous potential for designing future THz devices. Exploring the production of SBCs from bio-waste will give a future direction for the conversion of biomass into valuable nanostructures on a large scale, which will significantly contribute to the green economy and environmental sustainability. Besides, the findings not only provide a green method for designing sustainable THz shielding materials but also indicate opportunities for a plethora of applications, such as strain sensing, water purification, energy storage and harvesting. Also, the sustainability of the designed material ensures an easy disposal

of the device after a lifetime, which could significantly help to reduce the production of carbon dioxide and global warming. The interesting results from this research were communicated in *Chemical Engineering Journal* 467, 143213 (2023).

Nanomaterials research for catalysis. One of the major activities of the department is also the research of carbon-based layered materials for catalysis. The specific surface of graphitic carbon nitride (g-C_3N_4) was successfully increased up to 86 m^2/g, and the photocatalytic properties were tested under visible light illumination for degradation of bisphenol A. The transmission electron microscopy studies of highly beam-sensitive materials present a unique challenge, and we developed a protocol for quantitative determination of the interlayer spacing variation. The samples were synthesised and optimised by the Inorganic Chemistry and Technology research team, the National Institute of Chemistry, and the research was performed in collaboration with colleagues from the Centre for Energy Research, Institute of Technical Physics and Materials Science (Budapest, HU). The composites of g-C_3N_4 with TiO_2 were explored as photocatalysts for visible-light-triggered photocatalytic oxidation of bisphenol A. Results were published in *ACS Catalysis, 13, 20, 13282 - 13300 (2023)* and in the *Journal of Alloys and Compounds, 947, 169585 (2023)*.

Additionally, we studied noble metal nanoparticles on an oxide support for catalysis. With colleagues from the National Institute of Chemistry, the University of Maribor, and University of Nova Gorica, we explored several different systems of metallic nanoparticles on an oxide support. Au nanoparticles on ZrO_2-CeO_2 prove to be a cost-effective synthesis procedure in the hydrogenation of CO_2. Here, the TEM methods were used for the analysis of the phase composition of the ZrO_2-CeO_2 catalyst, as well as for finding the crystal structure, size and morphology of the Au NPs. Results were published in *Applied Surface Science* 619, 1–12, 156737 (2023). The plasmonic Au nanoparticles on TiO_2 substrates were explored for heterogeneous photocatalysis, while Pt NPs on TiO_2 substrates were explored for their photo, thermal and photothermal activities to be used for plasmon-driven environmental applications.

Precipitate-enhanced Al-based alloys. In a joint research with colleagues from the Technical University of Darmstad (Germany), University of Kassel (Germany), and Azarbaijan Shahid Madani University (Iran) we are exploring functionally graded AA70xx series components produced via hot stamping, currently a bottleneck for industrial applications of lightweight alloys substituting steels as structural materials in automotive and aviation industries. The thermal treatment of materials has a vital effect on the microstructure, precipitate formation and size, and the final mechanical properties of the material. Due to the nanosize of the features, electron microscopy methods were essential in obtaining the correlation between the nanostructure and the final properties. Due to the differences in the chemistry and etching rate of bulk Al and precipitates, we optimised the sample-preparation method to preserve the original microstructure and structural defects, such as dislocations. The results of the extensive research were published in *Advanced Engineering Materials 15(25)*, 2201879 (2023).

Further, we explored the low-cycle fatigue of stress-aged 70xx alloys and the influence of nanoprecipitates on the performance of the materials; here, the materials were tested under extreme external mechanical deformations, and nanoprecipitates played a crucial role in improving the mechanical properties (*Advanced Engineering Materials* 15(25), 2300090 (2023)). The summary of the correlation between processing parameters on the final material properties, together with the simulated forming process, was published in the *Journal of Manufacturing Processes 86, 336–353* (2023).
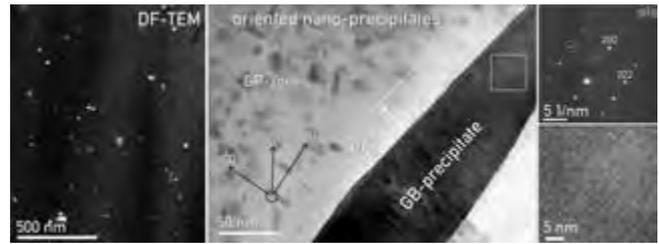

Figure 9: TEM micrographs visualising coherent Si-Mg precipitates, and the interaction of grain boundaries, Guinier-Preston (GP) zones and precipitate-free-zone (PFZ) evolution

Figure 10: Dr Alexandre Nominé won the Jaean André Rist Medal for his contributions to sustainable materials by design.

Figure 11: Dr Uroš Cvelbar obtained the Zois Recognition Award for his contributions to Plasma Physics.

Some outstanding publications in the past year

1. Kovačič, Ana, Modic, Martina, Hojnik, Nataša, Štampar, Martina, Gulin, Martin Rafael, Nannou, Christina, Koronaiou, Lelouda-Athanasia, Heath, David John, Walsh, James L., Žegura, Bojana, Lambropoulou, Dimitra A., Cvelbar, Uroš, Heath, Ester. Degradation and toxicity of bisphenol A and S during cold atmospheric pres-

sure plasma treatment. *Journal of Hazardous Materials*. [Online ed.]. 2023, vol. 454, [article no.] 131478, pp. 1–12, illustr. https://www.sciencedirect.com/science/article/pii/S0304389423007616?via%3Dihub,

2. Santhosh, Neelakandan Marath, Upadhyay, Kush K., Filipič, Gregor, Zavašnik, Janez, Montemor, Maria De Fátima, Cvelbar, Uroš. Widening the limit of capacitance at high frequency for AC line-filtering applications using aqueous carbon-based supercapacitors. *Carbon*. [Print ed.]. 2023, vol. 203, pp. 686–694. ISSN 0008-6223. DOI: 10.1016/j.carbon.2022.12.026. [COBISS.SI-ID 133767683]

3. Shaji, Nitheesha, Santhosh, Neelakandan Marath, Zavašnik, Janez, Cvelbar, Uroš, Lee, Chang Woo, et al. Moving toward smart hybrid vertical carbon/MoS2 binder-free electrodes for high-performing sodium-ion batteries. *ACS Sustainable Chemistry & Engineering*. 2023, vol. 11, iss. 8, pp. 3260–3269, illustr. ISSN 2168-0485. https://pubs.acs.org/doi/pdf/10.1021/acssuschemeng.2c05996, DOI: 10.1021/acssuschemeng.2c05996. [COBISS.SI-ID 142325507]

4. Roškarič, Matevž, Zavašnik, Janez, Dániel Zámbó, Dániel, Kotnik, Tomaž, Kovačič, Sebastijan, Žerjav, Gregor, Pintar, Albin. Optimisation method based on simplex for surface area improved photocatalytic performance of g–C3N4. *ACS Catalysis*. 2023, vol. 13, iss. 20, pp. 13282–13300, illustr. ISSN 2155-5435. https://pubs.acs.org/doi/10.1021/acscatal.3c03394#, DiRROS - Digitalni repozitorij raziskovalnih organizacij Slovenije, DOI: 10.1021/acscatal.3c03394. [COBISS.SI-ID 167925507]

5. A. R. Pai, Y. Lu, S. Joseph, N. M. Santhosh, R. Degl'Innocenti, H. Lin, R. Letizia, C. Paoloni, S. Thomas, Ultra-broadband shielding of cellulose nanofiber commingled biocarbon functional constructs: A paradigm shift towards sustainable terahertz absorbers. *Chemical Engineering Journal*. 2023, vol. 467, 143213. https://doi.org/10.1016/J.CEJ.2023.143213

6. Baranov, Oleg B., Belmonte, Thierry, Levchenko, Igor, Bazaka, Kateryna, Košiček, Martin, Cvelbar, Uroš. Hierarchical nanomaterials by selective deposition of noble metal nanoparticles: insight into control and growth processes. *Advanced Theory and Simulations*. ISSN 2513-0390. DOI: 10.1002/adts.202300288. [COBISS.SI-ID 157161475]

7. Košiček, Martin, Baranov, Oleg B., Zavašnik, Janez, Cvelbar, Uroš. In search of the limits of CuO thermal oxidation nanowire growth by combining experiment and theory. *Applied Physics Letters*. [Online ed.]. 2023, vol. 123, pp. 041601-1-041601-7. ISSN 1077-3118. DOI: 10.1063/5.0151293. [COBISS.SI-ID 159860483]

8. Baranov, Oleg B., Bazaka, Kateryna, Belmonte, Thierry, Riccardi, Claudia, H. Eduado, Roman, Mohandas, Mandhakini, Xu, Shuyan, Cvelbar, Uroš, Levchenko, Igor. Recent innovations in the technology and applications of low-dimensional CuO nanostructures for sensing, energy and catalysis. *Nanoscale Horizons*. 2023, 12 pp. ISSN 2055-6764. DOI: 10.1039/D2NH00546H. [COBISS.SI-ID 145573635]

9. Northage, Naomi, Simon, Stéphane, Shvalya, Vasyl, Modic, Martina, Juergens, Thorsten, Eschborn, Sascha, Horsburgh, Malcolm J., Walsh, James L. Efficient endoscope inner channel surface disinfection using a two-step atmospheric pressure plasma treatment. *Applied Surface Science*. [Online ed.]. 2023, vol. 623, [article no.] 156936, pp. 1–12, illustr. ISSN 1873-5584. https://www.sciencedirect.com/science/article/pii/S0169433223006128?via%3Dihub, DOI: 10.1016/j.apsusc.2023.156936. [COBISS.SI-ID 145561347]

10. Nemanič, Vincenc, Kovač, Janez, Žumer, Marko, Zavašnik, Janez. Impact of surface oxide on hydrogen permeability of chromium membranes. *International Journal of Hydrogen Energy*. [Online ed.]. 2023, vol. 48, iss. 26, pp. 9723–9733, illustr. ISSN 1879-3487. DOI: 10.1016/j.ijhydene.2022.11.267. [COBISS.SI-ID 135652611]

Awards and Appointments

1. Neelakandan Marath Santhosh, Plasma enabled design of hybrid carbon nanostructures for energy storage, Jožef Stefan Golden Emblem Prize, 23 March 2023
2. Vasyl Shvalya et al, Bacterial DNA recognition with advanced nanoplasmon sensor, Excellence in Science 2023, 21 November 2023, ARIS
3. Uroš Cvelbar, Zois Award for Significant Achievements in Plasma Physics, 28 November 2023
4. Alexandre Nominé, Jaean André Rist Medal, 2023

Organization of conferences, congresses and meetings

1. Third International Workshop on Plasma-Tailord Nanostructures and Applications (SWOPTAN), Rogla, Slovenia, 29 January to 1 February 2023

Patent granted

1. Aswathy Vasudevan, Gregor Filipič, Janez Zavašnik, Uroš Cvelbar, Method for in-situ synthesis and deposition of metal oxide nanoparticles with atmospheric pressure plasma, EP 3 960 703 B1, European Patent Office, 7. 6. 2023

INTERNATIONAL PROJECTS

1. Max Planck Partner Group
   Asst. Prof. Janez Zavašnik
   Max-Planck-Institut für Eisenforschung GmbH
2. COST CA18113; EuroMicropH - Understanding and Exploiting the Impact of Low pH on Microorganisms
   Dr. Martina Modic
   COST Association Aisbl
3. COST CA18116; Aniridia: Networking to Address an Unmet Medical, Scientific and Societal Challenge
   Prof. Uroš Cvelbar
   COST Association Aisbl
4. COST CA19110; Plasma Applications for Smart and Sustainable in Agriculture
   Dr. Martina Modic
   COST Association Aisbl
5. NATO; NOOSE - Nanomaterials for Explosive Traces Detection with SERS
   Prof. Uroš Cvelbar
   Nato - North Atlantic Treaty Organisation
6. COST CA20114; Therapeutical Applications of Cold Plasma
   Dr. Martina Modic
   COST Association Aisbl
7. COST CA20129; Multiscale Irradiation and Chemistry Driven Processes and Related Technologies
   Prof. Uroš Cvelbar
   COST Association Aisbl
8. Free Radicals and Oxidative Stress in Microbial Biofilms
   Dr. Martina Modic
   Slovenian Research Agency
9. How Plasma Influences Catalytic Activity of Nanomaterials
   Prof. Uroš Cvelbar
   Slovenian Research Agency
10. Unrevealing the Interface Growth of 1D Nanostructures and Thin Films for Solar Cells
    Prof. Uroš Cvelbar
    Slovenian Research Agency
11. HE - EUROfusion; WP07: ENR-DeHydroc-1,2,3_HE-FU
    Asst. Prof. Janez Zavašnik
    European Commission
12. HE - EUROfusion; WP18: MAT_HE-FU, IREMEV-MAT-1_HE-FU, IREMEV-MAT-2_HE-FU, IREMEV-MAT-3_HE-FU
    Asst. Prof. Janez Zavašnik
    European Commission
13. HE - EUROfusion; WP05: PWIE-1,2,3,_HE-FU, PWIE-4-Accelerator
    Dr. Vincenc Nemanič
    European Commission
14. HE - ThermoDust; A Paradigm Shift for the Future's Thermal Management Devices through Radical Innovation in New Materials and Additive Manufacturing

Asst. Prof. Janez Zavašnik
European Commission
15. ERASMUS+; HERawS - Highlights on European Raw Materials Sustainability
    Prof. Uroš Cvelbar
    European Commission

RESEARCH PROGRAMMES

1. Vacuum technique and materials for electronics
   Dr. Vincenc Nemanič
2. Plasma and quantum structures
   Prof. Uroš Cvelbar

R & D GRANTS AND CONTRACTS

1. Controlling plasma-bio interactions for global food security
   James Leon Walsh
2. Detection of defects and hydrogen by ion beam analysis in channelling mode for fusion
   Asst. Prof. Janez Zavašnik
3. Formation and Design of AM-processed Fe-Al alloys with self-forming Hydrogen Permeation Barriers for the harshest of environments
   Asst. Prof. Janez Zavašnik
4. Plasma activated nanobubbles: A new approach for high-level disinfection of flexible endoscopes
   James Leon Walsh
5. Advanced DNA-scale Plasmonic Vibroscopy for Nanomedicine Research
   Vasyl Shvalya
6. Plasma-assisted removal of emerging genotoxic contaminants from wastewater
   Dr. Martina Modic
7. Plasmon-Mediated Sensors for DNA Damage Diagnostics
   Vasyl Shvalya
8. Hybrid plasma-enabled nanostructures for advanced supercapacitors
   Prof. Uroš Cvelbar
9. Designing Low Environmental Footprint Yarns with Atmospheric Pressure Plasma Processing
   Prof. Uroš Cvelbar
10. Atmospheric pressure plasma for removal of airborne allergens (RemoveALL)
    Dr. Nataša Hojnik
11. Multifunctional Vertical Graphene Hybrids for High-Density Supercapacitors
    Dr. Neelakandan Marath Santhosh
12. VEGA - Vertical Graphene for Aluminium-Ion Batteries
    Prof. Uroš Cvelbar
    Ministry of Education, Science and Sport
13. Plasma and quantum structures
    Prof. Uroš Cvelbar
    Slovenian Research Agency

VISITORS FROM ABROAD

1. Prof. Dr Wonho Choe, Prof. Dr Sanghoo Park, KAIST, Daejeon, South Korea, 15 February to 18 February 2023
2. Assoc. Prof. Dr Alexandre Francois Rene Nominé, University of Lorraine, Nancy, France, 19–25 February 2023
3. Assoc. Prof. Dr Alexandre Francois Rene Nominé, University of Lorraine, Nancy, France, 22–30 April 2023
4. Dr Iryna Bennett, Dr Dinusha Jayasundara, Central Engineering Department, Providing services on behalf of United Kingdom Atomic Energy Authority, United Kindgom, 3 May 2023
5. Prof. Dr Thomas Strunskus, Kiel University, Kiel, Germany, 24 May 2023
6. Assoc. Prof. Dr Alexandre Francois Rene Nominé, University of Lorraine, Nancy, France, 10–25 July 2023
7. Dr Bob Nemanich, Arizona State University, Arizona, USA, 15 September 2023
8. Prof. Dr Anton Nikiforov, University of Gent, Belgium, 17–19 September 2023
9. Assoc. Prof. Dr Alexandre Francois Rene Nominé, University of Lorraine, Nancy, France, 19 October to 1 November 2023
10. Prof. Dr Oleh Baranov, Kharkiv University, Kharkiv, Ukraine, 17 November to 4 December 2023
11. Arijeta Bafti, Faculty of Chemical Engineering and Technology, Zagreb, Croatia, 11–15 December 2023
12. Prof. Dr Vilko Mandić, Faculty of Chemical Engineering and Technology, Zagreb, Croatia, 11 December 2023
13. Assist. Prof. Dr Marko Rukavina, Faculty of Chemical Engineering and Technology, Zagreb, Croatia, 11 December 2023
14. Floren Radovanović Perić, Faculty of Chemical Engineering and Technology, Zagreb, Croatia, 11 December 2023
15. Ivana Panžić, Faculty of Chemical Engineering and Technology, Zagreb, Croatia, 11 December 2023

Jožef Stefan Institute

STAFF

Researchers
1. **Prof. Uroš Cvelbar, Head**
2. Dr. Martina Modic
3. Dr. Vincenc Nemanič
4. Dr. Alexandre Francois Rene Nomine
5. Dr. Vasyl Shvalya
6. Dr. James Leon Walsh
7. Asst. Prof. Janez Zavašnik

Postdoctoral associates
8. Dr. Nataša Hojnik
9. Dr. Andrea Jurov
10. Dr. Martin Košiček

11. Dr. Neelakandan Marath Santhosh

Postgraduates
12. Ardita Kurtishaj Hamzaj, M. Sc.
13. Juš Polanšek, B. Sc.
14. Jelena Štrbac, B. Sc.
15. Marko Žumer, B. Sc.

Technical officers
16. Jaka Olenik, B. Sc.
17. Damjan Vengust, B. Sc.

Technical and administrative staff
18. Urška Kisovec, B. Sc.

DEPARTMENT FOR COMPLEX MATTER
F-7

The research within the Department of Complex Matter encompasses a variety of research fields, ranging from fundamental investigations of elementary excitations in quantum materials, nonequilibrium quantum matter, self-organizing behaviour adaptive functionality in complex systems and soft matter as well as nano-biosystems, biomolecules and various nanomaterials. The department's experimental activities are complemented well by theory on different levels and supported by diverse synthesis routes for materials. Our research into ultrafast, non-equilibrium transitions, investigations of new emergent hidden orders and ferroic liquids are of great interest worldwide.

Head:
Prof. Dragan D. Mihailović

erc

European Research Council
Established by the European Commission

The research achievements of the department are quite diverse, and we are able to report on important research developments in a number of areas.

The year 2023 was exceptionally successful with a number of important projects coming to fruition with a large number of publications in journals like Nature, multiple papers in Nature Communications, Science Advances, Small and other renowned journals. Of course this is the culmination of work performed in previous years, but 2023 was the year when a number of important papers were finally published, sometimes after great efforts in the refereeing process. Collaborations with a number of world-leading laboratories also gave excellent results, and subsequent publications.

On the experimental front, our new laboratory for resonant XUV ellipsometry started operation (Fig. 1). Using the first XUV light, a few test experiments were performed with promising results and the promise of New Physics. The new apparatus, which is currently available only at a few free-electron laser ffacilities, will expand the range of ultrafast spectroscopies available at JSI and in Slovenia, providing more direct and detailed insight into exotic electronic states, ultrafast spin dynamics in composite materials, non-collinear spin textures, etc. Great attention during the designing of the system was devoted to stability and sensitivity. By using a special normalization routine in combination with the polarization sensitivity of the broadband detector it will be possible to also measure weak signals, which are normally inaccessible with noisy FEL and HHG sources. This is especially important in correlated materials, which are extremely susceptible to external perturbations.

Apart from the XUV beam line, effort has been spent on establishing the technological foundations for new research directions. The completion of the Advanced Quantum Devices Laboratory (AQDL) last year, as a joint-venture facility of F7 and the Nanocenter, has already yielded a number of results, including the opening up of an extended collaboration with Google Quantum AI in the field of quantum processor development. Thus, various devices and elaborate chip circuits can be nanofabricated using e-beam patterning in an oxygen-free environment with multilayer depositions. The controlled atmosphere is of particular importance when the devices use oxygen- or water-sensitive materials, such as CCM memory devices and superconducting resonators and transmon qubits. Moire single-atomic-layer heterostructures, with materials such as hBN, graphene and transition-metal dichalcogenides were fabricated for experiments of multiple users worldwide.

The AQDL thus supplements the experimental methods already used at the department, which includes different femtosecond laser spectroscopies from THz to XUV, a variety of optical techniques, ultrafast transport and superconducting device studies as well as synthetic chemistry and thin-film deposition methods such as MBE, AfiD and EBE, laser biomedical studies, femtosecond STM and magnetometry.
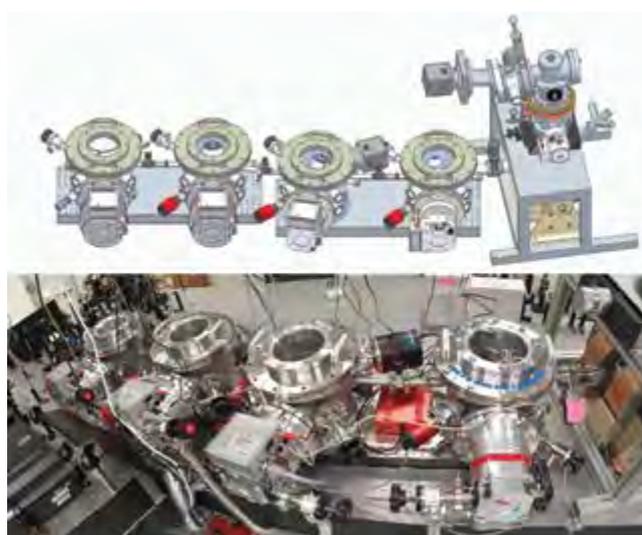

Figure 1: Time-resolved resonant XUV ellipsometry setup

Microscopic investigation of an emergent domain-wall state in 1T-TaS2

In a manuscript published in **Nature Communications** (https://doi.org/10.1038/s41467-023-43800-3) we explored the microscopic properties of the emergent metastable electronic domain-wall structure in 1T-TaS2 and observed its dynamics under applied electrical current using a multi-tip, low-temperature, scanning tunnelling

microscope (STM). The domain-wall structure created in the current path shows remarkable stability at lower current, but starts to reconfigure and disappear at higher currents. We analysed the domain networks in terms of a Wigner-Seitz (WS) cell construction, which revealed the underlying topological rules and allowed us to observe charge fractionalization within the network created by charge injection. Through WS analysis we identified non-trivial defects at some domain-wall crossings in the form of pentagon/heptagon pairs, which are homotopically equivalent to crystal dislocations. The non-trivial topological defects at the domain-wall junctions protect the mesoscopic network structure from external perturbations and only start to annihilate at higher current values, which sheds light on the remarkable longevity of the metastable state at low temperatures. By employing Monte-Carlo simulations of gradual charge injection based on the Mott-Wigner lattice gas model we observed the creation of intricate fractionally charged networks with close resemblance to the measured data. Surprisingly, it appears that the effective charge of the electrons is no longer integer, but takes on fractional values such as 13/10, 23/40 and 3611/5000. The number of such fractional states is large, but finite. Device thermal modelling of the experimental setup (in collaboration with the Electrotechnical Faculty at the University of Ljubljana) shows that the switching between states is non-thermal and does not occur via the high-temperature NC state, but directly from the H to the C state.
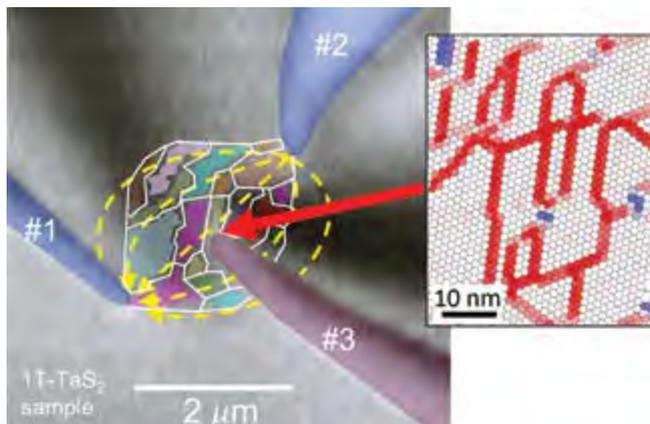

Figure 2: Scanning electron microscope image of the STM setup. Two outer STM tips (#1 and #2) were used for current sourcing and tip #3 was used to obtain STM images. The domain structure is schematically indicated with coloured domains (not to scale) and the current path is shown schematically with yellow arrows. Zoom-in shows a WS cell construction of the domain-wall network induced by the electrical current.
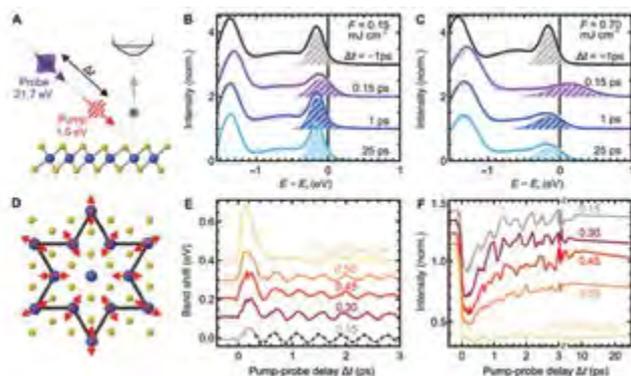

Figure 3: Dynamical transition to the H phase. (A) Sketch of the trARPES experiment with pump-probe delay Δt. (B) EDCs (dots) at Γ for selected delays after excitation at fluences below and (C) above the threshold fluence of the H phase (T = 160 K, rep. rate = 10 kHz). Solid lines mark best fits using three Gaussian peaks. The shaded areas indicate the Gaussian peak capturing the LHB. E and F indicate the time dynamics at different fluences showing clear non-linear behaviour associated with transitions to the H state.

Coherent light control of a metastable hidden state

Metastable phases present a promising route to expand the functionality of complex materials. Of particular interest are light-induced metastable phases that are inaccessible under equilibrium conditions, as they often host new, emergent properties switchable on ultrafast timescales. However, the processes governing the trajectories to such hidden phases remain largely unexplored. Here, using time- and angle-resolved photoemission spectroscopy, we investigated the ultrafast dynamics of the formation of a hidden quantum state in the layered dichalcogenide 1T-TaS2 upon photoexcitation. Our results revealed the non-thermal character of the transition governed by a collective charge-density-wave excitation. Using a double-pulse excitation of the structural mode, we show vibrational coherent control of the phase-transition efficiency. Our demonstration of exceptional control, switching speed, and stability of the hidden states are key for device applications at the nexus of electronics and photonics. This work was performed jointly with the Göttingen group of Laurenz Rettig and was published in **Science Advances**, Julian Maklar *et al.* Coherent light control of a metastable hidden state. *Sci. Adv.* **9**, eadi4661 (2023).

Cavity control of electronic ordering transition temperature in a quantum material.

Placing quantum materials into optical cavities provides a unique platform for controlling the quantum cooperative properties of matter, by both weak and strong light–matter coupling. Here we report experimental evidence of reversible cavity control of a metal-to-insulator phase transition in a correlated solid-state material. We embed the charge density wave material 1T-TaS2 into cryogenic, tunable terahertz cavities and show that a switch between conductive and insulating behaviours, associated with a large change in the sample temperature, is obtained by mechanically tuning the distance between the cavity mirrors and their alignment. The large thermal modification observed is indicative of a Purcell-like scenario in which the spectral profile of the cavity modifies the energy exchange between the material and the external electromagnetic field. Our findings provide opportunities for controlling the thermodynamics and macroscopic transport properties of quantum materials by engineering their electromagnetic environment. Cavity-mediated thermal control of the metal-to-insulator transition is achieved by embedding the charge density wave material 1T-TaS2 into cryogenic tunable terahertz cavities. The work was performed with the group of Daniele Fausti, Martin Eckstein and Peter Prelovšek. Jarc, G. *et al.* Cavity-mediated thermal control of metal-to-insulator transition in 1T-TaS2. *Nature* **622**, 487–492 (2023).

Crystallization of polarons through charge- and spin-ordering transitions in 1T-TaS$_2$

The interaction of electrons with the lattice in metals can lead to a reduction of their kinetic energy to the point where they may form heavy, dressed quasi-particles–polarons. Unfortunately, polaronic lattice distortions are difficult to distinguish from more conventional charge- and spin-ordering phenomena at low temperatures. Here, we present a study of local symmetry breaking of the lattice structure on the picosecond timescale in the prototype layered dichalcogenide Mott insulator 1T-TaS2 using X-ray pair-distribution function measurements. We identifies symmetry-breaking polaronic lattice distortions at temperatures well above the ordered phases, and record the evolution of broken symmetry states from 915 K to 15 K. The data imply that charge ordering is driven by polaron crystallization into a Wigner crystal-like state, rather than Fermi surface nesting or conventional electron-phonon coupling. At intermediate temperatures the local lattice distortions are found to be consistent with a quantum spin liquid state. The work was performed jointly with the group of Emil Bozin at BNL and Gianguido Baldinozzi (CNRS Unive. Paris-Saclay) and was published in Nature Communications. Bozin, E. S. *et al.* Crystallization of polarons through charge and spin ordering transitions in 1T-TaS2. *Nat. Commun.* **14**, 7055 (2023).

Figure 4: A quantum crystal in between two mirrors displays peculiar properties. Jarc, G. et al., Nature 622, 487–492 (2023).

Chiral domain dynamics and transient interferences of mirrored superlattices in non-equilibrium electronic crystals

Mirror symmetry plays a major role in determining the properties of matter and is of particular interest in condensed many-body systems undergoing symmetry-breaking transitions under non-equilibrium conditions. Typically, in the aftermath of such transitions, one of the two possible broken symmetry states is emergent. However, synthetic systems and those formed under non-equilibrium conditions may exhibit metastable states comprising both left (L) and right (R) handed symmetry. Here we explore the formation of chiral charge-density wave (CDW) domains after a laser quench in 1T-TaS2 with scanning tunnelling microscopy. Typically, we observed transient domains of both chiralities, separated spatially from each other by domain walls with different structure. In addition, we observed transient density of states modulations consistent with interference of L- and R-handed charge density waves within the surface monolayer. Theoretical modelling of the intertwined domain structures using a classical charged lattice gas model reproduces the experimental domain-wall structures. The superposition (S) state cannot be understood classically within the correlated electron model but is found to be consistent with interferences of L- and R-handed charge-density waves within domains, confined by surrounding domain walls, vividly revealing an interference of Fermi electrons with opposite chirality, which is not a result of inter-layer interference, but due to the interaction between electrons within a single layer, confined by domain-wall boundaries. Ravnik, J. *et al.* Chiral domain dynamics and transient interferences of mirrored superlattices in nonequilibrium electronic crystals. *Sci. Rep.* **13**, 19622 (2023).

Extreme ultraviolet-light modulator based on electronic phase transitions

In the last two decades, a number of approaches for generating high-quality coherent beams in EUV and soft X-ray spectral ranges became widely available. However, the absence of efficient light modulators for this scientifically and technologically useful energy range limits the real-life application of such photons, particularly when even slight complexity of the beam patterns is required. We have presented a novel approach to reversible imprinting of a holographic mask in an electronic Wigner crystal material with a sub-90-nm feature size. The structure is imprinted on a sub-picosecond time-scale using EUV laser pulses and acts as a high-efficiency diffraction grating that deflects EUV or soft X-ray light. The imprinted nanostructure is stable after the removal of the exciting beams at low temperatures but can be easily erased by a single heating beam. Modelling shows that the efficiency of the device can exceed 1%, approaching state-of-the-art etched gratings, but with the benefit of being programmable and tunable over a large range of wavelengths. The observed effect is based on the rapid change of lattice constant upon transition between metastable, electronically ordered phases in a layered transition-metal dichalcogenide. The proposed approach is potentially useful for creating tunable light modulators in the EUV and soft X-ray spectral ranges. The report is available as a preprint (arXiv 2311.08809) and was submitted to *Nature Photonics*.
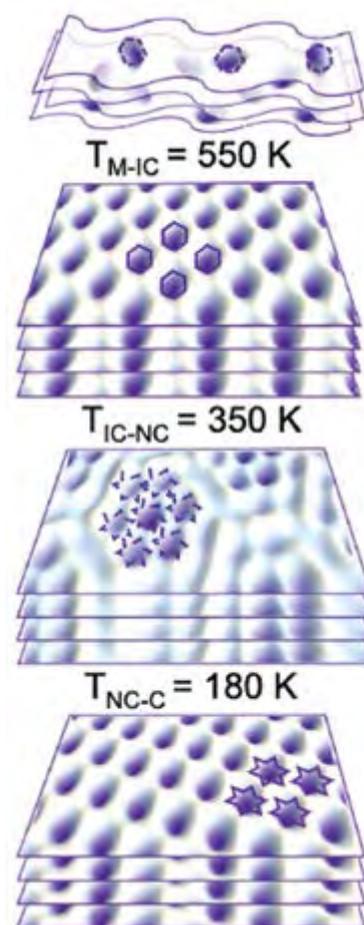

Figure 5: Four stages of polaron crystallization into ordered charge density waves deduced on the basis of picosecond local structure snapshots determined using X-ray pair-distribution function analysis. Bozin, E. S. et al. Crystallization of polarons through charge and spin ordering transitions in 1T-TaS2. Nat. Commun. 14, 7055 (2023).

Ultrafast dynamics in correlated systems

We investigated temperature (T) dependent ultrafast near-infrared (NIR) transient reflectivity dynamics in coexisting superconducting (SC) and charge density wave (CDW) phases of layered 2H-NbSe$_2$ using NIR and visible excitations. With visible pump-photon excitation (400 nm) we found a slow high-energy quasiparticle relaxation channel which is present in all phases. In the CDW phase, we observed a distinctive transient-response
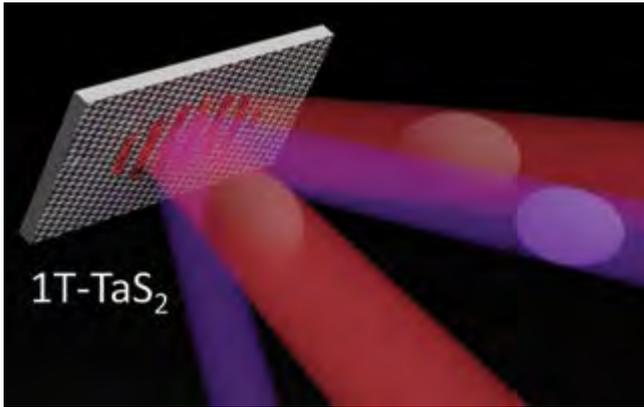
Figure 6: Schematics of the experimental geometry for testing EUV light modulator
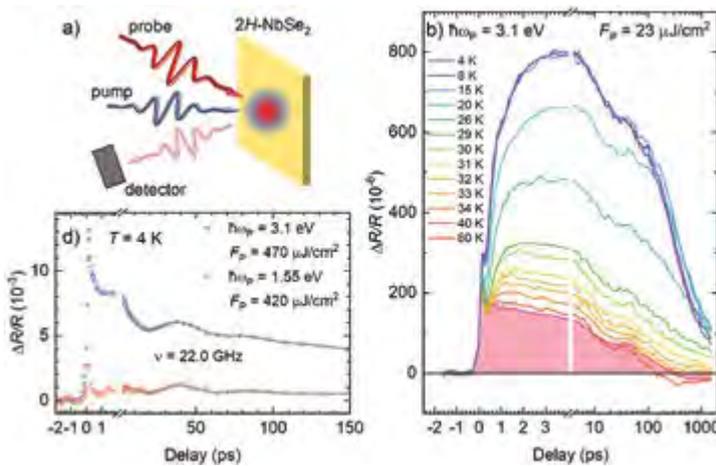

Figure 7: Temperature-dependent ultrafast transient reflectivity in 2H-NbSe2 with the experimental schematics.
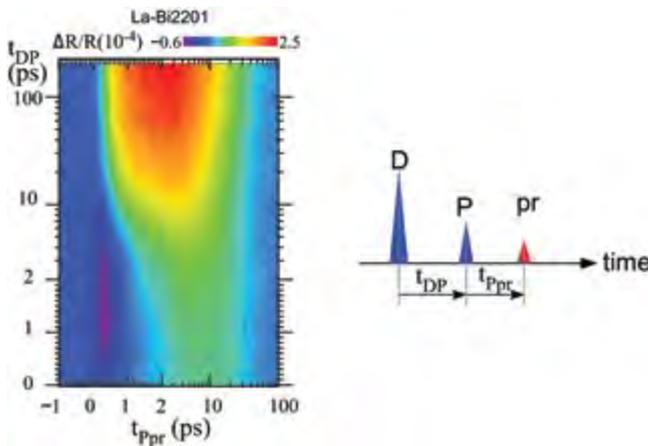

Figure 8: Results of the 3-pulse quench spectroscopy at T = 10 K in La-Bi2201 (left). Schematic of the 3-pulse quench experiment with the delay notations (right). After optical quench, the superconducting component (red) emerges only after recovery of the pseudo-gap component (violet).

component, irrespective of the pump-photon energy. The component is marked by the absence of coherent amplitude mode oscillations and a relatively slow, picosecond rise time, which is different than in most of the typical CDW materials. In the SC phase, another tiny component emerges that is associated with optical suppression of the SC phase. The transient reflectivity relaxation in the CDW phase is dominated by phonon diffusive processes with an estimated low-T heat diffusion constant anisotropy of $\sim$ 30. Strong excitation of the CDW phase reveals a weakly non-thermal CDW order-parameter suppression. Unlike CDW systems with a larger gap, where the optical order parameter suppression involves only a small fraction of phonon degrees of freedom, the suppression in $2H$-NbSe$_2$ is characterized by the excitation of a large number of phonon degrees of freedom and slower dynamics. The paper was published in **Phys. Rev. B 108, 235160 (2023)**.

Optimally doped Bi$_2$Sr$_{1.7}R_{0.3}$CuO$_{6+\delta}$ (R-Bi2201, R = Eu and La) were investigated from the viewpoint of photoinduced nonequilibrium quasiparticle dynamics of high-T_c cuprates with low T_c. The temperature dependencies of the superconducting (SC) and pseudo-gap (PG) responses demonstrated that the out-of-plane disorder, enhanced by replacing La with Eu, reduces the SC transition temperature and increases the PG energy. SC fluctuations are observed in each sample, especially in R = La, where large SC fluctuations penetrate deeply into the PG state. From the fluence-dependent dynamics, the planar optical destruction energy densities of the SC state are found to be consistent with the T_c^2 dependence noted previously for other high-T_c superconductors. Upon an optical quench we find that the SC state recovery starts only after the completion of the PG recovery. The paper was published in **Phys. Rev. B 109, 014503 (2024)**.

New tabletop extreme UV beamline development

In 2023 we continued the commissioning of the extreme UV (EUV) beamline for time-resolved resonant ellipsometry. Following the first light in 2022, during 2023 we have optimized the performance of the setup, and now we routinely generate EUV light in Ar, He and other noble gases. With the light source up and running, we have started commissioning the polarization-sensitive detector. The accessible spectral range covers absorption M edges of such elements as Fe, Co, Ni, which are of great importance for studies of ultrafast dynamics in magnetic materials. The first spectra of Co-Pt alloys were already successfully acquired. In addition to magnetic signals, electronic responses can be measured in "direct" spectroscopy mode, by acquiring only the intensity of the reflected light or with a polarization-sensitive detector over N and O edges of heavier transition metals, such as Mo, Ta, Ir, Pt etc.

The 2023 terahertz science and technology roadmap

Terahertz (THz) radiation encompasses a wide spectral range within the electromagnetic spectrum that extends from microwaves to the far infrared (100 GHz to $\sim$ 30 THz). Within its frequency boundaries there exists a broad variety of scientific disciplines that have presented, and continue to present, technical challenges to researchers. During the past 50 years, for instance, the demands of the scientific community have substantially evolved and with a need for advanced instrumentation to support radio astronomy, Earth observation, weather forecasting, security imaging, telecommunications, non-destructive device testing and much more. Furthermore, applications have required an emergence of technology from the laboratory environment to production-scale supply and in-the-field deployments ranging from harsh ground-based locations to deep space. Addressing the challenges in the field, we collaborated with a group of experts in delivering a 'snapshot' introduction to the current status of the field and provide suggestions for exciting future technical development directions. Ultimately, we intend the roadmap to portray the advantages and benefits of the THz domain and to stimulate further exploration of the field in support

of scientific research and commercial realisation. Leitenstorfer, A. *et al.* The 2023 terahertz science and technology roadmap. *J. Phys. D: Appl. Phys.* **56**, 223001 (2023).

Theoretical studies on the nanoscale

Noisy intermediate-scale quantum (NISQ) devices are spearheading the second quantum revolution. Of these, quantum annealers are the only ones currently offering real-world, commercial applications on as many as 5000 qubits. The size of the problems that can be solved by quantum annealers is limited mainly by errors caused by environmental noise and intrinsic imperfections of the processor. We address the issue of intrinsic imperfections with a novel error-correction approach, based on machine-learning methods. Our approach adjusts the input Hamiltonian to maximize the probability of finding the solution. In our experiments, the proposed error-correction method improved the performance of annealing by up to three orders of magnitude and enabled the solving of a previously intractable, maximally complex problem. The results were published in Quantum Mach. Intell. 5, 4 (2023). https://doi.org/10.1007/s42484-022-00092-y

We perform theoretical modelling of the intertwined domain structures using a classical charged lattice gas model and reproduced the experimental domain-wall structures. The superposition state cannot be understood classically within the correlated electron model but is found to be consistent with interferences of L- and R-handed charge-density waves within domains, confined by surrounding domain walls, vividly revealing an interference of Fermi electrons with opposite chirality, which is not a result of inter-layer interference, but due to the interaction between electrons within a single layer, confined by domain-wall boundaries. The results were published in Sci Rep 13, 19622 (2023). https://doi.org/10.1038/s41598-023-46659-y.

We also modelled carrier injection into a Wigner crystal that reveals the origin of formation of fractionalized, topologically entangled networks, which defines the spatial fabric through which single particle excitations propagate. The possibility of manipulating the topological entanglement of such networks suggests the way forward in the search for elusive metastable states in quantum many-body systems. The results were published in **Nat Commun** 14, 8214 (2023). https://doi.org/10.1038/s41467-023-43800-3

A theory was developed for the effect of the gap opening on the surface of 3D topological insulator on its transport properties. The theory simultaneously explains the unusual magnetoresistance and non-linearity of the Hall effect observed in $(Bi,Sb)_2(Te,Se)_3$ films. The results are published in Phys. Rev. B, 108, 115401 (2023) https://doi.org/10.1103/PhysRevB.108.115401.

The spin phenomena observed at a clean metal-insulator interface are typically reduced to the Rashba-Edelstein effect, which leads to spin accumulation over a few monolayers. We demonstrated that the presence of interface disorder expands the range of potential phenomena. Specifically, the skew scattering at the metal-insulator boundary gives rise to the "kinetic Rashba-Edelstein effect," where spin accumulation occurs on a much larger length scale, comparable to the mean free path. Moreover, at higher orders of spin-orbit interaction, skew scattering is accompanied with spin relaxation resulting in the interface spin-Hall effect—a conversion of electrical current to spin current at the metal surface. Unlike the conventional spin-Hall effect, this

phenomenon persists even within the Born approximation. These two predicted phenomena can dominate the spin density and spin current in devices of intermediate thickness. The results are published in Phys. Rev. Research, 5, 033215 (2023) https://doi.org/10.1103/PhysRevResearch.5.033215

Preparation process of graphene dispersion in PDMS with the simultaneous use of ultrasound and vacuum

We synthesised using chemical vapour transport reactions different TMD`s crystals that were basic parts in research areas at superconductors, charge-density wave, metastability and others. In $2H-NbSe_2$ was mainly investigated for temperature-dependent ultrafast near-infrared (NIR) transient reflectivity dynamics. Tantalum diselenide $1T-TaS_2$ was included in many research areas including visualization of microscopic dynamics investigation of the ultrafast dynamics of the formation of a hidden quantum state, investigation of chiral charge-density wave (CDW) domains after a laser quench with STM and energy efficiency scaling of charge configuration memory (CCM) devices as a function of device size. The European patent application EP 4282905A1 was granted for the process for the preparation of a graphene dispersion and its derivatives based on noble metals in PDMS using the simultaneous application of ultrasound and vacuum. Furthermore, we developed a new method for an effective and facile homogenous decoration of graphene oxide and graphene flakes dispersed in water with gold and platinum nanoparticles.

Soft Matter

Liquid crystals

The recently discovered ferroelectric nematic fluids offer a full, new range of potential applications for nematic liquid crystals, beyond the well-stablished, multi-billion-euro market for displays. The design of new applications, especially in the field on nonlinear optics, is directly intertwined with our fundamental understanding of the materials and our ability to process, control and fabricate polarization structures. In this context, in collaboration with researchers from Ghent University (Belgium), University of Leeds (UK), and South China University of Technology (China) we proposed a unique approach to fabricate electric polarization structures in ferroelectric liquids exploiting flexoelectric coupling of the nematic director and the polarization by using photopatterning alignment technology. Similarly, as in piezoelectricity, where strain induces polarization, splay deformations of the orientational director field in nematic materials can result in electric polarization. We created a series of splayed structures, which exploit and experimentally visualize the flexoelectric coupling between polarization and nematic deformations, giving rise to alternation of the polarization direction with the change of the splay sign. The potentialities of guiding polarization, through splay-guiding channels, either in a uniform or a bend background were shown for a series of structures. This work was published in Nature Communications 14, art. 3029 (2023) and selected as Editor's Highlight.

In collaboration with the University of the Basque Country (UPV/EHU) we investigated the origin of the astonishingly large dielectric permittivity values reported for ferroelectric nematics. For that, we studied the effect of the thickness of the measuring capacitor in the apparent dielectric permittivity of ferroelectric nematic materials, showing that while measured permittivity exhibits a linear dependence on the cell thickness, the characteristic relaxation frequency decreases inversely proportionally to it. The measurements were analysed in terms of different available models and the relaxation processes were interpreted in terms of collective and non-collective dynamics (Journal of Molecular Liquids 387, 122566 (2023) and Journal of Chemical Physics 159, 184502 (2023).) We additionally investigated the effect of a photovoltaic field generated on the surface of iron-doped lithium niobate crystals on sessile droplets of a ferroelectric nematic liquid crystalline and a standard nematic liquid crystalline material present on this surface. A wide range of dynamic phenomena were observed including the formation of conical spikes evolving into jet streams. This work was published in Opt. Mater. Express (OME) 13, 282–294 (2023), Liq. Cryst., 50, 1478-1485 (2023), and Journal of Optical Microsystems (JOM), 3, 041209-1-11 (2023).

In collaboration with the University of Belgrade, Serbia, we studied the optical switching of bent-core liquid crystals with azocinnamoyl units. While UV illumination had no significant effect on the nematic phase, visible changes in optical transmittance were observed in the smectic phase, most pronounced near the transition to the nematic phase. The characteristic switching and relaxation times were determined as a function of temperature and the results were published in Liq. Cryst., 50, 1599-1607 (2023).

DNA repeat sequences (G4C2)n are known for their involvement in neurodegenerative diseases, especially amyotrophic lateral sclerosis (ALS). In previous research, we used dynamic light scattering and atomic force microscopy to confirm that the shortest of these sequences (n = 1, 2, 4) form DNA-quadruplex structures. We have recently extended our investigations to (G4C2)n concentrated solutions, which are more similar to the DNA conditions inside living cells. Although finding the right experimental conditions has proven to be a challenging task (DAAAM International scientific book 2023, 101-110 (2023)), by using polarisation optical microscopy we were able to observe that (G4C2) and (G4C2)2 sequences form lyotropic liquid crystalline phases in concentrated solutions.

In collaboration with the Nankai University from Tianjin in China we investigated complex configurations of cholesteric liquid crystals doped with organic dye molecules acting as an intriguing optical amplification material for the construction of microscale laser systems. We studied dual-wavelength lasing with orthogonal circular polarizations generated in a polymer-cholesteric liquid-crystal superstructure and showed that an external electric field can be used for tuning the relative intensity of two spectral components of the output laser beam. The results
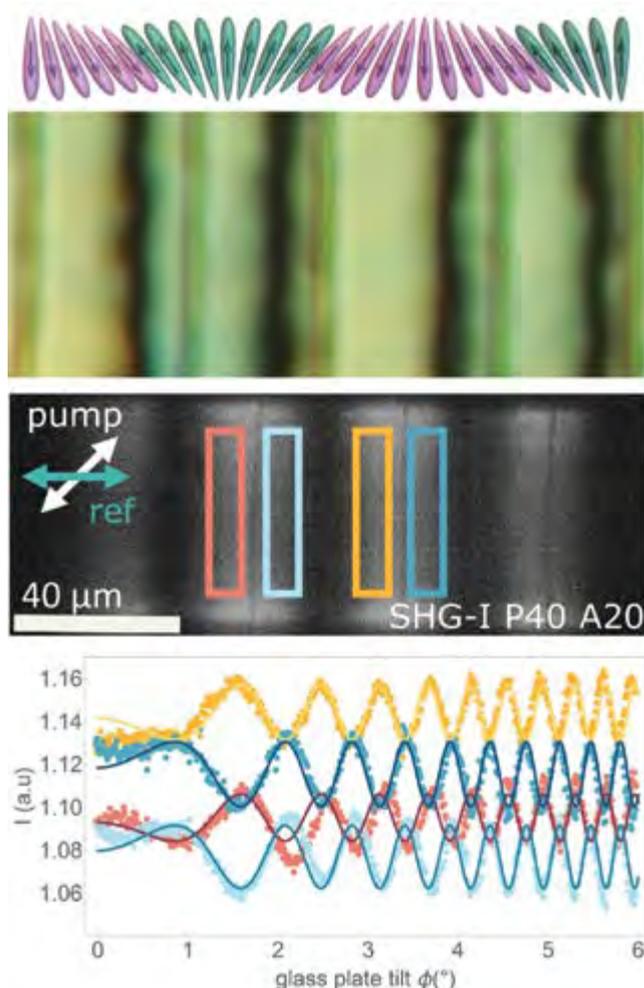

Figure 9: Schematic of inscribed surface alignment, corresponding polarizing optical microscopy image and Second Harmonic Generation interferometry image and interferogram for one of the studied patters of ferroelectric nematic fluids.

of this works were published in Polymers, 15, 1226 (2023) and Polymers, 15, 4656 (2023). We also demonstrated lasing in a cholesteric liquid-crystal-based topological superstructure. The existence of a robust topological interface optical state at the visible wavelength range ensures a superb stability of the lasing wavelength with respect to mechanical perturbances, but, on the other hand, it can be thermally tuned. Such soft-matter-based composite structures bring about the possibility to realize tunable and compact topological photonic devices at low cost. (Laser & Photonic Reviews, 17, 220643 (2023).

Magneto-Responsive Soft Materials

Magnetic soft matter research was carried out in close collaboration with the Experimental Soft Matter Laboratory at the Faculty of Mathematics and Physics, University of Ljubljana, the Faculty of Mechanical Engineering, University of Ljubljana, the departments F-5 and K-8 at JSI, and also with industrial pharmaceutical partners. The research was focused around two topics: colloidal dispersions of magnetic nanoparticles forming ferromagnetic fluids, and magnetoactive elastomers (MAEs), where magnetic microparticles are dispersed in an elastomer matrix.

In the field of ferromagnetic fluids, we studied the influence of alternating magnetic field on the form of stable colloidal dispersions of magnetic nanoplatelets and observed the formation of an unusual highly periodic striped structure, visible under a polarising microscope. We experimentally confirmed that the individual lines are magnetic domains and observed fluid flow in the boundaries between individual domains. The fluid in adjacent lanes moves in the opposite directions despite the applied magnetic field being uniform. The formation of bidirectional flow lanes was explained by spontaneous breaking of the chiral symmetry and the results were published in Small, 19, 2304387 (2023).

We continued our collaboration with researchers from TU Braunschweig and Otto von Guericke University, Magdeburg, Germany in the investigation of the role of an ionic surfactant in the magnetic dynamics of self-assembled dispersions of nanoplatelets, showing that the control of electrostatic interactions with an ionic surfactant leads to the development of new dynamic modes in magnetic response spectra (Journal of Molecular Liquids 382, 121900 (2023)). We extended our studies of magnetic nanoplate suspensions to investigations of the domain formation dynamics in confined geometries and to the appearance of flow-induced magnetisation. The results of this work led to the successful defence of a PhD thesis.

Our main research interest in MAEs is associated with their ability to generate dynamically tunable or on-demand responses. They are soft rubber composites that respond to external magnetic fields. The material, fabricated in the collaborating group at OTH Regensburg in Germany was used to study the effect of strain on a cylindrical MAE shape when exposed to uniform magnetic fields (Journal of Magnetism and Magnetic Materials, 579, 170826 (2023)). An important research focus was the surface of MAEs, on which we used laser micromachining, carried out at the Faculty of Mechanical Engineering, University of Ljubljana, to additionally modify the surface either to make it rougher or to introduce periodic shapes like lamellae. Such modifications, combined with magnetic actuation, lead to the tuneability of their surface interaction with the environment. We demonstrated magnetically controlled water droplet impact, in particular, switching between rebound and deposition regimes (Advanced Materials Interfaces, 10, 11, 2202471, (2023)). In another study lamellated surfaces were used for the propulsion and tuneable size separation of liquid droplets and small solid objects (Advanced Engineering Materials, 25, 22, 2301000, (2023)). We also demonstrated that light reflection from a MAE surface can be dynamically switched, and we developed a theoretical model for the sticking regime of lamellated MAE surface (Soft Matter, 19, 18, 3357-3365, (2023)). This involved stability estimates for a MAE cantilever beam which we also applied to lamellar structures from silicon to elucidate the limits of a new fabrication method for fabrication of grating structures for X-ray spectral region (Advanced Functional Materials, 33, 16, 2212660, (2023)).

In collaboration with the Institute of Biophysics, Faculty of Medicine, University of Ljubljana we demonstrated a novel method for the controlled poration of lipid membranes, which are crucial for numerous biomimetic applications such as targeted drug delivery. We utilized the mechanical shockwave generated by the photo-acoustic effect, which occurs when an optically opaque microparticle (which can be also simultaneously magnetic) is illuminated by a near-infrared laser of optical tweezers. We showed that the shockwave effectively porates membranes of giant unilamellar vesicles in close proximity to the microparticle without damaging nearby cells, which is a desirable outcome for potential targeted drug delivery. The poration effect is nonspecific and operates on both liquid- and gel-phase membranes. Since the photo-acoustic effect can be triggered by standard optical tweezers, this method holds broad applicability in various experimental settings within the field of soft matter research. (RSC advances, 35, 24830–24834 (2023)).

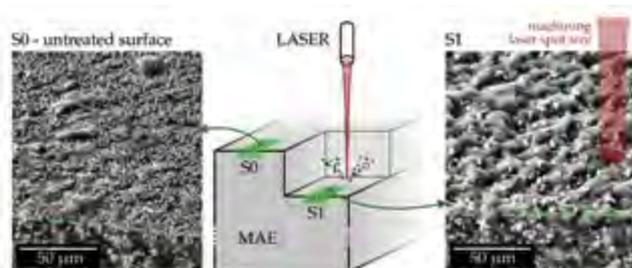Figure 10: Magnetoactive elastomers are composite materials made from a polymer matrix with embedded magnetic micro particles, shown in white on SEM images. Their many interesting surface properties can by enhanced by laser micromachining, creating complex structures which can deform in a presence of an external magnetic field. The figure depicts changes in local surface topography as a consequence of lase micro-structuring.
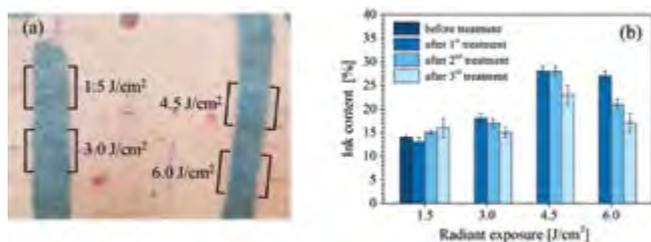
Figure 11: (a) Photograph of a black tattoo in a human volunteer 4 weeks after the 1st laser treatment with different radiant exposures (see the labels). (b) The assessed amount of tattoo ink after the 1st, 2nd and 3rd removal treatment with different radiant exposures. (Lasers Surg. Med. 2023, 55, 724)

Our innovative technique for non-invasive characterization of the structure and composition of human skin in vivo was adapted for the objective monitoring of black tattoos' removal with different laser settings, providing a unique insight into the involved processes.
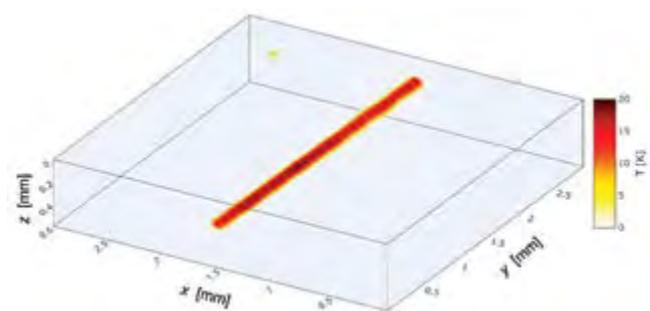

Figure 12: Tomographic image of a human hair, suspended in optically scattering agarose gel at a subsurface depth of ~0.20 mm. The image was reconstructed from a single radiometric record using a custom code in only 400 iteration steps (Proc. SPIE 2023, 12629, 126290I)

Biomedical optics

Our recently developed approach for the non-invasive characterization of human skin, which combines diffuse reflectance spectroscopy and pulsed photo-thermal radiometry with a dedicated numerical model of light transport in strongly scattering media, enables us to assess several physiologically relevant parameters of human skin. We have adapted the described technique for the objective characterization of black tattoos, in vivo, and applied it to monitoring of laser tattoo removal in human volunteers with different irradiation parameters in an extended treatment protocol. The results provide a unique assessment of the relative decrease of the ink content and demonstrate the incremental increase of the depth of the tattoo layer with subsequent treatment sessions. Collaboration with Fotona d.o.o., Ljubljana. (**Lasers Surg. Med. 2023, 55, 724**)

Using the same approach, we have analysed the influence of aging on optical properties of human skin. Based on measurements in 24 volunteers (age 23–63 years), we showed that a reduced scattering coefficient of the dermis in visible spectral range is strongly correlated with person's age, on average decreasing by 0.2 mm per decade ($p < 0.0001$). However, this assessment was possible only after the separation of the much stronger influence of the highly variable blood contents by multiple linear regression analysis. (**Proc. SPIE 2023, 12629, 126290J**)

We have implemented and tested an innovative principle of tomographic imaging of optically scattering samples, utilizing photothermal radiometry. The sample is irradiated with a millisecond laser pulse and its surface imaged with a fast mid-infrared camera. The laser-induced temperature field is reconstructed by running multidimensional optimization, using analytically formulated forward problem of heat transport and IR emission. Nonlinear compression of the acquired radiometric record enabled reconstruction of sharp images of human hairs, suspended in an optically scattering agarose block at a depth of >0.2 mm, with no significant noise or artifacts in the imaged volume of 3 x 3 x 0.6 mm^3 in only 45 seconds. (**Proc. SPIE 2023, 12629, 126290I**)

We studied the collective dynamics of active particles and observed shape fluctuations and movement of droplets in which active particles are trapped, depending on their activity.

Some outstanding publications in the past year

1. Mraz, Anže, Diego, Michele, Kranjec, Andrej, Vodeb, Jaka, Karpov, Peter, Gerasimenko, Yaroslav, Ravnik, Jan, Vaskivskyi, Yevhenii, Venturini, Rok, Kabanov, Viktor V., Lipovšek, Benjamin, Topič, Marko, Vaskivskyi, Igor, Mihailović, Dragan. Manipulation of fractionalized charge in the metastable topologically entangled state of a doped Wigner crystal. Nature communications. 2023, vol. 14, article no. 8214, str. 1-8, ilustr. ISSN 2041-1723. https://www.nature.com/articles/s41467-023-43800-3#Abs1, DOI: 10.1038/s41467-023-43800-3

2. Jarc, Giacomo, Mathengattil, Shahla Yasmin, Mihailović, Dragan, Prelovšek, Peter, Fausti, Daniele, et al. Cavity-mediated thermal control of metal-to-insulator transition in 1T–TaS21 2. Nature. [Online ed.]. 19 Oct. 2023, vol. 622, iss. 7983, str. 487-492, ilustr. ISSN 1476-4687. https://www.nature.com/articles/s41586-023-06596-2#article-comments, DOI: 10.1038/s41586-023-06596-2

3. Božin, Emil S., Abeykoon, A. M. Milinda, Conradson, Steven D., Baldinozzi, Gianguido, Šutar, Petra, Mihailović, Dragan. Crystallization of polarons through charge and spin ordering transitions in 1T–TaS21. Nature communications. 2023, vol. 14, article no. 7055, str. 1-9, ilustr. ISSN 2041-1723. https://www.nature.com/articles/s41467-023-42631-6#Abs1, DOI: 10.1038/s41467-023-42631-6.

4. Sebastián Ugarteche, Nerea, Lovšin, Matija, Osterman, Natan, Petelin, Andrej, Drevenšek Olenik, Irena, Mertelj, Alenka, et al. Polarization patterning in ferroelectric nematic liquids via flexoelectric coupling. Nature communications. 2023, 14, art. 3029. DOI: 10.1038/s41467-023-38749-2

5. Derganc, Jure, Zemljič Jokhadar, Špela, Majaron, Boris, Kokot, Gašper. Locally induced shockwaves for selective perforation of cargo loaded lipid vesicles with temporal and spatial control. RSC advances. 2023, iss. 35, str. 24830–24834.

6. Potrč, Melani, Vujica-Herzog, Nataša, Drevenšek Olenik, Irena, Spindler, Lea. Fabrication of containment cells for lyotropic liquid crystalline materials. in: KATALINIĆ, Branko (ed.). DAAAM International scientific book 2023. pp. 101-110. 10.2507/daaam.scibook.2023.08.

7. Shumilin, Andrei, Kabanov, Viktor V. Interface disorder as the cause for the kinetic Rashba-Edelstein effect and interface spin-Hall effect at a metal-insulator boundary. Physical review research. Sep./Nov. 2023, vol. 5, iss. 3, [article no.] 033215, str. 033215-1-033215-9, ilustr. ISSN 2643-1564. https://journals.aps.org/prresearch/abstract/10.1103/PhysRevResearch.5.033215, DOI: 10.1103/PhysRevResearch.5.033215

8. Brence, Jure, Mihailović, Dragan, Kabanov, Viktor V., Todorovski, Ljupčo, Džeroski, Sašo, Vodeb, Jaka. Boosting the performance of quantum annealers using machine learning. Quantum machine intelligence. Jun. 2023, vol. 5, iss. 1, article no. 4, str. 1-11, ilustr. ISSN 2524-4914. DOI: 10.1007/s42484-022-00092-y

Organization of Conferences, Congresses and Meetings

1. Nonequilibrium Quantum Workshop, Krvavec, Slovenia, 10. 12. - 14. 12. 2023

Patent granted

1. Dragan Mihailović, Damjan Svetin, Anže Mraz, Rok Venturini, Memory device and method for its operation, EP 3 881 365 B1, European Patent Office, 11. 1. 2023

INTERNATIONAL PROJECTS

1. COST CA17140; Nano2Clinic - Cancer Nanomedicine - From the Bench to the Bedside
   Prof. Boris Majaron
   COST Association Aisbl
2. COST CA20129; Multiscale Irradiation and Chemistry Driven Processes and Related Technologies
   Asst. Prof. Lea Spindler
   COST Association Aisbl
3. H2020 - INTERFAST; Gated INTERfaces for FAST information processing
   Asst. Prof. Tomaž Mertelj
   European Commission
4. H2020 - MAGNELIQ; A Magneto-Electric Liquid - Better Sensing
   Asst. Prof. Alenka Mertelj
   European Commission
5. Diffractive Structures from Polymeric Composite Materials with Ferroelectric and Ferromagnetic Liquid Crystals
   Asst. Prof. Alenka Mertelj
   Slovenian Research Agency
6. On the Way to Soft Multiferroic Materials
   Asst. Prof. Alenka Mertelj
   Slovenian Research Agency
7. COST CA21144; Superconducting Nanodevices and Quantum Materials for Coherent Manipulation
   Prof. Viktor Kabanov
   COST Association Aisbl

RESEARCH PROGRAMMES

1. Medical physics
   Prof. Matija Milanič
2. Light and Matter
   Prof. Irena Drevenšek Olenik
3. Nonequilibrium Quantum System Dynamics
   Prof. Dragan Dragoljub Mihailović

4. Physics of quantum technologies
   Prof. Dragan Dragoljub Mihailović

R & D GRANTS AND CONTRACTS

1. Methods and materials for photoalignment templates for chiral liquid crystal lenses and photonic components
   Prof. Irena Drevenšek Olenik
2. Fourier correlation microscopy for particle characterization and velocimetry in complex soft matter
   Prof. Natan Osterman
3. Two-dimensional materials-based piezophotonic composites for tailor-made ultrasounds in biological systems (2D-UltraS)
   Dr. Aleš Mrzel
4. Multi-scale modeling of non-equilibrium quantum materials
   Dr. Denis Golež
5. Liquid Magnets: fundamental studies of ferromagnetic order in liquids
   Nerea Sebastian Ugarteche
6. Surface-selective hybridization technology for magneto-electric hybrids
   Asst. Prof. Alenka Mertelj
7. Magneto Responsive Surfaces for Manipulation of Light and Liquids
   Prof. Irena Drevenšek Olenik
8. Exploitation of the magneto-mechanical effect in the treatment of neurodegenerative diseases
   Asst. Prof. Alenka Mertelj
9. Single-flux-quantum controlled charge configurational memory (CCM) devices
   Prof. Dragan Dragoljub Mihailović
10. Tracking domain formation during ultrafast switching of van der Waals devices
    Prof. Dragan Dragoljub Mihailović
11. Time-resolved tunneling microscope
    Prof. Dragan Dragoljub Mihailović
12. Structuring of domains and topological defects in ferroelectric nematic liquids
    Asst. Prof. Alenka Mertelj
13. Physics of quantum technologies
    Dr. Jaka Vodeb
    Slovenian Research Agency

VISITORS FROM ABROAD

1. Mag. Martens FABIAN TU Dortmund University, Dortmund, Germany, 20. 2. - 10. 3. 2023
2. Dr Mamin RINAT, Zavoisky Physical-Technical Inst., FRC Kazan Scientific Center of RAS, Russian Federation, 31. 3. - 11. 4. 2023
3. Prof. dr Martin FALLY, University of Vienna, Faculty of Physics, Vienna, Austria, 17. 4. - 18. 4. 2023
4. Prof. dr Liana LUCCETTI, Polytechnic University of Marche, Ancona, Italy, 19. 4. 2023 -21. 4. 2023
5. Prof. dr Hrvoje PETEK, The University of Pittsburgh, Pittsburgh, USA, 9. 7. – 11. 7. 2023
6. Mag. Alexander JAROSIK, Univerze Otto-von-Guericke, Magdeburg, Germany, 20. 8. – 9. 9. 2023
7. Mag. Yu Wang in Mag. Donghao Yang, TEDA Institute of Applied Physics & School of Physics Nankai University, China, 14. 10. – 28. 10. 2023
8. Prof. dr Martin FALLY, University of Vienna, Faculty of Physics, Vienna, Austria, 7. 12. – 9. 12. 2023

STAFF

Researchers

1. *Dr. Steven Daniel Conradson, left 01.02.23*
2. Prof. Irena Drevenšek Olenik*
3. Prof. Viktor Kabanov
4. Dr. Matjaž Lukač*
5. Prof. Boris Majaron
6. Asst. Prof. Alenka Mertelj
7. Asst. Prof. Tomaž Mertelj
8. **Prof. Dragan Dragoljub Mihailović, Head**
9. Prof. Matija Milanič*
10. Dr. Aleš Mrzel
11. Prof. Natan Osterman*
12. Dr. Nerea Sebastian Ugarteche
13. Asst. Prof. Lea Spindler*
14. Dr. Igor Vaskivskyi
15. Asst. Prof. Mojca Vilfan

Postdoctoral associates

16. Dr. Yelyzaveta Chernolevska
17. Dr. Luka Cmok
18. Dr. Patricija Hribar Boštjančič
19. *Dr. Qing Hu, left 01.07.23*
20. Dr. Gašper Kokot
21. Dr. Anže Mraz
22. Dr. Andrei Shumilin
23. Dr. Ivan Spajić

24. Dr. Jaka Vodeb
25. Dr. Hui Zhao

Postgraduates

26. Neža Golmajer Zima, B. Sc.
27. *Žiga Gregorin, B. Sc., left 01.06.23*
28. Gregor Humar, B. Sc.
29. Gregor Jecl, B. Sc.
30. Matija Lovšin, B. Sc.
31. Peter Medle Rupnik, B. Sc.
32. Jaka Strohsack, B. Sc.
33. Yevhenii Vaskivskyi, M. Sc.
34. Dr. Rok Venturini

Technical officers

35. Davor Grabnar, B. Sc.
36. Damjan Svetin, B. Sc.
37. Petra Šutar, B. Sc.
38. Damjan Vengust, B. Sc.

Technical and administrative staff

39. *Ula Groznik, B. Sc., 25.09.23, transferred to Department F8*
40. Nataša Kutnjak, B. Sc.
41. Barbara Paternoster, B. Sc.
42. Eva Trpin, B. Sc.

Note:
* part-time JSI member

DEPARTMENT OF REACTOR PHYSICS F-8

Our main areas of work are:
- ***theoretical, experimental, and applied reactor physics***
- ***plasma physics***
- ***neutron-transport calculations in fusion reactors***
- ***medical physics***

In **reactor physics**, our research in 2023 focused on developing new computational and experimental methods for analyzing research and power fission and fusion reactors.

The main objective of the project "Stability of Nuclear Reactors during Load-Following Operation", launched in 2020, is to investigate the limitations of load-following operation in nuclear power plants, particularly regarding the reactor core and the fuel, and to provide effective solutions to operators for plant-performance optimization. In 2023 we focused on analyzing the effective fuel temperature. Results show that temperature models are crucial for accurate reactor neutronics calculations. When all the data is available, weighting using the total reaction rate on U-238 is recommended. If only temperature profiles are available, the Rowland model can be used, though a correction factor should be increased for burnups exceeding 50 MWd/kgU, as the effective temperature is underestimated. We also published a paper analyzing the feasibility of using nuclear power to balance daily solar power fluctuations in Slovenia by 2050. The study is based on a nonlinear pressurized water reactor (PWR) model with two-point kinetics and a novel simplified control approach. Results indicate that a nuclear power plant can effectively compensate for expected power variations. In 2023 we developed a new sensitivity calculation based on simultaneous sampling for uncertainty propagation in PWR transient analyses. The method was validated on the Godiva uranium sphere (ICSBEP), showing good agreement with reference data and a high computational efficiency.

At the end of 2022 we launched the project "Design of Selective Catalytic Processes for CO_2 Conversion to Ethanol", aiming to investigate the effects of neutron and gamma radiation on CO_2 decomposition. Experiments will be conducted under high-radiation fields of the IJS TRIGA research reactor, both during operation (gamma and neutron fields) and after shutdown (gamma only), using irradiations in and near the reactor core. The experiments will be modeled using Monte Carlo particle transport codes. Catalyst design will be optimized for the fraction of radiation energy leading to stable CO_2 decomposition.

In the project "Sensitivity of Nuclear Reactor Physical Parameters to Thermal Nuclear Data", we developed and verified systematic methods for calculating thermal neutron scattering cross-sections for materials not yet included in existing data libraries. Work focused on zirconium hydride in its two most common phases, δ (ratio 1.5) and ε (ratio 2), often used in research reactors such as TRIGA. We used VASP to generate the interatomic forces and Phonopy to compute the density of states. A procedure for generating thermal scattering cross-sections for use in Monte Carlo codes, based on NJOY modules (LEAPR, RECONR, BROADR, THERMR, ACER), was established and validated against experimental and calculated data.

In the related project "Advanced Methods for Analysis of Thermal Scattering Cross-Sections", the goal is to obtain data for thermal neutron scattering for unexplored materials such as uranium-hydride fuels, diamond, and conventional moderators (e.g., polyethylene, PMMA, Teflon, graphite). Research again focused on zirconium hydride, due to its exceptional moderation and thermal properties. We performed multistep calculations using various programs and validated results at each stage against experimental and other computational results, ensuring reliability. Data for use in Monte Carlo simulations were validated using experimental measurements sensitive to ZrH.

The European project TOURR, launched in 2020, concluded successfully at the end of 2023. A joint strategy for the future of European research reactors was developed, analyzing their current status (utilization, age, upgrade potential) and drafting plans for refurbishment and new construction. The main conclusion is that Europe needs
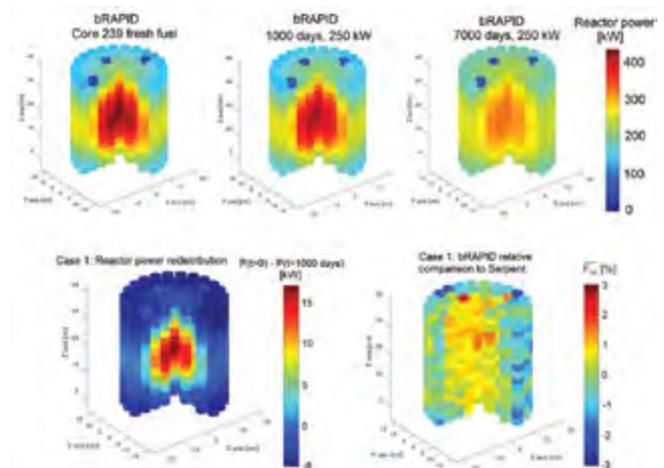
Head:
Prof. Luka Snoj

Figure 1: Comparison of 3D Power Distribution in the Reactor Between Fresh Fuel and Fuel with a Burnup of 15.4 MWd/kg. The absolute comparison between fresh fuel and the power distribution is shown in the bottom-left image, while the relative comparison of the fission source distribution, calculated with the Serpent code, is shown in the bottom-right image.
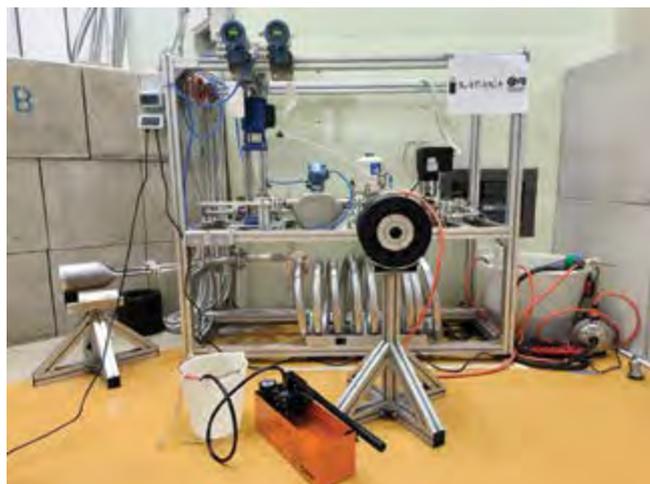
Figure 2: Irradiation Device with Activated Water (KATANA) at the TRIGA Research Reactor, Jožef Stefan Institute (IJS)
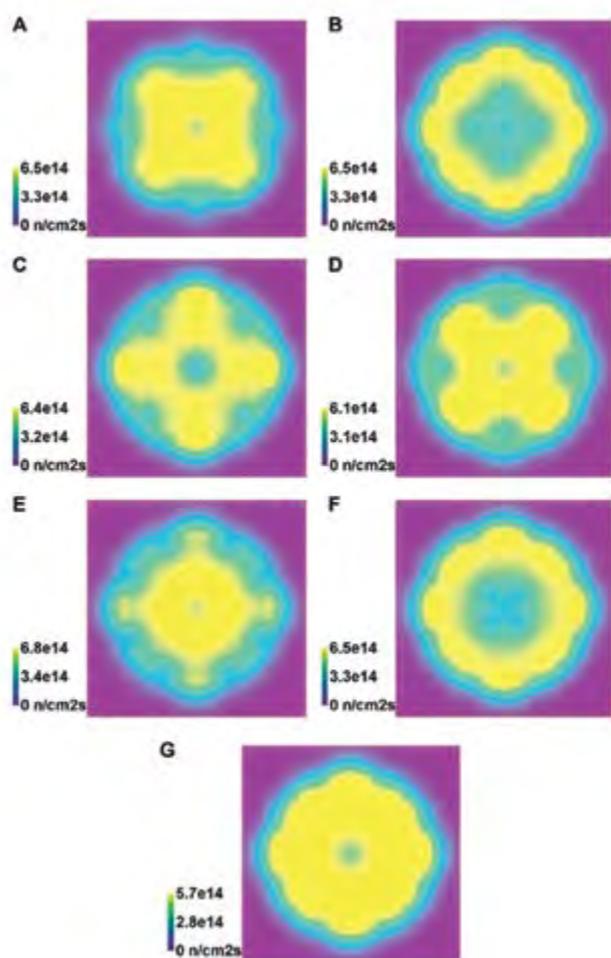

Figure 3: Neutron flux distribution in xy plane approximately in the middle of active core height, normalized to the maximum reactor power of 2 GW for cycle 28 HZP configuration calculated using MCNP core model for individual control rod completely inserted. Normalized neutron flux values are represented with colors, ranging from low values in blue to high values in yellow. (A) A bank. (B) B bank. (C) C bank. (D) D bank. (E) SA bank. (F) SB bank. (G) All rods out (ARO).

at least two new research reactors: one zero-power reactor for training and reference experiments, and a multipurpose 5-10 MW reactor for material irradiation, isotope production, and general neutron use. Results were presented at ANIMMA 2023 and RRFM 2023, with a scientific article expected in late 2024/early 2025. A digital platform enabling access to research infrastructure was created, and the IJS TRIGA reactor was included. In 2023 we supported the operation of the Krško Nuclear Power Plant (NEK), particularly after a shutdown caused by a leak in the high-pressure safety injection system. We assisted with fuel-leakage remediation, core redesign, and independent cycle 33.5 calculations, and performed startup physics tests. We also provided support for NEK's spent-fuel dry-storage project, focusing on the sensitivity analysis of parameters affecting spent fuel characterization.

As part of our cooperation with the IAEA, we contributed to the "Characterization of Spent Fuel" project. We analyzed 3D effects on fuel characterization and calculated SKB-50 test cases, including basic sensitivity studies.

In the SFDS support project, we improved source term modeling and reduced uncertainties in future core calculations. We modernized computational tools for core-parameter calculations, ensuring compatibility with modern compilers and Linux parallel execution.

We continued work in the EURAD European project, in WP3 CORI (cement-organic radionuclide interactions) and WP8 SFC (spent fuel characterization). In WP8, we analyzed SKB-50 cases and studied the impact of temperature models on fuel isotopic evolution and spent fuel characterization.

In the ENEEP project, aimed at establishing a European nuclear experimental educational platform, we collaborated with partners from Slovakia, Czech Republic, Austria and Italy. In 2023 we organized seven demonstration courses, with IJS participating in four.

In collaboration with CEA Cadarache we continued several ARRS-CEA projects and industrial partnerships. In 2023 we completed the "Reference Experiment for Instrumentation Response Modeling" project. Monte Carlo simulations of experiments performed in 2022 were conducted, including activation rate measurements using foils, neutron and gamma flux with fission and ionization chambers, self-powered detectors, and TLDs. Final data analysis confirmed the value of measurements for improving modeling and simulations.

We continued the ARRS-CEA project "New Inelastic Scattering Reactions for Epithermal Dosimetry", conducting experiments using TRIGA to irradiate standard and activation materials.

In the "Water Activation in Nuclear Reactors" project, we characterized the radiation field around the KATANA loop, aiming to develop it as a stable source of 6-7 MeV gamma rays. In 2023 we also tested SiC detectors developed at CEA on the TRIGA reactor.

In the EURO-LABS project, we performed shielding calculations for a new irradiation setup aimed at reducing low-energy neutron components that contribute to material activation in electronics. We proposed cadmium shielding in the TRIGA reactor's tangential irradiation channel, reducing silicon damage by 4-5% and activation of typical materials by 10% to two orders of magnitude.

On nuclear radiation as a catalyst for chemical reactions, we studied literature and LET-based metrics. We proposed new metrics—average reaction distance and deposited energy per reaction—based on particle energy. We also studied materials converting neutrons/gamma into ionizing radiation.

In the IAEA-funded project "Activation Measurements Using Neutron Filters for Dosimetry Data Validation", we acquired enriched boron carbide neutron filters and performed preliminary measurements in TRIGA channels.

In the SANDA project, we developed XSUN-2023, a new version of our sensitivity/uncertainty analysis software, and submitted it to the NEA Data Bank. We used it for benchmark experiments and nuclear data validation.

In **neutron transport calculations for fusion reactors** we advanced work in EUROfusion and collaborations for DEMO, IFMIF-DONES, JET, and FNG. For DEMO, we performed activation and decay heat calculations for components near equatorial ports under a 5-year irradiation scenario. We contributed to safety reviews and limiter-EC integration studies by calculating nuclear heating and helium production. For FUTURE, we analyzed neutron characteristics of the divertor and upper port.

Figure 4: Characteristic Metabolic Disease Patterns in the Differential Diagnosis Algorithm for Neurodegenerative Disorders Based on FDG-PET Imaging and SSM/PCA. PD/NI denotes patients with Parkinson's disease, MSA/NI denotes patients with multiple system atrophy, and PSP/NI denotes patients with progressive supranuclear palsy.

We applied machine learning in the "Optimization of Neutron Characteristics of Fusion Reactors" project, using genetic algorithms on simplified tokamak models.

We contributed to the EUROfusion WPENS project supporting IFMIF-DONES. In 2023, we analyzed gas-production uncertainties, dose rates around the facility, modeled the LIPAc accelerator, prepared IFMIF-DONES geometry, and tested the FENDL-3.2 data library.

We worked with European partners on JET data analysis. Our calculations focused on neutron fields and activation of samples during the TT campaign. We modeled detector responses in various plasma modes and conducted the world's first water activation experiment in a D-T fusion tokamak (JET WACT), setting the foundation for ITER simulations.

In collaboration with RIC and international partners we installed the KATANA loop in the TRIGA reactor. This closed water loop serves as a stable source of high-energy gamma and neutron radiation for calibration and method validation.

We continued our long-term involvement in EUROfusion since 2000. In 2023 we presented a new simultaneous sampling method for nuclear data sensitivity at M&C (Canada) and analyzed JEFF-4T data for fusion experiments. Results were published in Fusion Engineering and Design.

We also conducted sensitivity and uncertainty analysis for neutron-induced reaction rates in the WCLL experiment at FNG. We compared deterministic and Monte Carlo methods for geometry uncertainty propagation and extracted first-order sensitivity equations.

We remained active in the Fusion Technology programme, involving top experts from four IJS departments and two University of Ljubljana faculties.

In 2023 we worked on the RAPTOR project (https://raptor-consortium.com), developing neural network-based methods for transferring CT structure labels to daily images, enabling uncertainty estimation and robust adaptive therapy planning.

We maintained strong collaboration with the University of Wisconsin, holding regular research meetings and manuscript reviews.

In **medical physics** we advanced multi-level imaging using optical methods, combining hyperspectral macro and microscopic imaging with OCT. We analyzed tissue phantoms and collaborated internationally on data visualization and storage. We contributed to FDG-PET-based diagnosis of neurodegenerative diseases, developing a multinomial logistic regression algorithm achieving high AUC values: PD (0.93),

Figure 5: Vessel segmentation from a tissue oxygen saturation image. A) tissue oxygen saturation image, B) processed image with automatic B-COSFIRE segmentation, C) vessel skeleton, and D) oxygen saturation profile along the segments marked in image C). Adapted from: T. Tomanič et al. 2023, Journal of Biophotonics, 16(1). CAD rendering of the modular polarization-sensitive hyperspectral microscope design.

PSP (0.95), and MSA (0.90). The algorithm requires no control images and allows expansion to new conditions.

We also began developing a new hyperspectral, polarization-sensitive microscope for studying spectral and birefringent properties of histological samples, reflecting tissue structural order.

In microscopy we implemented Fourier-based algorithms to assess tissue-sample structure, supporting optical microscopy research.
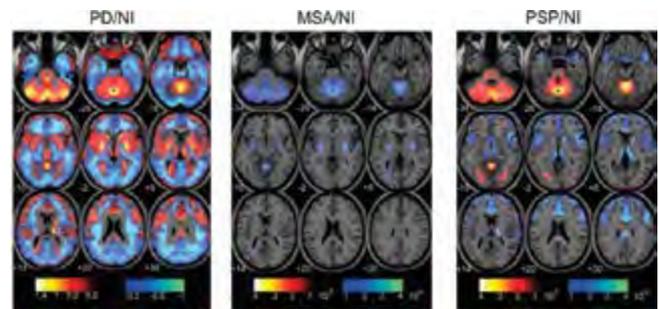
Some outstanding publications in the past year
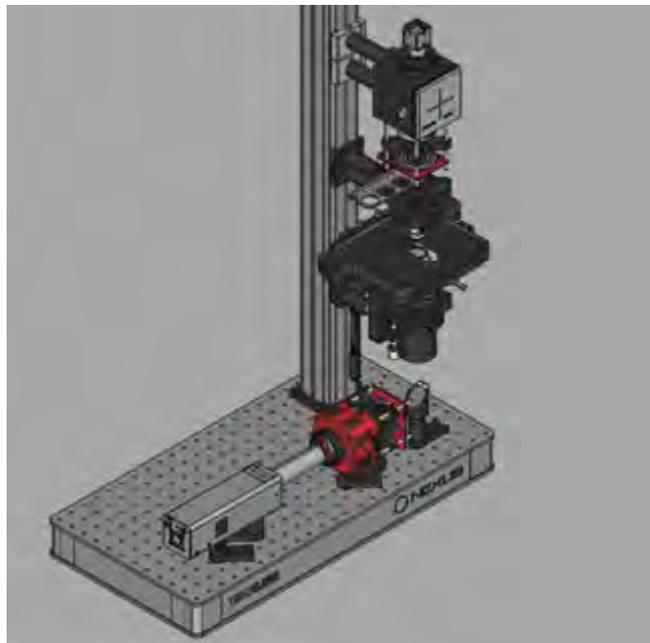
1. Pungerčič, A., Mascolino, V., Haghighat, A., & Snoj, L. (2023). Verification of a novel fuel burnup algorithm in the RAPID code system based on Serpent-2 simulation of the TRIGA Mark II research reactor. Nuclear Engineering and Technology, 55(10), 3732–3753. https://doi.org/10.1016/j.net.2023.06.040

2. Tomanič, T., Rogelj, L., Stergar, J., Markelc, B., Božič, T., Kranjc Brezar, S., Serša, G., & Milanič, M. (2023). Estimating quantitative physiological and morphological tissue parameters of murine tumor models using hyperspectral imaging and optical profilometry. Journal of Biophotonics, 16, e202200181. https://doi.org/10.1002/jbio.202200181

3. Stergar, J., Hren, R., & Milanič, M. (2023). Design and validation of a custom-made hyperspectral microscope imaging system for biomedical applications. Sensors, 23, 2374. https://doi.org/10.3390/s23052374

4. Vella, D., Lukač, M., Jernejčič, U., Lukač, N., Klaneček, Ž., Milanič, M., & Jezeršek, M. (2023). Measurements of hair temperature avalanche effect with alexandrite and Nd:YAG hair removal lasers. Lasers in Surgery and Medicine, 55(1), 1–10. https://doi.org/10.1002/lsm.23622

5. Simončič, U., & Milanič, M. (2023). Hyperspectral imaging with active illumination: A theoretical study on the use of incandescent lamp and variable filament temperature. Sensors, 23(23), 9326. https://doi.org/10.3390/s23239326

6. Simončič, U., & Milanič, M. (2023). Tail artifact removal via transmittance effect subtraction in optical coherence tail artifact images. Sensors, 23(23), 9312. https://doi.org/10.3390/s23239312

7. Manojlović, T., Tomanič, T., Štajduhar, I., & Milanič, M. (2023). Rapid extraction of skin physiological parameters from hyperspectral images using machine learning. Applied Intelligence, 53(13), 16519–16539. https://doi.org/10.1007/s10489-022-04327-0

8. Klaneček, Ž., Hren, R., Simončič, U., Tašič Muc, B., Lukač, M., & Milanič, M. (2023). Finite element method (FEM) modeling of laser-tissue interaction during hair removal. Applied Sciences, 13, 8553. https://doi.org/10.3390/app13148553

9. Stokelj, E., Tomše, P., Tomanič, T., Dhawan, V., Eidelberg, D., Trošt, M., & Simončič, U. (2023). Effect of the identification group size and image resolution on the diagnostic performance of metabolic Alzheimer's disease-related pattern. EJNMMI Research, 13, 1–19. https://doi.org/10.1186/s13550-023-01001-5

10. Olatunji, E., Jeraj, R., Studen, A., et al. (2023). Challenges and opportunities for implementing hypofractionated radiotherapy in Africa: Lessons from the HypoAfrica clinical trial. ecancermedicalscience, 17, 1508. https://doi.org/10.3332/ecancer.2023.1508

11. Klaneček, Ž., Studen, A., Hertl, K., Jarm, K., Krajc, M., Vrhovec, M., Jeraj, R., et al. (2023). Uncertainty estimation for deep learning-based pectoral muscle segmentation via Monte Carlo dropout. Physics in Medicine & Biology, 68, 115007. https://doi.org/10.1088/1361-6560/acd221

12. Fortuna, M., Blanchard, P., Čufar, A., Vallar, M., Weisen, H., Žohar, A., Snoj, L., et al. (2023). Evaluation of neutron dose rates at the TCV tokamak facility. Fusion Engineering and Design, 191, 113562. https://doi.org/10.1016/j.fusengdes.2023.113562

13. Goričanec, T., Kos, B., Ambrožič, K., Trkov, A., Snoj, L., & Kromar, M. (2023). Determination of neutron flux redistribution factors for a typical pressurized water reactor ex-core measurements using Monte Carlo technique. Frontiers in Energy Research, 11, 1137867. https://doi.org/10.3389/fenrg.2023.1137867

14. Kotnik, D., Basavaraj, A. K., Snoj, L., & Lengar, I. (2023). Design optimization of the closed-water activation loop at the JSI irradiation facility. Fusion Engineering and Design, 193, 113632. https://doi.org/10.1016/j.fusengdes.2023.113632

Figure 6: CAD rendering of the modular polarization-sensitive hyperspectral microscope design.

Awards and Appointments

1. Anže Pungerčič: Award for Best Poster, Portorož, International Conference "32nd International Conference Nuclear Energy for New Europe – NENE 2023," September 2023, with the title "Experimental and Computational Validation of Novel Depletion Algorithm in the RAPID Code System using JSI TRIGA reactor," co-authored with Alireza Haghighat and Luka Snoj.

2. Tanja Goričanec: Award for Best Young Authors, Portorož, International Conference "32nd International Conference Nuclear Energy for New Europe – NENE 2023," September 2023, for the paper titled "Intermediate Range Detectors for Control Rod Worth Measurements with Rod Insertion Method," co-authored with Luka Snoj and Marjan Kromar.

Organization of conferences, congresses and meetings

1. Experimental Educational Course "Experimental Reactor and Radiation Physics," experimental exercises as part of a course for students from UK Research and Innovation, Centres for Doctoral Training (UKRI CDT), United Kingdom, conducted by the Reactor Physics Department and Reactor Infrastructure Centre (RIC) at the Reactor Centre and TRIGA Reactor, Jožef Stefan Institute (IJS), 19. 6. – 22. 6. 2023
2. Course "Pedagogical Activities on Nuclear Instrumentation, In-pile Experiments in the JSI-TRIGA Reactor, Hands-on Activities, Seminars, Visits of Installations and Exhibitions within the Framework of the MOBIL-APP Project" for students of Aix-Marseille University, Marseille, France, conducted by the Reactor Physics Department and Reactor Infrastructure Centre (RIC) at the Reactor Centre and TRIGA Reactor, Jožef Stefan Institute (IJS), 26. 6. – 6. 7. 2023

INTERNATIONAL PROJECTS

1. Irradiation Services for the Rolls-Royce Civil Nuclear SAS Company
   Dr. Vladimir Radulović
   Rolls-Royce Civil Nuclear Sas
2. E-SiCure2 - Enhancing Security at Borders and Ports
   Prof. Luka Snoj
   Nato - North Atlantic Treaty Organisation
3. IAEA RC 24324 - Spent Fuel Characterization Uncertainties Due to Variations in Fuel Characteristics and Irradiation History; CRP T13018: Spent Fuel Characterization
   Asst. Prof. Marjan Kromar
   IAEA - International Atomic Energy Agency
4. H2020 - EURAD; European Joint Programme on Radioactive Waste Management
   Dr. Vladimir Radulović
   European Commission
5. H2020 - SANDA; Supplying Accurate Nuclear Data for Energy and Non-Energy Applications
   Prof. Ivan Aleksander Kodeli
   European Commission
6. H2020 - ARIEL; Accelerator and Research Reactor Infrastructures for Education and Learning
   Prof. Ivan Aleksander Kodeli
   European Commission
7. H2020 - TOURR; Towards Optimized Use of Research Reactors in Europe
   Prof. Luka Snoj
   European Commission
8. Thermal Scattering Law from First Principles
   Dr. Aljaž Čufar
   Slovenian Research Agency
9. Thermal Scattering Law Analysis
   Prof. Andrej Trkov
   Slovenian Research Agency
10. Measurements and Simulations to support the Calibration of the Reactor Anti-Neutrino Detectors from the Chandler Series for Determination of the Isotopic Composition of a Reactor Core
    Dr. Klemen Ambrožič
    Slovenian Research Agency
11. Three-Dimensional Fuel Burnup Experimental Benchmark for Validation and Development of the bRAPID Nautronics and Burnup Code using the JSI TRIGA Mark-II Reactor
    Prof. Luka Snoj
    Slovenian Research Agency
12. Neutron Transport in Fusion and Fission Reactors by Coupling of Deterministic and Monte Carlo Methods
    Prof. Igor Lengar
    Slovenian Research Agency
13. Structure Optimization of SiC Based Pixel Radiation Detectors for Nuclear Monitoring Applicatios
    Dr. Aljaž Čufar
    Slovenian Research Agency
14. HE - EUROfusion; WP08: DES-1,2_HE-FU
    Dr. Aljaž Čufar
    European Commission
15. HE - EUROfusion; WP19: SAE-1_HE-FU
    Domen Kotnik
    European Commission

16. HE - EUROfusion; WP10: BB_HE-FU
    Dr. Gašper Žerovnik
    European Commission
17. HE - EUROfusion; WP06: PrIO-5_HE-FU; WPPrio-ITERneutronics&Safety
    Prof. Igor Lengar
    European Commission
18. HE - EUROfusion; WP04: AC- TSVV-4,7_HE-FU
    Dr. Jernej Kovačič
    European Commission
19. HE - EUROfusion; WP25: PMU_HE-FU, RU-Mgmt-1_HE-FU
    Prof. Luka Snoj
    European Commission
20. HE - EUROfusion; WP24: TRED_HE-FU, EDU_HE-FU
    Prof. Luka Snoj
    European Commission
21. HE - EUROfusion; WP20: ENS_HE-FU
    Dr. Aljaž Čufar
    European Commission
22. HE - EURO-LABS; EUROpean Laboratories for Accelerator Based Science
    Prof. Luka Snoj
    European Commission
23. HE - DETMED; Novel Detector Concept for Medical Gamma Probe
    Dr. Klemen Ambrožič
    European Commission
24. Activation Measurements for Dosimetry Data Validation Using Neutron Spectrum Filters
    Dr. Vladimir Radulović
    IAEA - International Atomic Energy Agency
25. Training Costs for IAEA"s Fellow Mr. Jeffrey D. Tare, Phillipines, (FS-PHI0016-2302462), 18 September 2023 - 10 November 2023
    Prof. Luka Snoj
    IAEA - International Atomic Energy Agency

RESEARCH PROGRAMMES

1. Medical physics
   Prof. Robert Jeraj
2. Reactor Physics
   Prof. Luka Snoj
3. Fusion technologies
   Prof. Igor Lengar

R&D GRANTS AND CONTRACTS

1. Unlocking the Selective Catalytic Conversion Processes of CO2 to Ethanol – UliSess
   Prof. Luka Snoj
2. Sensitivity of nuclear reactor physical parameters to thermal nuclear data
   Prof. Andrej Trkov
3. New inelastic scattering nuclear reactions for epithermal neutron dosimetry
   Dr. Gašper Žerovnik
4. Nuclear radiation catalyzed chemistry
   Dr. Vladimir Radulović
5. Water activation in nuclear reactors
   Dr. Aljaž Čufar

6. Stability of nuclear reactors in load follow mode of operation
Prof. Luka Snoj
7. Efficiency of the use of material resources in small modular reactors
Prof. Andrej Trkov
8. Machine learning-based optimization of fusion reactor neutronics performance
Dr. Aljaž Čufar
9. Order models for optical microscopy of biological tissues
Dr. Jošt Stergar
10. Independent supervision throughout the preparation and execution of the first spent fuel transfer campaign to dry storage
Dr. Dušan Čalič
Elektroinštitut Milan Vidmar
11. Fusion technologies
Prof. Igor Lengar
Slovenian Research Agency
12. Irradiations on the TRIGA Reactor
Prof. Luka Snoj
13. Irradiations of FT-TIMS Capsule on the TRIGA Reactor for Years 2020-2023
Prof. Luka Snoj
CEA-Commissariat a l' Energie Atomique et aux
14. Experimental Testing of the MONACO Acquisition System at the JSI TRIGA Reactor
Dr. Vladimir Radulović
CEA Saclay
15. Testing of SiC Neutron Detectors at JSI TRIGA Reactor
Dr. Vladimir Radulović
CEA Saclay
16. Development of Electronic Systems for Ex-Core Nuclear Instrumentation
Dr. Vladimir Radulović
CEA Saclay
17. Summer School on Experimental Nuclear Engineering for Students of King Fahd University of Petroleum & Minerals, Ljubljana, Slovenia, From 03 July 2023 to 14 July 202
Dr. Vladimir Radulović
King Fahd University Of Petroleum & Minerals
18. Pedagogical Activities on Nuclear Instrumentation for Aix-Marseille University
Dr. Vladimir Radulović
Aix Marseille Université
19. Implementation of the Course „Experimental Reactor and Radiation Physics" for UK Centres for Doctoral Training, From 19 June 2023 to 22 June 2023
Prof. Luka Snoj
Imperial College London

NEW CONTRACTS

1. L2-2612 co-financing of L-project: Stability of nuclear reactors in load follow mode of operation
Prof. Luka Snoj
Gen Energija, d. o. o.
2. Reload Operational Core Analysis, Post Refuelling Nuclear Design Check Tests, PIS and KFSS Cycle Specific Data for Future Fuel Cycles (Cycle 32)
Asst. Prof. Marjan Kromar
Krško Nuclear Power Plant
3. Reload Operational Core Analysis, Post Refuelling Nuclear Design Check Tests, PIS and KFSS Cycle Specific Data for Future Fuel Cycles (Cycle 33)
Asst. Prof. Marjan Kromar
Krško Nuclear Power Plant
4. Support for reviews and calculations in the SFDS project for 2022 and 2023
Prof. Luka Snoj
Krško Nuclear Power Plant
5. Reload Operational Core Analysis, Post Refuelling Nuclear Design Check Tests, PIS and KFSS Cycle Specific Data for Future Fuel Cycles (Cycle 34)
Asst. Prof. Marjan Kromar
Krško Nuclear Power Plant
6. Co-financing of L2-50051 project (Efficiency of the use of material resources in small modular reactors)
Prof. Andrej Trkov
Gen Energija, d. o. o.
7. Reload Operational Core Analysis, Post Refuelling Nuclear Design Check Tests, PIS and KFSS Cycle Specific Data for Future Fuel Cycles (Forced Outage 2023)
Asst. Prof. Marjan Kromar
Krško Nuclear Power Plant

VISITORS FROM ABROAD

1. Caleb Barnes, Virginia Tech University, USA, 23. 9. – 23. 12. 2023
2. Dr Christophe Domergue, Hervé Philibert, CEA, Cadarache, France, 5. 6. – 9. 6. 2023
3. Dr Tim Valentine, Dr Andy Worrall, Oak Ridge National Laboratory, Oak Ridge, TN, in Dr Sean Tyson, DOE, USA, 8. 9. 2023
4. Eleni T. Mowery, MIT, Springfield, USA, 9. 6. – 28. 8. 2023
5. Jeffrey D. Tare, IAEA - International Atomic Energy Agency, Manila, Philippines, 18. 9. – 10. 11. 2023
6. Muhammad Zaki Abbas Awan, Politecnico di Milano, Milano, Italy, 1. 7. 2023 – 30. 4. 2024
7. Prof. Alireza Haghighat, Director, Nuclear Engineering, Virginia Tech, Virginia, USA, 24. 5. – 27. 5. 2023
8. Prof. Andreas Solders, Uppsala University, Uppsala, Sweden, 3. 10. 2023
9. Prof. Dr Piero Ravetto, Politecnico di Torino, Dipartimento Energia, NEMO Group, Turin, Italy, 22. – 27. 10. 2023

STAFF

Researchers
1. Dr. Klemen Ambrožič
2. Dr. Dušan Čalič
3. Dr. Aljaž Čufar
4. Prof. Tomaž Gyergyek*
5. Prof. Robert Jeraj
6. Prof. Ivan Aleksander Kodeli
7. Dr. Bor Kos
8. Asst. Prof. Marjan Kromar
9. Prof. Igor Lengar
10. Prof. Matija Milanič*
11. Dr. Vladimir Radulović
12. Asst. Prof. Urban Simončič*
13. **Prof. Luka Snoj, Head**
14. Prof. Andrej Trkov
15. Dr. Gašper Žerovnik
Postdoctoral associates
16. Dr. Tanja Goričanec
17. Dr. Jošt Stergar
18. *Dr. Andrej Žohar, left 01.06.23*

Postgraduates
19. Domen Govekar, B. Sc.
20. Ylenia Kogovšek Žiber, B. Sc.
21. Domen Kotnik, B. Sc.
22. Jan Malec, B. Sc.
23. Anže Mihelčič, B. Sc.
24. Julijan Peric, B. Sc.
25. Anže Pungerčič, B. Sc.
26. Ingrid Švajger, B. Sc.
Technical officers
27. Benjamin Barbarič, B. Sc.
28. Aljaž Robek, B. Sc.
29. Saša Škof, B. Sc.
Technical and administrative staff
30. Ula Groznik, B. Sc.
31. Sebastian Pleško, B. Sc.
32. *Slavko Slavič, B. Sc., retired 01.09.23*
33. Bojan Žefran

Note:
* part-time JSI member

DEPARTMENT OF EXPERIMENTAL PARTICLE PHYSICS F-9

Departmental research is devoted to experimental studies of elementary particles, to reveal the ultimate building blocks of matter and the nature of the interactions between them. Experiments are carried out within large collaborative programmes at international centres for particle physics at CERN near Geneva and at KEK in Tsukuba. The department is also engaged in developing and applying the technologically advanced particle detectors required for such measurements. Astroparticle physics is an emerging field applying experimental techniques of particle physics to solve astrophysical problems. Slovenian researchers are participating in the measurements of ultra-high-energy cosmic rays at the Pierre Auger Observatory spread over a surface of 3000 km² near Malargue in Argentina.

Head:
Prof. Borut Paul Kerševan

With the aim of revealing the ultimate secrets of nature in the world of elementary particles, accelerators with higher and higher energies are needed. Their cost, both in terms of money and human resources, has grown to the level where they are affordable only as joint international enterprises. Thus, future accelerators will be unique facilities of their kind, an example is the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN) near Geneva. Researchers exploit this facility to perform experiments in presently inaccessible regions of energy, which, though pushed higher and higher, still remain minute compared to that of the vast blast of the Big Bang that led to the creation of the Universe.

Together with colleagues from the Physics Department of the Faculty of Mathematics and Physics and the Faculty of Electrical Engineering of the University of Ljubljana, and from the Faculty of Chemistry and Chemical Technology of the University of Maribor, we are performing measurements at CERN and the Japanese centre KEK in Tsukuba. We are taking part in two experiments, each conducted as an international collaboration:

- ATLAS at the Large Hadron Collider (LHC) at CERN (3000 researchers, 185 institutions from 42 countries),
- Belle II at the asymmetric electron-positron collider (KEK-B) at KEK (1200 researchers, 130 institutions from 27 countries)

In the field of astroparticle physics we are part of the Pierre Auger collaboration (500 researchers, 91 institutions from 18 countries), which uses the giant scale (3000 km²) observatory near Malargue in Argentina for detecting ultra-high-energy cosmic rays. This endeavour is carried out in collaboration with colleagues from the University of Nova Gorica.

A more detailed report on the 2023 activities follows, focused on the contributions of our researchers.

ATLAS experiment at the Large Hadron Collider (LHC) at CERN

After three years of upgrades to the Large Hadron Collider (LHC), as well as its detectors, a new experimental period called Run 3 started at CERN in 2022, and continued in 2023, at a record proton collision energy of 13.6 TeV. Over the entire data-taking period of the last two years, the ATLAS experiment recorded a large amount of exciting proton collisions with an integrated luminosity of 70 fb^{-1}. Combined with the previously recorded data from the Run 2 period (2015–2018), these newly obtained data already allow the most accurate analyses ever in the search for new physics processes beyond the Standard Model. Using state-of-the-art methods in data analysis, such as the use of graph neural networks in machine learning methods, new frontiers were set in the search for pair production of Higgs bosons. In addition, the search for dark matter continued, along with the search for new physics signals, as predicted by the current theories related to extensions of the

- **The data recorded until the end of 2023 already allow the most accurate analyses ever in the search for new physics processes beyond the Standard Model. Very precise measurements of the Standard Model's predictions took place and were published in Nature Physics.**
- **In parallel to precise measurements of the Standard Model, the search for dark matter continues, along with the searches for new physics signals, predicted by the current theories related to extensions of the Standard Model.**
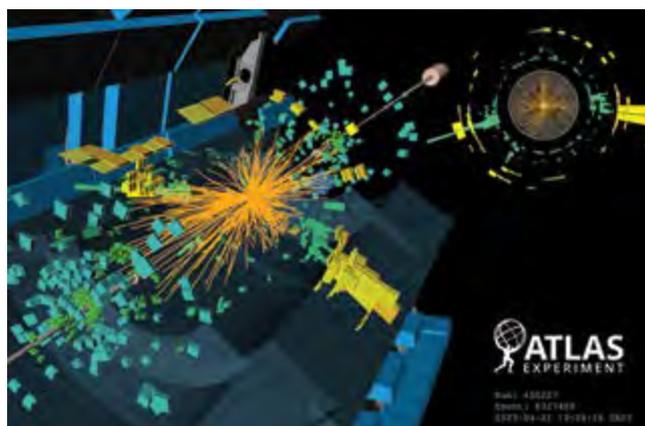
Figure 1: Display of a collision event, recorded by ATLAS on 21 April 2023 when stable beams of protons at an energy of 6.8 TeV per beam were delivered to ATLAS by the LHC. The image shows a cut-out view of the ATLAS detector in the proton-proton collision event; starting from the centre, the view shows the tracks of charged particles as they are reconstructed in the Inner Detector (orange lines), as well as energy deposits in the electromagnetic (squares in different hues of green) and hadronic (yellow boxes) calorimeters.

Standard Model. In parallel, very precise measurements of the Standard Model's predictions took place, along with the most precise measurements of the properties of the Higgs boson, published in Nature on the tenth anniversary of the discovery of the Higgs boson, and also in the journal Nature Physics [1]. Obviously, more data will be needed to make new discoveries and increase the precision of the measurements that the ATLAS experiment will record in the coming years of Run 3 – so the years ahead will also be full of challenges and expectation of ground-breaking events. In 2023 the ATLAS Collaboration published more than 100 scientific papers in the most distinguished scientific journals, bringing the total number of published papers by the ATLAS collaboration to 1260, with more than 100 further papers in preparation.

The ATLAS Ljubljana group plays the leading role in designing, building and operating several beam and radiation monitoring systems: ATLAS Beam Condition Monitor (BCM), Beam Loss Monitor (BLM) and Radiation Monitor (RADMON). BCM was built to monitor the conditions of the LHC beams and issue warnings at unexpected and potentially dangerous situations. In the first part of LHC's operation it served as the main luminosity monitor of ATLAS. BLM on the other hand is solely a safety system, protecting the ATLAS Inner Detector from potential damage due to imperfections or deviations of LHC beams. BLM operates independently in parallel with BCM. It fired a few times and successfully extracted LHC beams, preventing potential damage to the detectors. RADMON records the doses received by different parts of the ATLAS Inner Detector. In 2023 readout electronics and control software of BCM and BLM were upgraded and integrated in the ATLAS data acquisition system. They operated smoothly during data taking in 2023.

Atlas detector upgrade

In 2022 the LHC started a new data-taking period called Run 3, which will continue until the end of 2025. After Run 3 a major upgrade of LHC to the High Luminosity LHC (HL-LHC) will start. The beginning of the HL-LHC operation is scheduled for 2029. To adapt to HL-LHC conditions, a major upgrade of the ATLAS detector will be made during the shutdown period from 2025 to 2029. A large part of the ATLAS collaboration, including the group from the F9 department, is intensively working on the development and building of detector systems for the upgrade.

Inner Tracker ITk

The ATLAS collaboration continued assembling components for the upgrade of the Inner Tracker (ITk) in 2023. We will use microstrip silicon detectors as sensors. Intensive evaluation of a serial production of components is underway. Our group participates in the sensor quality assurance process. So far, approximately 60% of silicon sensors have been delivered. The total area covered with silicon sensors will be approximately 165 m², the production is expected to be completed in the second half of 2025 while the evaluation should be completed in 2026. Test structures manufactured together with strip sensors on the same silicon wafers are regularly irradiated at the Reactor Centre in Podgorica. The response of the irradiated test structures to electrons from a ^{90}Sr source is measured with the ALIBAVA multi-channel readout system. Regular measurements show the expected signal degradation. The signal after irradiation with $1.6 \cdot 10^{15}$ n_{eq}cm^{-2} decreases to about a third, which corresponds to about 7500 electrons. In 2023 we tested about one third of the total planned production.

In addition to the sensor development we took part in the development of special multilayer flexible circuits, working together with company Elgoline d.o.o. These radiation-hardened circuits connect sensors with peripheral read-out electronics in the two endcaps of ITk. The preproduction (5% of the whole production) was completed in 2021. After evaluating the quality of the preproduction, the main production started in the middle of 2022 and continued in 2023. Together with Oxford University, a robot for testing these circuits was developed. Elgoline from Cerknica produced already about 70% of more than 1000 large flexible circuits and they were tested on the robot. Each circuit is tested three times in different stages of the assembly process.

For the upgrade of the Inner Tracker more than 20,000 microstrip silicon sensors will be produced by the end of 2025. Silicon sensors will cover an area of approximately 165 m².
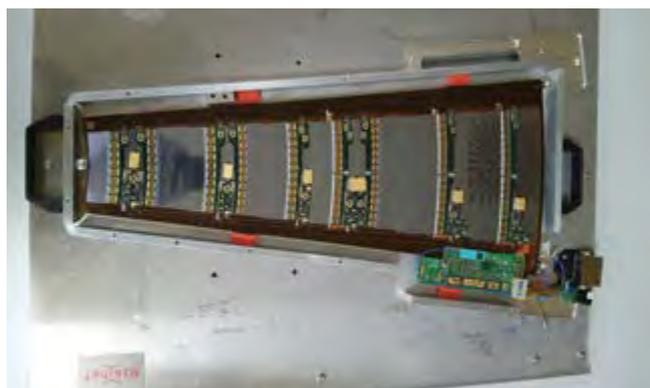

Figure 2: Fully assembled "petal" – a part of the ITk. Strip sensor modules are connected to flexible circuits produced by ELGOLINE Ltd., Podskrajnik, Slovenia. Such assemblies are building blocks for the ATLAS Inner Tracker strip detector end-caps.

The JSI group participates in the production of silicon sensors, based on Low Gain Avalanche Detector (LGAD) technology, which is expected to last until the end of 2025.

High-Granularity Timing Detector

High-Granularity Timing Detector for the ATLAS experiment has entered into the production phase. The JSI group participates in the production of silicon sensors based on the Low-Gain Avalanche Detector

(LGAD) technology which is expected to last until the end of 2025. We have importantly contributed to the final design of the sensors, including the doping levels and co-implantation of carbon to improve the sensor radiation hardness, as well as to the design of the test structures for production quality control. We set up two test stations for the quality control of sensors throughout the production. The JSI will be the main site to monitor the sensor radiation hardness. Test structures will be irradiated in the JSI TRIGA reactor and tested with the new transient current technique that we introduced for a high sample throughput and calibrated against the standard methods for charge collection characterization. We also continued with the generic research and development activities in the field of radiation hard timing detectors, where we investigated the process for improving radiation hardness with a partial thermal activation of the acceptor dopants in the sensor, as well as performed the measurements of timing properties of a particle test beam.

Figure 3: Left: photo of a silicon wafer with 52 detectors for HGTD. The size of each detector is 2 × 2 cm2 and it consists of 225 LGAD sensors with dimensions of 1.3 × 1.3 mm2. HGTD will be built of 16064 detectors. Right: dependence of the LGAD gain layer depletion voltage on the neutron fluence. Such measurements are part of radiation resistance control of the detectors and will be carried out at the IJS.

BCM'

The F9 department's team has played the leading role in developing an advanced system called BCM', which utilizes pCVD diamond sensors. This system will replace the current beam abort and luminosity monitor. New versions of dedicated rad-hard ASIC readout chip Calypso were manufactured and tested in 2023. The chip's functionality and radiation hardness were verified through several irradiation and test beam experiments in 2023. The performance of the diamond sensor readout with a new chip was successfully demonstrated. The system comprises several components that have been designed, manufactured, and functionally verified. BCM' is located near the interaction point and serves as a subsystem of the pixel detector. To comply with strict engineering and radiation hardness constraints, the support structure, electrical and data connections must be harmonized with those of the pixel detector system.

The F9 department's team has played the leading role in developing an advanced system called BCM', which utilizes pCVD diamond sensors and dedicated rad-hard ASIC readout chip Calypso.

Radiation monitor

An upgraded system for online measurements of integrated doses (RadMon) will be installed in the ITk to monitor the high-radiation environment arising from the proton-proton interactions near the interaction point. In 2023 our group evaluated prototype readout electronics and worked on the development of the readout software and preparations for integrating the system into the ATLAS experiment.

Belle and Belle II at the asymmetric electron-positron collider SuperKEKB at KEK

The department colleagues continued research on the Belle and Belle II experiments at the KEKB electron-positron collider or SuperKEKB in Tsukuba, Japan. The primary motivation of both experiments, which fall within the experimental efforts at the so-called precision frontier, is the search for processes and particles not accounted for in the Standard Model (SM) of interactions, collectively referred to as New Physics (NP). Among other effects, NP processes must be responsible for the observed prevalence of matter over antimatter in the universe. The Standard Model is extremely successful and experimentally confirmed in describing processes at the level of fundamental particles at currently accessible energies and precision; to search for deviations from the Standard Model, experiments at the precision frontier include highly accurate measurements and compare results with similarly precise theoretical predictions within the SM framework.

The Belle detector completed data acquisition in 2010, yet numerous analyses of the captured data are still ongoing. Among the results published in 2023, there are several measurements of the quark mixing matrix (the so-called Cabibbo-Kobayashi-Maskawa matrix) to resolve discrepancies between the values of matrix elements |Vub| and |Vcb| measured with inclusive and exclusive methods. A significant emphasis was also placed on searching for anomalies in B meson decays involving leptons in the final state. Searches for decays involving a pair of leptons of different flavours (tau lepton and light lepton) in association with a K meson, were also finalized and published.

- **Among the results published in 2023, there are several measurements of the quark mixing matrix (the so-called Cabibbo-Kobayashi-Maskawa matrix) resolving discrepancies between the values of matrix elements |Vub| and |Vcb| obtained with inclusive and exclusive methods. An emphasis was also placed on searching for anomalies in B meson decays involving leptons in the final state.**
- **The measurement that undoubtedly attracted the most attention from the scientific community in 2023 was that of a very rare decay of the B meson into a charged kaon and a pair of neutrinos. This decay channel of the B meson is highly sensitive to potential contributions from new physics, making any deviation from the SM prediction a real sensation.**

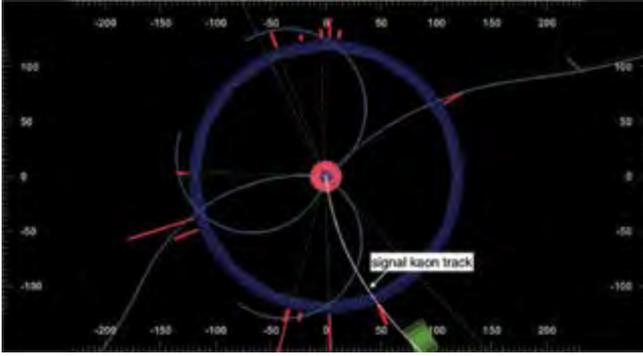Figure 4: A particularly rare event, detected by the Belle II spectrometer, in which one of the B mesons decays into a charged kaon and two neutrinos, while the other B meson decays through one of a much more common modes.
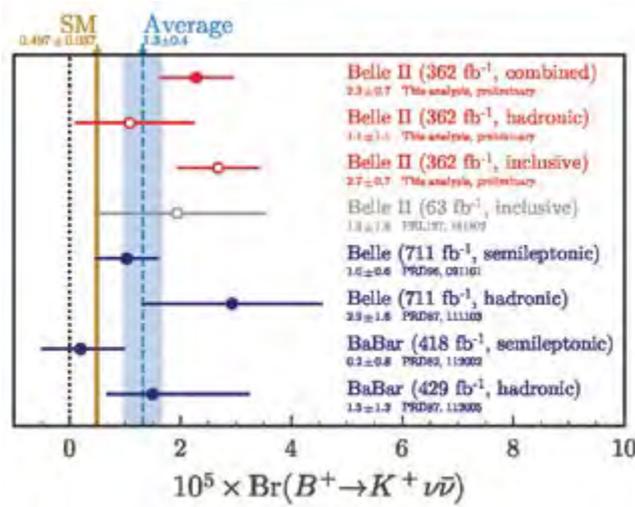

Figure 5: Probability for the decay of a B meson into a charged kaon and two neutrinos as measured in our study (marked in red) and a comparison with previous measurements and with the prediction of the Standard Model.

The Belle II experiment has so far collected data corresponding to a luminosity of 428 fb^{-1}. Among the significant results of the Belle II research group in 2023 is a most precise measurement of the tau lepton mass [5], which is one of the critical parameters of the Standard Model. In 2023 several research topics of the Belle II experiment were also dedicated to the searches for candidates for dark matter and possible carriers of interactions between dark matter particles and ordinary matter. Among other things, evidence was sought for states decaying into pairs of tau leptons [6]. The measurement result also included an upper limit on the coupling of such a hypothetical state to the ordinary matter as a function of its mass.

However, the measurement that undoubtedly attracted the most attention from the scientific community in 2023 was the measurement of the very rare decay of the B meson into a charged kaon and a pair of neutrinos. This decay channel of the B meson is highly sensitive to potential contributions from new physics, making any deviation from the SM prediction a real sensation. The measurement is very challenging due to the rarity of the process and because both neutrinos leave the detector without being detected, as clearly seen in the event corresponding to the searched-for process (Figure 4). The measurement result is surprising. Not only have we succeeded in measuring the probability of this process with statistical significance exceeding 3 standard deviations, but the measured probability is significantly higher than predicted by the SM (Figure 5). In 2024, we plan to verify the obtained result on an independent sample of data collected in the Belle experiment and in the decay channels of the B meson, where its excited state K* appears instead of the charged kaon K, which decays into a kaon and a pion.

Pierre Auger Observatory

The Pierre Auger Observatory is an international cosmic ray observatory in Argentina designed to detect ultra-high-energy cosmic rays: sub-atomic particles traveling nearly at the speed of light and each with energies beyond 10^{18} eV. In Earth's atmosphere such particles interact with air nuclei and produce various other particles. Secondary particles forming the so-called "air shower" can be detected and measured in order to clarify the origin of the highest-energy primary particles and their properties like energy, arrival direction and the particle type (photons, protons, atomic nuclei). But since these high-energy particles have an estimated arrival rate of just 1 per km^2 per century, the Auger Observatory has created a detection area of 3000 km^2 to be able to record a significant number of these events. It is located in the western Mendoza Province, Argentina, near the Andes.

The Pierre Auger Observatory combines two complementary techniques to measure air showers. On their way through the atmosphere the secondary particles stimulate nitrogen molecules in the air to emit fluorescent light. This light is measured with large telescopes. In addition, secondary particles reaching ground level are registered by an array of particle detectors. These are water Cherenkov detectors, measuring the light emitted by relativistic particles passing through a water tank.

The Pierre Auger Collaboration showed that the energy spectrum of cosmic rays exhibits a sharp drop of around 10^{20} eV. This drop is compatible with the Greisen-Zatsepin-Kuzmin (GZK) cut-off caused by the universe becoming opaque due to resonant collisions between ultra-high-energy protons and the photons of the cosmic microwave 2.7 K background radiation. Past measurements by the Pierre Auger Collaboration had already cast some doubt on this explanation, and this year's results further established that the GZK cut-off cannot be the entire story and even the extent of its contribution to the cut-off remains unclear.

One of the key goals of the observatory is to understand the origin of cosmic rays with energies of above $8 \cdot 10^{18}$ eV. To this end, the observatory has been studying the dipolar anisotropy of the arrival directions of cosmic rays. The anisotropy is a measure of how likely it is for cosmic rays to arrive from a certain direction. The observatory has found evidence for a dipolar anisotropy at the 99.8% confidence level, suggesting that cosmic rays may be coming

Commissioning the AERA system (Auger Engineering Radio Array) is also under way. AERA is a new antenna system, measuring short radio pulses emitted by cosmic-ray air showers of the highest energies. It consists of an array of antennas sensitive to frequencies in a range of 30–80 MHz with signal processing and electronics developed specifically for this purpose.

from a preferred direction. Additionally, the observatory has also detected a correlation between the arrival directions of ultra-high energy cosmic rays and nearby galaxies.

Collisions of ultra-high-energy cosmic rays with atmospheric molecules provide hadronic interactions at an energy that exceeds the LHC centre-of mass energy by one to two orders of magnitude. Although progress was made in incorporating LHC results, some mysteries were not solved. The number of muons in Monte Carlo simulations is significantly smaller than the number measured in experimental data. Also, the depth at which most muons that reach the Earth's surface are produced cannot be described by a Monte Carlo simulation for any reasonable composition mix of cosmic rays.

Figure 6: Fluorescence detector of the Pierre Auger Observatory

The Pierre Auger observatory is currently upgrading its detection capabilities. The key element of the upgrade is the installation of a plastic scintillator on top of each existing surface detector station. It will provide a complementary measurement of the showers, allowing the reconstruction of muons and electromagnetic particles. The surface scintillator detector stations (SSDs) are being deployed over the full 3000 km^2 area of the overall surface detector (SD). To enhance the capabilities of the surface detector, especially for composition measurements, it is being equipped with upgraded electronics that have a larger sampling rate and a larger dynamic range.

Commissioning the AERA system (Auger Engineering Radio Array) is also under way. AERA is a new antenna system measuring short radio pulses emitted by cosmic-ray air showers of the highest energies. It consists of an array of antennas sensitive to frequencies in a range of 30–80 MHz with signal processing and electronics developed specifically for this purpose.

The enhanced Pierre Auger Observatory will enter a new era of data analysis by exploiting the multi-hybrid measurements it will provide. Different analyses will harness the capabilities of both the existing and newly integrated detector components. A simultaneous analysis of the signals from different detectors will make it possible in the near future to obtain an estimate of a primary mass on an event-by-event basis by separating the muon and electromagnetic components. Machine learning (ML) techniques have already demonstrated their potential by extracting valuable information by combining the Phase I data set with the AugerPrime data. Statistics for mass composition studies will more than double by the end of Phase II. In addition, the promising inclusion of mass-composition estimators on an event-by-event basis with AugerPrime and the improved mass estimators with Phase I data will allow a better insight into the arrival direction results in the near future. The Observatory will also allow an expansion in the scope of its investigations in the field of cosmo-geophysics in the coming years. With the Auger Open Data Portal it will provide a good overview of the detectors and achievements of the Collaboration, as well as a direct invitation to the general public to use the released data.

Distributed computing

In 2023 we doubled the capacity of shared basic data storage Ceph, which increased the space available for services and user data to 9 PB. With the SiGNET Tier-2 computing centre, including over 3072 CPU cores, we continued our collaboration within international projects and organisations WLCG, EGI, NDGF-T1. Furthermore, we worked together with other computing centres, like the Institute's own NSC and centres Arnes in Ljubljana and Trdina in Novo mesto. As part of European initiative EuroHPC and Slovenian national supercomputing network SLING, we participated in the maintenance of the Vega supercomputer at IZUM in Maribor. The resources of the SiGNET center are used mainly for data analysis and international experiments ATLAS and Belle II, as well as other department's projects. Some of the resources were also available to other institute members and external collaborators. We also continued our work within the Leonardo project, in setting up and user support of one of the three pre-exascale HPC systems in Cineca, Bologna. We continued to participate in the Leonardo Quantum Computer procurement and integration with HPC, collaborating with Cineca and INFN. Apart from maintenance and administration, the department also collaborates in numerous projects related to the support, maintenance and planning of the computing infrastructure as well as the development, distribution and deployment of the distributed computing infrastructure, for example EuroHPC JU, Nordugrid, EuroCC, InterTwin, EuroHPC Containers Forum and Castiel 2.

Figure 7: New capacities (4.5 PB of space) for data storage of the SiGNET Tier-2 computing centre at the IJS on Jamova Street.

Detector development

Silicon and diamond detectors

Most of the work on silicon detector development in the last two decades was performed in the framework of ATLAS and CERN-RD50 collaborations which were started in 2002. RD50 was formed to develop "Radiation hard semiconductor devices for very high luminosity colliders". The collaboration very successfully ended its mission in 2023. Silicon sensors for the experiments at HL-LHC are currently in the production phase. RD50 played the key role in the development of those sensors including LGAD – a novel detector type with good timing resolution which will significantly improve the performance of HL-LHC experiments and will also be used in various other applications.

To continue the successful model of RD50 and extend it to other detector types, new collaborations dedicated to detector research and development – the so-called DRDs – were formed in 2023. Collaboration DRD3 is devoted to silicon detector development. More than 100 institutions from around the world are members of this collaboration and dr. G. Kramberger from F9 was elected as its first spokesperson.

> **Collaboration DRD3 is devoted to silicon-detector development. More than 100 institutions from around the world are members of this collaboration and dr. G. Kramberger from F9 has been elected as its first leader (spokesperson).**

Upgrading the ATLAS detector for HL-LHC is the core activity of the silicon detector development. This includes development of micro-strip silicon detectors and LGADs, as already described above.

Unexpected effects of irradiation with protons, accelerated to very high energy, on the strip detectors for ITk were intensively investigated in 2023 and are now mostly understood. Understanding the operation of detectors after proton irradiation is very important as high-energy protons contribute significantly to the radiation damage suffered by the detectors during data taking in the ATLAS experiment.

We continued work on the development of depleted CMOS detectors. This is a suitable technology for monolithic tracking detectors for high-radiation environments as well as applications in which the amount of material in tracking volume must be minimized. A depleted CMOS detector also ensures fast charge collection enabling good time resolution, which is becoming increasingly important in all types of applications. In 2023 we finished the measurements of timing properties and active pixels in an RD50-MPW2 chip and published a paper. Work was also done on more recent versions, RD50-MPW3 and MPW4 chips, where we measured detector properties before and after irradiation with neutrons.

In 2023 we continued to develop the system for measuring transients (the transient current technique – TCT) using the two-photon absorption effect, TPA-TCT. By exploring this effect we can release charge carriers in silicon, in a limited volume, in the detector and in this way measure the spatial dependence of the detector's response.

Studies of the effect of exposure to high temperatures on the performance of highly irradiated LGADs were completed and published. It was found that annealing irradiated sensors at approx. 350°C greatly improves their performance. Of course, the exposure of a detector system to such a high temperature causes a series of practical problems that still need to be solved.

Development of diamond detectors in 2023 was focused on the BCM' system. We carried out several measurements using diamond detectors with electrons from a 90Sr radioactive source as well as during the test beam. We used a diamond sensor with an area of 1×1 cm and a thickness of 500 µm. Several reading electrodes were made on the diamond surface which were connected to the Calypso reading chip, purpose-built for BCM'.

Photon detectors

Research of the photon sensors for the new generation of Cherenkov ring detectors (RICH) was continued in 2023. For the upgrade of the Belle II detector and the upgrade of the Cherenkov ring detector of the LHCb spectrometer, we are developing a single-photon detector that will be very fast, will have fine spatial granulation, will be sensitive to the light of longer wavelengths and will be able to withstand a radiation load, mainly from neutrons. At our department, we study the characteristics of both semiconductor candidates – silicon photomultiplier tubes and large area microchannel plate photomultipliers, LAPPD (Large Area Picosecond Photon Detector) – where we focus on measuring the local and temporal responses, which are important parameters for the selection of a suitable sensor for a Cherenkov ring detector. Due to radiation damage, silicon photomultipliers will not be suitable for single photon measurements at room temperature, so we determined the temperature at which the sensors still work for different radiation loads.

Detectors for medical applications

Experimental particle physics strives to develop and master the state-of-the-art technology. Innovations from our laboratories can be usefully transferred to other areas. Medical physics is a successful example of how we can introduce advances in photodetectors and reading electronics to improve the detector technology in nuclear medicine and imaging methods in biomedical optics.

We designed a positron emission tomography (PET) device with flat-panel detectors, which, based on ultra-fast detection, enables PET imaging with a significantly smaller amount of detection crystals, thus enabling a lower cost and greater flexibility (Figure 8). Through precise simulations, we have shown that such an approach achieves image quality comparable to the best current commercial devices, while also enabling more affordable simultaneous imaging of the whole body.

We are leading the PetVision international consortium, financed through the 2022 EIC Pathfinder Open Call of the European Innovation Council, with the aim to build and clinically test a flat-panel PET detector. The consortium consists of researchers from the Jožef Stefan Institute, the University of Barcelona, the Institute of Molecular Imaging Instrumentation in Valencia, Fondazione Bruno Kesler from Trento, Klinikum Rechst der Isar of the Technical University of Munich, the Yale University from New Haven, USA, and the company Oncovision from Valencia [https://www.petvision.org/].

Based on our expertise in using Cherenkov light in experimental particle physics we are developing another novel detection method for PET. By replacing traditionally used scintillators with radiators of Cherenkov light, PET detectors can be faster and more affordable. Within the CherPET project, funded with the ERC Proof of Concept Lump Sum Grant 2022-2 of the European Research Council, we are designing the first larger scale PET prototype using pure Cherenkov radiators.

Figure 8: Development of detectors for flat-panel positron emission tomography enables improvements in achievable image quality, in this case of the human brain.

We are leading the PetVision international consortium, financed through the 2022 EIC Pathfinder Open Call of the European Innovation Council, with the aim to build and clinically test a flat-panel PET detector.

Irradiations at the TRIGA reactor

A significant number of irradiations with neutrons, as well as with ionizing radiation of the reactor core when fission is stopped, was made for various institutions from around the world. The JSI reactor is the reference neutron irradiation site for the development of silicon detectors and electronics for LHC and other particle physics experiments.

EURO-LABS

The EURO-LABS project started in September 2022 as a part of the Horizon Europe program. The project budget is 14.5 million euros; 33 institutions from 18 countries are participating. EURO-LABS funds access to the infrastructure for detector research. Department F9 together with the Reactor Infrastructure Centre coordinates this work package. EURO-LABS provides access to the irradiation of detectors at the TRIGA reactor at the JSI. In 2023 more than 20 irradiation programs were carried out, thus contributing to detector development, primarily at European institutions, but also at several other institutions from all around the globe.

ERC projects

1. H2020 - FAIME; Flavour Anomalies with advanced particle Identification Methods
   Prof. Peter Križan
   European Commission
2. HE - CherPET; Cherenkov Light for Total-Body Positron Emission Tomography
   Prof. Peter Križan
   European Commission

Some outstanding publications in the past year

[1] ATLAS Collaboration, Observation of electroweak production of two jets and a Z-boson pair, Nature Phys. 19 (2023) 2, 237–253, DOI: 10.1038/s41567-022-01757-y

[2] ATLAS Collaboration, Observation of the $\gamma\gamma \rightarrow \tau\tau$ Process in Pb+Pb Collisions and Constraints on the τ-Lepton Anomalous Magnetic Moment with the ATLAS Detector, Phys. Rev. Lett. 131 (2023) 15, 151802, DOI: 10.1103/PhysRevLett.131.151802

[3] ATLAS Collaboration, Search for dark photons in rare Z boson decays with the ATLAS detector, Phys. Rev. Lett. 131 (2023) 25, 251801, DOI: 10.1103/PhysRevLett.131.251801

[4] ATLAS Collaboration, Observation of an Excess of Dicharmonium Events in the Four-Muon Final State with the ATLAS Detector, Phys. Rev. Lett. 131 (2023) 15, 151902, DOI: 10.1103/PhysRevLett.13

[5] I. Adachi et al. (Belle II Collaboration), Measurement of the τ-lepton mass with the Belle II experiment, Phys. Rev. D, 2023, 108, 3, 032006

[6] I. Adachi et al. (Belle II Collaboration), Search for a τ+τ− resonance in e+e− → μ+μ−τ⁺τ− events with the Belle II experiment, Phys. Rev. Lett., 2023, 131, 12, 121802

[7] AUGER Collaboration, Search for ultra-high-energy photons from gravitational wave sources with the Pierre Auger Observatory, The Astrophysical Journal. 2023, vol. 952, no. 1, art. no. 91, pp. 1–1

[8] AUGER Collaboration, Limits to gauge coupling in the dark sector set by the non-observation of instanton-induced decay of super-heavy dark matter in the Pierre Auger Observatory data, Physical Review Letters. [Print ed.]. 2023, vol. 130, iss. 6, art. no. 061001, pp. 1–9, illustr.

[9] G. Kramberger et al., Gain dependence on free carrier concentration in LGADs, Nucl. Linstr. and Meth. A 1046 (2023) p167669. DOI10.1016/j.nima.2022.167669

[10] Ž. Klaneček et al., Uncertainty estimation for deep learning-based pectoral muscle segmentation via MonteCarlo dropout, Physics in Medicine & Biology, 2023, 68, 115007, 10 str., DOI: 10.1088/1361-6560/acd221

[11] G. Razdevšek et al., Exploring the potential of a Cherenkov TOF PET scanner: a simulation study, IEEE transactions on radiation and plasma medical sciences, 2023, 7, 1, 52-61, DOI: 10.1109/TRPMS.2022.3202138

Awards and Appointments

1. Bojan Hiti: Jožef Stefan Golden Emblem Prize, Jožef Stefan Institute, Ljubljana, Slovenia, Ph. D. Thesis, 22 March 2023
2. Miha Mali: award for the best poster "Development of the BCM' system for beam abort and luminosity monitoring in ATLAS based on a segmented polycrystalline CVD diamond system and dedicated front-end ASIC", Oxford, Great Britain, 8 September 2023

Organization of Conferences, Congresses and Meetings

1. XRootD in FTS International workshop 2023, Jožef Stefan Institute, Ljubljana, Slovenia, 27–31 March 2023
2. International Event „ATLAS HGTD Collaboration Week", Ljubljana, Slovenia, 11–15 September 2023

INTERNATIONAL PROJECTS

1. ERC H2020 - FAIME; Flavour Anomalies with advanced particle Identification Methods
Prof. Peter Križan
European Commission
2. ERC HE - CherPET; Cherenkov Light for Total-Body Positron Emission Tomography
Prof. Peter Križan
European Commission
3. H2020 - JENNIFER2; Japan and Europe Network for Neutrino and Intensity Frontier Experimental Research 2
Prof. Rok Pestotnik
European Commission
4. H2020 - AIDAinnova; Advancement and Innovation for Detectors at Accelerators
Dr. Gregor Kramberger
European Commission
5. H2020 - HITRIplus; Heavy Ion Therapy Research Integration
Asst. Prof. Andrej Studen
European Commission
6. A Study of Lepton Anomalies
Prof. Peter Križan
Slovenian Research Agency
7. Fast Timing Detectors for Positron Emission Tomography
Prof. Rok Pestotnik
Slovenian Research Agency
8. HE - interTwin; An Interdisciplinary Digital Twin Engine for Science
Prof. Andrej Filipčič
European Commission
9. HE - EURO-LABS; EUROpean Laboratories for Accelerator Based Science
Prof. Marko Mikuž
European Commission
10. HE - SMASH; Machine Learning for Sciences and Humanities
Prof. Borut Paul Kerševan
European Commission
11. HE - PetVision; Next Generation Limited -Angle Time-of-Flight PET Images
Prof. Rok Pestotnik
European Commission
12. DIGITAL EU; EuroCC 2 - National Competence Centres in the Framework of EuroHPC Phase 2
Prof. Andrej Filipčič
European Commission

RESEARCH PROGRAMMES

1. Multimessenger astrophysics
Prof. Marko Zavrtanik
2. Experimental Particle Physics
Prof. Borut Paul Kerševan

R & D GRANTS AND CONTRACTS

1. Application of Machine Learning Methods in the Data Analysis at the Large Hadron Collider (LHC)
Prof. Borut Paul Kerševan
2. Atmospheric remote sensing for Cherenkov Telescope Array and its impact on science from large sky survey observations
Prof. Marko Zavrtanik
3. ITk - Upgrade of the ATLAS Tracker for High-Luminosity LHC
Prof. Marko Mikuž
4. Ring Imaging Cherenkov detectors for the next generation of flavor physics experiments
Prof. Peter Križan
5. Development of the proton CT system based on Low Gain Avalanche Detectors
Dr. Gregor Kramberger
6. Experimental test of lepton universality and improvements of particle identification at the Belle II experiment
Asst. Prof. Luka Šantelj
7. Radiation-hard digital analog silicon photomultipliers for future upgrades of Ring Imaging Cherenkov detectors
Asst. Prof. Rok Dolenec
8. Characterization of charge multiplication and charge collection in semiconductor detectors using advanced Transient Current Technique methods
Dr. Bojan Hiti
9. Collaboration CERN RD-39
Prof. Marko Mikuž
CERN
10. Collaboration CERN RD-50
Prof. Marko Mikuž
CERN
11. Collaboration DELPHI
Prof. Borut Paul Kerševan
CERN

12. Collaboration ATLAS
    Prof. Marko Mikuž
    CERN
13. Collaboration CERN RD-42
    Prof. Marko Mikuž
    CERN
14. Collaborations Belle in Belle II
    Prof. Peter Križan
    KEK - High Energy Accelerator Research
15. Irradiations in TRIGA Nuclear Reactor
    Prof. Vladimir Cindro
16. Research and Development of a Novel PET Scanner Using Flat Panel Geometry
    Asst. Prof. Rok Dolenec
    Massachusetts General Hospital
17. Monte Carlo Simulations of the PET Scanner
    Asst. Prof. Rok Dolenec
    Massachusetts General Hospital
18. Reconstruction of the Simulated List Mode Data of the New Configurations of Novel PET Scanne
    Asst. Prof. Rok Dolenec
    Massachusetts General Hospital
19. Belle II
    Prof. Peter Križan
    Slovenian Research Agency
20. Co-funding of the Project HE - SMASH; Machine Learning for Sciences and Humanities
    Prof. Borut Paul Kerševan
    Ministry of Higher Education, Science and Innovation

NEW CONTRACT

1. QC analysis of the manufacturing quality of flexible PCB production
   Dr. Andrej Gorišek
   Elgoline d. o. o.

VISITORS FROM ABROAD

1. Toru Iijima, KMI, University of Nagoya and KEK, Nagoya, Japan, 20 September 2023
2. dr. Jiri Kroll, Physics of the Czech Academy of Sciences (FZU), Prague, Czech Republic, 2–3 November 2023
3. dr. Jiri Kvasnicka, Physics of the Czech Academy of Sciences (FZU), Prague, Czech Republic, 2–3 November 2023
4. Radek Jirasek, Physics of the Czech Academy of Sciences (FZU), Prague, Czech Republic, 2–3 November 2023
5. dr. Roberto Mulargia, University of Turin, Turin, Italy, 13–27 November 2023

STAFF

Researchers
1. Dr. Karol Mateusz Adamczyk
2. Dr. Jyotirmoi Borah
3. Asst. Prof. Marko Bračko*
4. Prof. Vladimir Cindro
5. Dr. Gaetano De Marino
6. Asst. Prof. Rok Dolenec*
7. Prof. Andrej Filipčič
8. Prof. Boštjan Golob*
9. Dr. Andrej Gorišek
10. **Prof. Borut Paul Kerševan*, Head**
11. Prof. Samo Korpar*
12. Dr. Gregor Kramberger
13. Prof. Peter Križan*
14. Dr. Boštjan Maček
15. Asst. Prof. Igor Mandić
16. Prof. Marko Mikuž*
17. Asst. Prof. Miha Muškinja
18. Prof. Rok Pestotnik
19. Asst. Prof. Tomaž Podobnik*
20. Dr. Andrej Seljak
21. Prof. Marko Starič
22. Asst. Prof. Andrej Studen*
23. Prof. Marko Zavrtanik
24. Prof. Danilo Zavrtanik*
25. Asst. Prof. Dejan Žontar*

Postdoctoral associates
26. Dr. Dania Consuegra Rodriguez
27. Dr. Bojan Hiti
28. Dr. Gašper Razdevšek
29. Dr. Luka Šantelj

Postgraduates
30. Jernej Debevc, B. Sc.
31. Jan Gavranovič, B. Sc.
32. *Alissa Shirley-Ann Howard, M. Sc., left 01.10.23*
33. Aljaž Hvala, B. Sc.
34. *Dr. Blaž Leban, left 01.11.23*
35. Andrej Lozar, B. Sc.
36. Miha Mali, B. Sc.
37. Jakob Novak, B. Sc.
38. Anja Novosel, B. Sc.
39. Ihor Prudiiev, M. Sc.
40. Krištof Špenko, B. Sc.
41. Dr. Valentina Zhukova

Technical officers
42. Miha Dagarin, B. Sc.
43. *Jakob Merljak, B. Sc., left 01.11.23*
44. Brigita Novak, B. Sc.

Technical and administrative staff
45. Katja Adamič, B. Sc.
46. *Andreja Butina Čalič, B. Sc., left 01.11.23*
47. Jurij Eržen
48. Dejan Lesjak, B. Sc.
49. Erik Margan

Note:
* part-time JSI member

DEPARTMENT OF INORGANIC CHEMISTRY AND TECHNOLOGY K-1

The Department of Inorganic Chemistry and Technology is one of the world's leading groups for the synthesis of new inorganic compounds containing fluorine. The main research areas are: the synthesis of new coordination compounds with various ligands, the chemistry of noble gases, the chemistry of main-group elements, the synthesis of new hybrid materials and inorganic materials with special properties. A large part of the group's activities is devoted to technological, environmental and process safety issues in Slovenia and abroad. The group has been closely cooperating with industry for more than 30 years. It is also active in the field of education and in promoting science among secondary- and primary-school students as well among the public.

Head:
Asst. Prof. Gašper Tavčar

Experiments on the preparation of the new mixed cations $XeF_5M(AF_6)_3$ (M = Cu, Ni; A = Cr, Nb, Ta, Ru, Rh, Re, Os, Ir, Pt, Au, As), $XeF_5M(SbF_6)_3$ (M = Sn, Pb), and $XeF_5M(BF_4)_x(SbF_6)_{3-x}$ (x = 1, 2, 3; M = Co, Mn, Ni, Zn) salts were only successful in the preparation of $XeF_5Ni(AsF_6)_3$. In other cases, mixtures of different products, mostly XeF_5AF_6 and $XeF_5A_2F_{11}$ salts, were obtained. The crystal structures of $XeF_5Ni(AsF_6)_3$, XeF_5TaF_6, XeF_5RhF_6, XeF_5IrF_6, $XeF_5Nb_2F_{11}$, $XeF_5Ta_2F_{11}$ and $[Ni(XeF_5)_2](IrF_6)_2$ were determined for the first time on single crystals by X-ray diffraction. The crystal structures of XeF_5NbF_6, XeF_5PtF_6, XeF_5RuF_6, XeF_5AuF_6 and $(Xe_2F_{11})_2(NiF_6)$ were redetermined using the same method and with better accuracy than previously reported. The crystal structure of XeF_5RhF_6 represents a new structural type in the family of XeF_5AF_6 salts, which crystallize in four different structural types. The $XeF_5A_2F_{11}$ salts (M = Nb, Ta) are not isotypic and both represent a new structural type. They consist of $[XeF_5]^+$ cations and dimeric $[A_2F_{11}]^-$ anions.

The chemistry of the silver continues to be a part of the research topics at the department. A cover feature presents the scientific article about a unique two-dimensional silver(II) antiferromagnet $Cu[Ag(SO_4)_2]$ (Figure 1).

Research continued under the ERC Starting Grant project, "Challenging the Oxidation-State Limitations of the Periodic Table via High-Pressure Fluorine Chemistry - HiPeR-F," 2021-2026. The HiPeR-F project focuses on the study of chemical reactions involving fluorine under extremely high pressure: from 10,000 bar to over 100,000 bar. Within the bilateral Slovenian-Czech research project, the structures of xenon compounds and of other selected reactive compounds were studied using electron diffraction, and activities in the Polish-Slovenian project were focused on the study of transition-metal fluorides under high pressures.

We have continued the development and testing of new "naked" fluoride reagents. A new air-stable deoxyfluorination reagent $[IPrCl][F(HF)_2]$ was developed and tested for its properties. It behaves in a similar way to the commercially available Phenofluor, but the synthesis route does not require inert conditions or expensive reagents.

Previously synthesized imidazolium-based fluorinating reagents $[IPrH][F]$ were screened for their reactivity with various organofluorosilanes and organofluorogermanes to synthesize organofluorosilicates and organofluorogermanates, which could also be used as a source of nucleophilic fluoride in organic synthesis. We have successfully prepared and characterized $[IPrH][Ph_3SiF_2]$, $[IPrH][Ph_2SiF_3]$, $[IPrH][Et_2SiF_3]$, $[IPrH][PhSiF_4]$ and $[IPrH][EtSiF_4]$, showing different stabilities with the alkyl substituted species being much less stable. Moreover, we have successfully prepared and characterized rare organofluorogermanate species $[IPrH][Ph_3GeF_2]$.

The development and study of new pyrrole-based fluoride and polyhydrogen fluoride nucleophilic reagents led to the isolation of stable $[^{Me}CAACH][F(HF)_2]$ and $[^{Me}CAACH][F(HF)_3]$ salts. We have also characterised a salt with $[F(HF)_4]^-$ anions within the structure of $[^{Me}CAACH][F(HF)_{3.5}]$. However, the most interesting was $^{Me}CAAC(H)F$, i.e., not an ionic salt like the rest, but rather a neutral molecule that acts as a source of fluoride due to its low stability. Their reactivity in organic reactions was tested and $[^{Me}CAACH][F(HF)_2]$ was found to be the most suitable reagent with the additional utilization of a base. After a lot of effort, the unstable $[^{Me}CAACH][F(HF)]$ compound was also prepared by the reaction between $[^{Me}CAACH][F] + [^{Me}CAACH][F(HF)_2] \rightarrow [^{Me}CAACH][F(HF)] + [^{Me}CAACH][F(HF)]$. Use of this compound was also tested in the reactivity with some fluoroacids for its capability for the formation of discrete $[SiF_5]^-$, $[GeF_5]^-$, $[PF_6]^-$, $[AsF_6]^-$, $[SbF_6]^-$ anions as well as a rare example of the $[SnF_5]^-$ anion.

Figure 1: Cover Feature presenting the scientific article A Unique Two-Dimensional Silver(II) Antiferromagnet Cu[Ag(SO₄)₂] and Perspectives for Its Further Modifications by authors M. Domański, Z. Mazej and W. Grochala (Chemistry – A European Journal, 2023).

In research on complex copper compounds, it is worth mentioning the study of the influence of the charge of the cation as a tool for changing the dimensionality in organic-inorganic hybrids based on copper thiocyanate.

The concentrations of fluoride and aluminium in green and black teas packed in filter bags or in bulk were determined and their correlation investigated. We started with research into the potential toxicity of fluoride and aluminium on intestinal epithelial cells. The research was carried out in cooperation with the Institute of Microbiology and Immunology, Ljubljana.

Decarbonylation reactions of acetyl metal carbonyls, in particular of organocobalt compounds, and of amides were discussed in view of stabilization/resonance energy. Selected compounds sharing phonetic similarities with semi-systematic or trivial names of elements have been examined for their composition, structure, and chemical properties.

Regarding the topic of process safety in 2023 we researched and published works on diverse topics. We continued the work on the Horizon Europe project ATLANTIS, dealing with the safety and security (physical and cyber threats) of the European critical infrastructure at the systems level and their relationships; we analysed functional interdependencies at the micro level (organizations) and macro level (national and international). In the applicative area, we led the consequences and root cause investigation for the incident at UNIOR d.d., Zreče that occurred on 26 October 2022.

The EIT project RIS DustRec has commenced, focusing on the recovery of valuable elements such as zinc, iron, chromium, nickel, copper, and lead from EAF dust, a byproduct of the metallurgical industry. The non-metallic residue is intended for testing and potential use in the construction industry. To concentrate these elements, various beneficiation techniques, including gravity and magnetic methods, will be applied, followed by either pyrometallurgical or hydrometallurgical treatment processes. This project is a collaborative effort involving industry stakeholders, research institutes, and universities from Slovenia, Poland, Italy, and Serbia, coordinated by the JSI.

Additionally, we are partnering with MMR SARL to study the extraction and purification of critical metals, leading to the design of a pilot plant with a 60-ton capacity to be constructed in the Democratic Republic of the Congo according to our design.

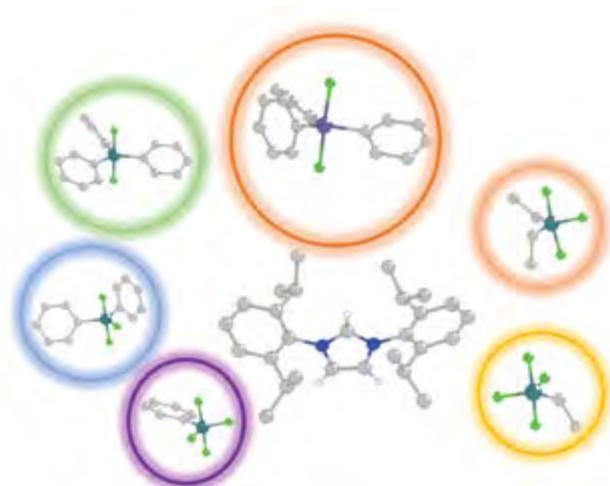**A new air-stable deoxyfluorination reagent [IPrCl][F(HF)$_2$] was developed.**

Figure 2: Pentacoordinated organofluorosilicates and germanates with imidazolium cation

Recovery and concentration of valuable elements from industrial byproducts is important.

We continued our activities in the field of the education and promotion of science. Members of the department actively participated in the work of the Jožef Stefan International Postgraduate School as lecturers and as mentors for M.Sc. and Ph.D. students. In addition, the School of Experimental Chemistry maintained very important relations with primary and secondary schools and even kindergartens. With demonstrations of chemical experiments, we participated in the Slovenian Science Festival, Festival Igraj se z mano, Znanstival. Some of the activities of the School of Experimental Chemistry were carried out as part of a project funded by the JSI and the City of Ljubljana.

The promotion of science, research and non-formal education is also linked to the project Researchers' Night under the Horizon Europe programme. At the end of September 2023 we organised and carried out a series of activities within the framework of this EU project. In the evening, in cooperation with the research departments and centres of the Jožef Stefan Institute, we opened the doors of the Institute in Ljubljana and Podgorica. Visitors were able to see some of the departments and centres, visit the nuclear reactor TRIGA and participate in various workshops. Members of the Department in the frame of this project conducted more than 20 interactive workshops for primary- and secondary-school students. Within the H2020 CSA Athena project (https://www.athenaequality.eu/), a member of the Department of Inorganic Chemistry and Technology was involved in the work package related to monitoring and evaluation of the activities required for the implementation of the Gender Equality Plan.

ERC project

1. H2020 - HiPeR-F; Challenging the Oxidation-State Limitations of the Periodic Table via High-Pressure Fluorine Chemistry
   Asst. Prof. Matic Lozinšek
   European Commission

Some outstanding publications in the past year

1. M. Domański, Z. Mazej, W. Grochala, A Unique Two-dimensional Silver(II) Antiferromagnet Cu[Ag(SO$_4$)$_2$] and Perspectives for Its Further Modifications, *Chemistry - A European journal*. 2023, 29, 1-10.
2. M. Jadwiszczak, P. Leszczyński, Z. Mazej, P. Malinowski, W. R. Grochala, et al., Redox-induced Diels–Alder revisited: impact of diene's oxidation on demanding cycloadditions. *Organic Chemistry Frontiers*. 2023, 10, 5637-5643.
3. J. Gnidovec, E. Gruden, M. Tramšek, J. Iskra, J. Kvíčala, G. Tavčar, Synthesis of imidazolium-based pentacoordinated organofluorosilicate and germanate salts. *Dalton Transactions*, 2023, 52, 5085-5094.
4. E. Gruden, G. Prinčič, J. Hočevar, J. Iskra, J. Kvíčala, G. Tavčar, From cyclic (alkyl)(amino)carbene (CAAC) precursors to fluorinating reagents: experimental and theoretical study. *Dalton Transactions,* 2023, 52, 9562-9572.
5. J. Jelen, G. Tavčar, Deoxyfluorination of electron-deficient phenols, *Organic letters*. 2023, 25, 3649–3653.

Awards and Appointments

1. Klemen Motaln, CCDC prize for the best lecture, 29th Slovenian-Croatian Crystallographic Meeting – SCCM29, June 2023, Topolšica, Slovenia
2. Erik Uran, Award for the best lecture, 29th Slovenian-Croatian Crystallographic Meeting – SCCM29, June 2023, Topolšica, Slovenija
3. Erik Uran, Award for poster presentation, Solid-State Science & Research meeting – SCIRES 2023, June 2023, Zagreb, Croatia
4. Olha Sanko, Award for poster presentation, Slovenian Chemistry Days 2023, September 2023, Portorož, Slovenia

Organization of conferences, congresses and meetings

1. Matic Lozinšek, member of the organizing committee, Slovenian Chemistry Days 2023, Portorož, Slovenia
2. Matic Lozinšek, member of the organizing committee, 29th Slovenian-Croatian Crystallographic Meeting, SCCM29, Topolšica, Slovenia

Patent granted

1. Adam Krzyszrof Budniak, Piotr J. Leszczyński, Zoran Mazej, Wojciech Rafal Grochala, Sposób oksydatywnego sprzęgania cząsteczek węglowodorów posiadających atomy węgla podstawione wodorem, PL 243170 B1, Urząd patentowy Rzeczypospolitej Polskiej, 10. 7. 2023

INTERNATIONAL PROJECTS

1. ERC H2020 - HiPeR-F; Challenging the Oxidation-State Limitations of the Periodic Table via High-Pressure Fluorine Chemistry
   Asst. Prof. Matic Lozinšek
   European Commission
2. Purifing of Tantalum Hydroxide and Niobium Hydroxide
   Prof. Gašper Tavčar
   Mining Mineral Resources S.a.r.l.
3. H2020 - ATHENA; Implementing Gender Equality Plans to Unlock Research Potential of RPOs and RFOs in Europe
   Dr. Melita Tramšek
   European Commission
4. Silicon and Fluorine: A Swiss-Army-Knife Combination for New Mixed Polymerization Blocks, Protection of Ozone Layer and CF3 Transfer
   Prof. Gašper Tavčar
   Slovenian Research Agency
5. Supramolecular Assemblies of Vinyl Monomers as Matrices for Template Polymerization
   Asst. Prof. Evgeny Goreshnik
   Slovenian Research Agency
6. Noble-Gas Reactivity in Extreme Space Environments
   Dr. Kristian Radan
   Slovenian Research Agency
7. High-Pressure Structural Study of Framework-Forming Xenon Compounds
   Asst. Prof. Matic Lozinšek
   Slovenian Research Agency
8. Charge Density Analysis and High-Pressure Structural Study of Compounds of Poly(Hydrogen Fluoride) Anions
   Dr. Miha Virant
   Slovenian Research Agency
9. HE - NOCMOC; (The Night has its Might), European Researchers' Night (NIGHT)
   Dr. Melita Tramšek
   European Commission
10. HE - ATLANTIS; Improved resilience of Critical Infrastructures AgainsT LArge scale transNational and sysTemic rISks
    Prof. Marko Gerbec
    European Commission
11. EIT RM; DustRec - Zero Waste Reprocessing of EAF and CF Dust with Competence Build-Up
    Prof. Gašper Tavčar
    Eit Rawmaterials E.v.
12. HE - NgCHEM; Noble-Gas Compounds Meet X-ray Charge Density and High-Pressure Research
    Valentina Milašinović
    European Commission

RESEARCH PROGRAMME

1. Inorganic Chemistry and Technology
   Prof. Gašper Tavčar

R & D GRANTS AND CONTRACTS

1. Holistic sustainability evaluation of critical raw materials - closing gaps and developing new methodological approaches
   Dr. Robert Kocjančič
2. The quest for high-temperature superconductvity and exotic magnetism in fluoridoargentates(II)
   Asst. Prof. Matic Lozinšek
3. Advanced reagents for (asymmetric) nucleophilic fluorination
   Prof. Gašper Tavčar
4. Structures of elusive noble-gas compounds elucidated by 3D electron diffraction
   Asst. Prof. Matic Lozinšek
5. High-pressure stabilization and phase transitions of elusive transition-metal fluorides
   Asst. Prof. Matic Lozinšek
6. Utilization of secondary lead slag as a secondary raw material for the production of lead
   Prof. Gašper Tavčar
7. P.439148; Method of Oligomerization of Unsaturated Hydrocarbons
   Dr. Zoran Mazej
   University of Warsaw

NEW CONTRACTS

1. Utilization of secondary lead slag as a secondary raw resource for the production of lead
   Prof. Gašper Tavčar
   Th Re-mining d. d.
2. Conduct of the Independent audit
   Prof. Marko Gerbec
   Unior Kovaška Industrija d. d.
3. Update of the Threat assessment report for the natural gas transmission system operated by the Plinovodi d.o.o.
   Prof. Marko Gerbec
   Plinovodi d. o. o.

VISITOR FROM ABROAD

1. prof. Alexander Sidorenko; Bilateral cooperation and lecture, Saint Joseph's University, Philadelphia, U.S.A., 3–10 March2023
2. Clara von Randow; visit and lecture; University of Oxford, United Kingdom, 19–20 September 2023
3. dr. Krešimir Molčanov; Bilateral cooperation; Ruđer Bošković Institute, Zagreb, Croatia, 18 December 2023
4. Petra Stanić; Bilateral cooperation; Ruđer Bošković Institute, Zagreb, Croatia, 18–20 December 2023

STAFF

Researchers
1. Prof. Marko Gerbec
2. Asst. Prof. Evgeny Goreshnik
3. Dr. Robert Kocjančič
4. Asst. Prof. Matic Lozinšek
5. Dr. Zoran Mazej
6. Dr. Valentina Milašinović
7. Prof. Maja Ponikvar-Svet
8. *Asst. Prof. Tomaž Skapin, retired 03.01.23*
9. **Prof. Gašper Tavčar**, Head
10. Dr. Melita Tramšek

Postdoctoral associates
11. Dr. Evelin Gruden
12. Dr. David Levovnik
13. *Dr. Olha Panteleieva, left 01.10.23*
14. Dr. Svitlana Petrusenko
15. Dr. Kristian Radan
16. Dr. Miha Virant

Postgraduates
17. Jan Gnidovec, B. Sc.
18. Andrii Hultiaiev, M. Sc.
19. Jan Jelen, B. Sc.
20. Klemen Motaln, B. Sc.
21. Tomaž Mržljak, B. Sc.
22. Klara Ogorevc, B. Sc.
23. Anja Pavlovič, B. Sc.
24. Olha Sanko, M. Sc.
25. Erik Uran, M. Sc.

Technical officers
26. Patricija Lap, B. Sc.
27. Tine Oblak, M. Sc.

Technical and administrative staff
28. Peter Frkal, B. Sc.
29. Marko Jeran, B. Sc.
30. Robert Moravec
31. Mira Zupančič

DEPARTMENT OF PHYSICAL AND ORGANIC CHEMISTRY K-3

The department is focused on investigating physicochemical processes on the surfaces of solids, such as corrosion and heterogeneous catalysis, and synthesising new compounds. The synergy of these fields is created in the studies of corrosion protection and functionalisation of materials by introducing an integrative experimental–modelling approach, combining experimental electrochemical and surface analysis techniques, modelling and simulation based on first principles using density functional theory (DFT).

Corrosion is a widespread phenomenon with enormous economic and environmental impacts. The cost of corrosion damage is estimated at € 2.5 trillion annually. Due to the enormous costs, protecting metals and alloys is essential. Corrosion protection, with the primary goal to prolong the lifetime of metallic materials, is one of the essential ways to reduce the need for a steeply increasing production, thus preserving resources for the following centuries. Corrosion protection plays a crucial role in sustainable development by enhancing the longevity and durability of infrastructure and reducing the need for frequent repairs or replacements. It contributes to resource conservation, reducing waste, and minimizing the environmental impact associated with the production and disposal of materials (Figure 1). Societies benefit from economic, environmental, and social sustainability by investing in advanced corrosion protection technologies and practices. Scientific and technological innovations in developing novel, sustainable materials with enhanced functional abilities are crucial in that framework. The challenges for the corrosion science, engineering, and technology community in developing a more sustainable society are elaborated in a prospective paper by I. Milošev and J.R. Scully, published in Corrosion Journal.

There are five primary methods of corrosion control: material selection, coatings, inhibitors, cathodic protection and design. Traditional ways of corrosion protection, such as conversion chromate coatings (CCCs), can no longer be used due to ecological restrictions. The needs of industry, in particular transportation, construction, machining, and electronics, postulate the requirements for developing efficient, sustainable, and environmentally friendly coatings, which at the same time exhibit additional functional characteristics. Our research work in the field of corrosion protection is devoted to all major surface treatments, such as corrosion inhibitors, environmentally suitable conversion coatings alternative to CCCs, organic coatings, and inorganic coatings for major metals and alloys, indispensable in today's era, such as major lightweight (Al), energy-efficient (Cu), and infrastructure (Fe and Zn) materials (Figure 1). Lightweight aluminium alloys and contemporary high-strength steels are used in various applications, especially in the transport industry, where there is a great need to reduce the weight of vehicles and, consequently, reduce emissions into the environment. Steels and alloys based on copper are indispensable materials in infrastructure, construction, and other industries. In our laboratory, we investigate the combinations of different strategies, e.g., hybrid sol-gel coatings and inhibitors, to achieve a barrier and active protection, where the coating after corrosion damage can self-heal. We also introduce modern methodologies into corrosion protection, such as atomic layer deposition (ALD).

We achieved a major breakthrough in understanding the mechanism of corrosion inhibition by organic compounds by introducing an **integrative** experimental–modelling approach (Figure 1) with a combination of experimental electrochemical and surface analysis techniques, modelling and simulations based on first principles using density-functional theory (DFT). This approach results in a more rational and ecologically oriented use of chemicals, aligning with the European Union's directives on sustainable development and circular economy.

Prof. I. Milošev, Prof. Dawai Zhang (University of Science and Technology Beijing, China) and Prof. Mikhail Zheludkevich (Helmholtz-Zentrum Hereon, Germany) were guest editors of the Intelligent Corrosion Control Collection published in the npj Materials Degradation journal. The issue reported on important advances in intelligent corrosion control, including smart coatings/surfaces with self-healing, corrosion-sensing or other functional properties, advanced computational modelling for the design/evaluation of protective coatings/surfaces, high-throughput/automated experiments for corrosion evaluation and materials design, and corrosion databases and machine learning for corrosion detection, diagnosis and prediction.
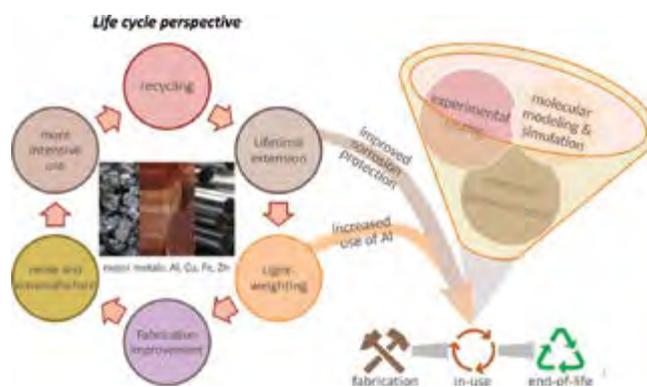

Figure 1: Life cycle of metals in a sustainable economy and our integrative approach to corrosion protection.

Head:
Prof. Ingrid Milošev

1. Integrative experimental–modelling approach of novel corrosion inhibitors

An in-depth fundamental knowledge of surface processes is needed when designing an effective corrosion protection because understanding the mechanism of corrosion inhibition at the atomic level is still very limited. To overcome this, we introduced a synergistic iterative approach that consists of the following three research directions: (1) inorganic and organic synthesis, (2) electrochemical and surface-analysis techniques, and (3) modelling and simulations based on DFT.

1.1. Experimental studies of novel corrosion inhibitors

Aluminium alloy (AA) 2024 is widely used as a structural material in automotive, aerospace and construction industries due to its high strength-to-weight ratio. To find an effective and reliable corrosion inhibitor for AA2024, it is crucial to understand the mechanism governing the corrosion processes and corrosion inhibition. In AA2024, copper-containing intermetallic particles (IMPs) represent the weak spots for corrosion initiation due to their enhanced cathodic character compared to the surrounding Al matrix. Therefore, addressing and controlling the localised electrochemical corrosion response (i.e., accurately measuring the potentials and currents) at these sites is particularly challenging. Since the degradation of AA2024 is mainly due to the local galvanic coupling between the IMPs and the surrounding matrix, a reasonable approach would be to mimic the intermetallic phases of the AA2024 system by testing a suitable galvanic couple model, such as Al/Cu, to provide the key information needed to better understand the behaviour of associated alloy systems. We contributed to advancing the understanding of the activation and inhibition effects on surface properties through detailed *in-situ* localised monitoring and characterisation of the film formation and degradation of 2-mercaptobenzimidazole (MBI) and octylphosphonic acid (OPA) corrosion inhibitor layers formed at the metal-liquid interface of an Al/Cu galvanic couple. For this purpose, three different operating modes of scanning electrochemical microscopy (SECM) were used, namely the substrate generation-tip collection (SG-TC), redox competition (RC) and feedback modes. Hydrogen evolution was observed from the propagating pits on aluminium, while an oxygen-reduction response was recorded on copper at the free corrosion potential in the presence of an aggressive electrolyte such as 0.5 M NaCl. Additionally, the scanning vibrating electrode technique (SVET) was used as a method complementary to the experiments performed with SECM.

> **Two PhD theses were completed in 2023 by Matjaž Dlouhy and Damir Hamulić, supervised by Prof. Anton Kokalj and Prof. Ingrid Milošev, respectively.**

The results revealed that it would be tempting to attribute the observation of localised increases in the cathodic currents corresponding to a reduction in the available dissolved oxygen at the tip (i.e., the concentration of oxygen remaining in the electrolyte which was not consumed at cathodic locations) to the pit topography or some other localised surface depression. However, the methodology proposed based on alternative monitoring of the concentration profiles of molecular hydrogen and dissolved oxygen ruled out the influence of topography and attributed it to the emergent redox sites. At the sites on the aluminium surface where hydrogen evolves, oxygen reduction reaction (ORR) does not occur but is only noted in the immediate vicinity of the anodic sites. It was also observed that the Pt tip became ineffective over time when it was placed over a copper surface galvanically connected to aluminium during feedback mode measurements, a feature that we attribute to the oxidation of the tip to $Pt(OH)_2$ due to the increase in pH of the adjacent electrolyte at sufficiently high potentials. To successfully avoid this unwanted effect in the tip, an experimental connection-disconnection procedure was developed.

Finally, the impressive corrosion resistance generated at the MBI solution–Al/Cu interface, established immediately upon immersion in a chloride solution containing MBI and increased to a higher level with the immersion time, must be due to the formation of a protective Cu-MBI layer that effectively blocks the cathodic sites. More importantly, MBI exhibits excellent protection against localised corrosion, even in the chloride solution, which does not contain an MBI reservoir. On the other hand, OPA does not provide sufficient barrier properties against the penetration of aggressive ions, such as chloride, based on the high faradaic currents detected at various locations on the Al surface, which are associated with the onset of pitting corrosion. An energy dispersive X-ray spectroscopy (EDS) analysis of the cross-section revealed that MBI does not entirely prevent the dealloying of Al and Mg but reduces the dissolution rate and the rate of oxygen reduction by forming an insoluble Cu–MBI film on the partially dealloyed AlCu-based particles, i.e., porous copper remnants (Figure 2). Therefore, MBI has the potential to be used as a corrosion inhibitor of Cu-based aluminium alloys, while OPA,
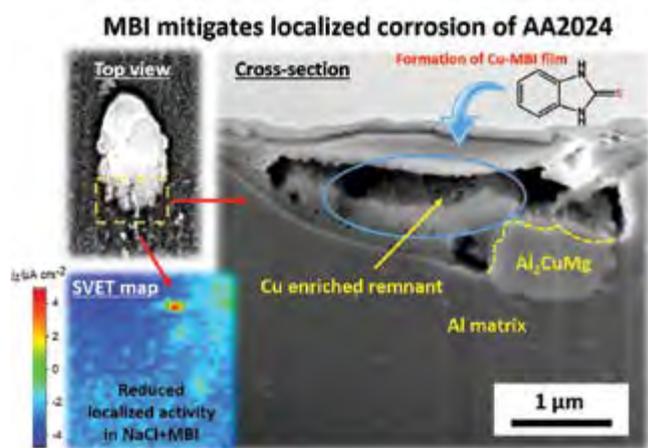
Figure 2: (top left) Scanning electron microscopy image (top view) of the aluminium alloy 2024 immersed for 24 h in 0.5 M NaCl containing 1 mM of 2-mercaptobenzimidazole. The area denoted by the yellow rectangle was analysed in a cross-section made by a focused ion beam (FIB) (right). Selective dissolution of intermetallic particles Al_2CuMg leads to an enrichment with copper. The formation of a Cu-MBI film on the Cu-rich remnants reduces dealloying and decreases the corrosion rate, as confirmed by scanning the vibrating electrode map (down left).

although it acts inhibitorily on the Al matrix, is a corrosion activator of Cu-rich sites leading to the propagation of localised corrosion. This study also reveals that the transition of the inhibition mechanism from pure metals (Cu and Al) to an alloy (AA2024) is not straightforward and requires further adjustments to achieve complete protection.

1.2. Modelling studies in corrosion inhibition

We extended our study to the mechanism with which organic layers on aluminium substrates hinder the penetration of Cl⁻ ions, which are known to trigger localized corrosion. In one of our previous works, we had established experimentally that long-chain *n*-alkyl carboxylic acids form protective layers against Cl⁻ corrosion on Al substrates. In subsequent work, we identified, using implicit models of the organic layer and metal substrate, two essential effects, with which organic layers hinder the penetration of Cl⁻ ions toward the metal substrate. The first effect is due to an inferior solvation of ions in the organic layer compared to that in an aqueous solvent. The second effect is due to the electric field at the electrochemical interface, and the extent to which it affects the penetration of Cl⁻ depends on the electrode potential

> **Prof. I. Milošev was a keynote speaker at the 34th Topical Meeting of the International Society of Electrochemistry, Mar del Plata, Argentina, in March 2023, and at the 19th Asian Pacific Corrosion Control Conference in Guangzhou, China, in November 2023.**

and the thickness of the organic layer. Encouraged by these studies, we continued our investigation and explicitly modelled the organic monolayer and Al substrate using density-functional-theory (DFT) calculations. We confirmed the findings of simplified implicit models, according to which the energy barrier for the Cl⁻ penetration increases with the thickness of the organic monolayer and with the Cl⁻ concentration in the monolayer.

Furthermore, we proposed a new mechanism by which Cl⁻ penetrates the organic monolayer. Due to the considerably inferior solvation of Cl⁻ in the organic layer compared to that in water, it is energetically easier to locally "open" the organic monolayer by creating a hole large enough to accommodate water molecules and Cl⁻ (Figure 3a). The presence of water molecules ensures a stronger Cl⁻ solvation and a better electrostatic screening between anions. Although the energy barrier for the Cl⁻ penetration via the local "opening" mechanism is smaller than that for the penetration of Cl⁻ into a dense homogeneous organic monolayer (Figure 3b), it is still high enough to represent a considerable kinetic barrier at room temperature.
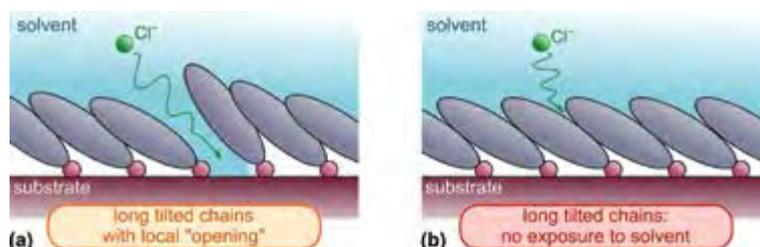

Figure 3: Two mechanisms of Cl⁻ penetrating an organic self-assembled monolayer (SAM): (a) the local "opening" mechanism, where the hole is created in the SAM, which is large enough to accommodate water molecules, and Cl⁻ with its water solvation shell; and (b) a naked Cl⁻ penetrating a homogeneous tilted-SAM model. According to DFT calculations, the local "opening" mechanism is more probable.

1.3 Theoretical studies in corrosion inhibition

In addition to modelling, we also explained two concepts that are often utilized in corrosion-inhibition studies: synergism and adsorption isotherms. Despite their frequent utilization, the theoretical foundations underlying them are not always well understood and, consequently, various pitfalls are sometimes made.

Synergism is often quantified with the synergistic parameter. According to the literature, this parameter has only been applied to binary inhibitor mixtures until recently. In the corresponding equation, the mixture's inhibition efficiency is evaluated against the threshold inhibition efficiency based on the performance of pure compounds (Figure 4a), and the threshold of Aramaki–Hackerman is almost always used. However, we showed that the threshold value is not unique, proposed several other reasonable values, and extended the corresponding synergistic models to multi-component mixtures.

In corrosion-inhibition studies, the standard adsorption

Figure 4: (a) Equation for the synergistic parameter can be easily extended to multi-component mixtures if corrosion activity is used instead of corrosion efficiency. (b) Based on the analysis of the functional dependence of various adsorption models on the c/θ (concentration/coverage) vs c plot [(b) left], a new general-purpose type-I adsorption isotherm was proposed [(b) right].

Gibbs energy is often estimated via the linear regression of the Langmuir adsorption isotherm in the $c/\theta = 1/K + c$ form (c = inhibitor concentration, θ = fractional surface coverage, K = adsorption equilibrium constant), where both the intercept and the slope are estimated, although the Langmuir isotherm requires a slope of 1. Hence, $c/\theta = 1/K + mc$ is used instead, where m is the slope (Figure 4b). We provided a theoretical basis for this equation and proposed a new general-purpose type–I adsorption isotherm (Figure 4b) based on considering a functional dependence of various adsorption models on the c/θ vs c plot. The new isotherm is flexible enough to describe
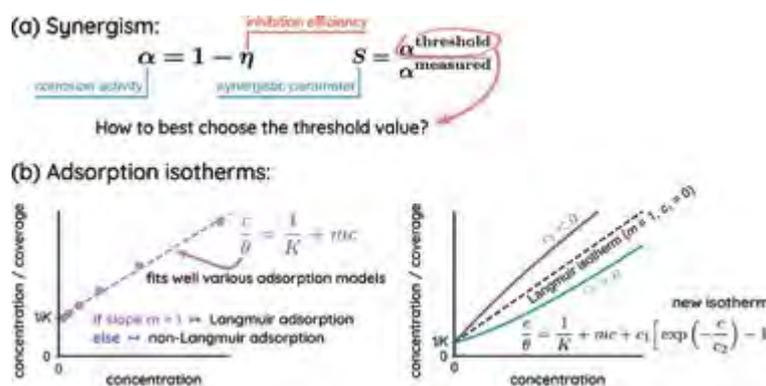
various adsorption scenarios and provide relatively accurate estimates of the standard adsorption Gibbs energy, provided that surface coverages are reliably determined experimentally. Among various adsorption models that the new isotherm can describe are those that consider lateral inter-adsorbate interactions, molecular size, surface heterogeneity, and mobile adsorption.

2 Hybrid sol-gel coatings used for corrosion protection

The sol-gel synthesis process is a versatile method used to produce a wide variety of materials and is increasingly used as a surface modification method to alter porosity, wettability, catalytic activity, biocompatibility, and corrosion performance of underlying substrates. Sol-gel coatings remain one of the important fields of our research work.

Hybrid sol-gel polybutyl methacrylate PBMA-siloxane was optimised by curing and determining the minimum thickness for optimal corrosion protection (Figure 5). The optimisation was carried out toward a lower curing temperature compared to the currently known literature data. It turned out that a lower curing temperature slows the process of polycondensation (formation of siloxane bonds) and, consequently, the polymerisation process. At the same time, there is less coating shrinkage at lower temperatures, which in turn causes a greater total porosity. All these properties consequently affect the corrosion properties of the coatings cured at a lower temperature, exhibiting poorer corrosion protection. According to the thermal analysis results obtained with differential scanning calorimetry and corrosion properties analysis obtained using electrochemical impedance spectroscopy and a salt spray chamber, 150 °C is the optimal curing temperature of the PBMA-siloxane coating. An analysis of Fourier transform infrared (FTIR) spectra also confirmed that the chemical changes of the coating due to copolymerisation and polycondensation are mostly completed after curing at 150 °C. In addition to the curing effect, the optimal coating thickness that still provides durable protection for several weeks is 4 μm. The thickness of the coating can be controlled with different withdrawal rates. The studied coating presents a promising approach to corrosion protection of structural steel for applications where only a few micrometre-thick coating is required.
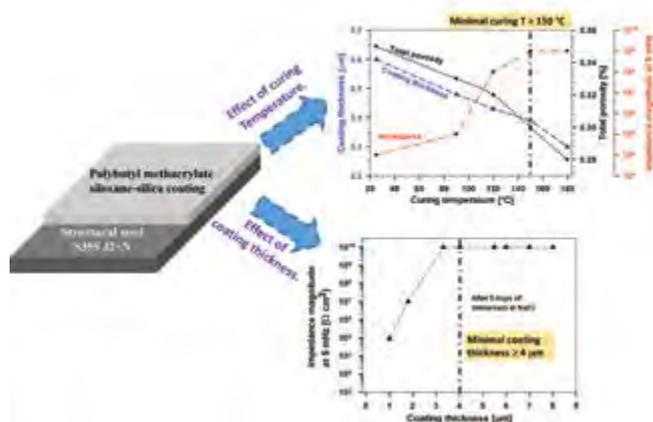

Figure 5: (left) Schematic representation of a hybrid sol-gel polybutyl methacrylate silane coating applied to structural steel. (top right) Dependence of coating thickness, porosity, and impedance magnitude at 10 mHz in NaCl solution on drying temperature. (bottom right) Dependence of impedance magnitude at 10 mHz on drying temperature after five days of immersion in NaCl solution.
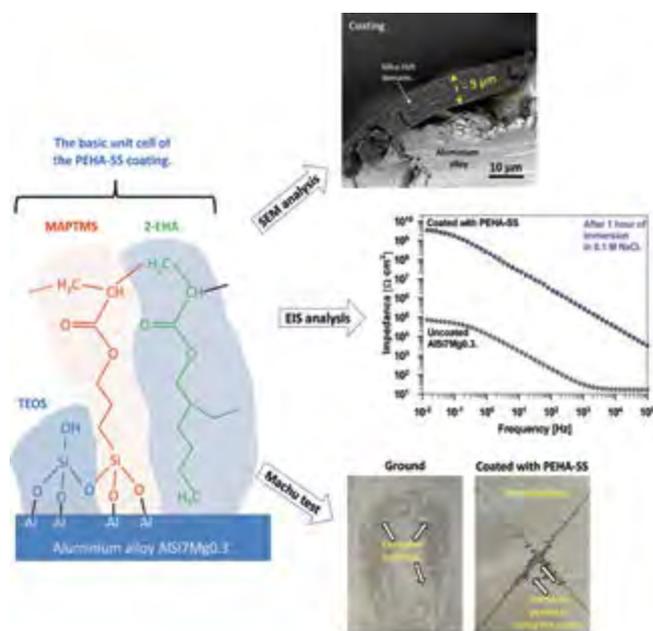
In another study, we presented a novel corrosion-protective coating based on polyacrylic/siloxane-silica (PEHA-SS) deposited on lightweight cast aluminium alloy Al-Si7-Mg0.3 (Figure 6). The synthesis of PEHA-SS comprises organic monomer 2-ethylhexyl acrylate (2-EHA), organically modified silane, 3-(trimethoxysilyl)propyl methacrylate (MAPTMS), as well as an inorganic silane, tetraethyl orthosilicate (TEOS). The steps during the synthesis process were monitored using real-time infrared spectroscopy. The high degree of hydrolysis and condensation reactions of the formed siloxane-silica coating hybrid sol-gel network ensures a dense and uniform coating. The coating deposited onto the Al-Si7-Mg0.3 surface was characterised using various techniques, including infrared spectroscopy, 3D contact profilometry, and scanning electron microscopy (SEM) coupled with EDS. The SEM/EDS analysis confirmed some silica-rich regions randomly distributed in the coating formed during controlled coating preparation. The corrosion resistance of the coated alloy in sodium chloride solutions was evaluated using electrochemical impedance spectroscopy (EIS). The accelerated testing of the uncoated and coated sample was performed using the Machu test. This novel, nine-micrometre-thick PEHA-SS coating achieved durable corrosion (barrier) protection of the Al-Si7-Mg0.3 alloy in 0.1 M NaCl during the first four months of immersion or under accelerated corrosion conditions in a Machu chamber containing NaCl, acetic acid, and hydrogen peroxide at 37 °C. The results provide a strong foundation for further studies that use either an individual PEHA-SS coating or combine it with other corrosion protection systems to achieve an even more durable corrosion protection of cast aluminium alloys.

We prepared hybrid sol-gel coatings TMZ from TEOS and MAPTMS by adding zirconium(IV) tetrapropoxide (ZTP) crosslinked with methacrylic

Figure 6: (left) Schematic representation of a hybrid sol-gel polyacrylic/siloxane-silica (PEHA-SS) coating applied to an $AlSi_7Mg_{0.3}$ aluminium alloy. (top right) Scanning electron microscope image of the cross-section of the coating. (right middle) Bode electrochemical impedance diagrams for an uncoated Al-Si7-Mg0.3 alloy sample and a PEHA-SS coated sample after 1 h immersion in 0.1 M NaCl. (bottom right) Snapshot of the surface of the sample after the Mach test.

acid (MMA), and deposited them on aluminium (Figure 7). The study focused on combining two corrosion protection strategies: barrier protection, provided by a 3.8 μm thick hybrid sol-gel TMZ coating, sealed with a 100 nm thick layer of aluminium oxide. The synthesis of the Si–O–Zr hybrid sol-gel was evaluated at various stages using real-time infrared spectroscopy. After hydrolysis and condensation, chelating reactions stopped at a certain level, at which an efficient incorporation of zirconia into the siloxane network occurred. The reactions were completed after thermal curing. A 100 nm thick Al_2O_3 film was prepared via atomic layer deposition at 160 °C using trimethyl aluminium and water as the precursors. The coating properties were assessed via focused ion beam (FIB) and SEM/EDS analysis. Sealing with the Al_2O_3 film did not affect the microstructure and composition of the underlying sol-gel coating. The coating's corrosion performance in 0.1 M NaCl solution was evaluated using EIS. Compared to individual coatings, the multilayer TMZ/Al_2O_3 coating ensured prolonged (over three weeks) corrosion protection for the aluminium. After 1 h of immersion, the impedance magnitude at a frequency of 10 mHz ($|Z|_{10 mHz}$) of the TMZ-Al_2O_3 sealed coating was larger by two orders of magnitude than that of the uncoated substrate, increasing from 16 kΩ cm^2 to almost 830 MΩ cm^2. After four weeks in the NaCl solution, the pore sealing of the sol-gel coating using an ALD alumina film produced a protective multilayer coating system, with $|Z|_{10 mHz}$ remaining above 5 MΩ cm^2, indicating a high barrier corrosion protection.

In addition to conducting laboratory investigations and testing of sol-gel coatings developed in our laboratory, we conducted field and environment testing. Six hybrid sol-gel coatings based on siloxane and acrylic networks deposited on structured steel were tested in the laboratory and appropriate environments for corrosion protection and anti-fouling ability. The coatings differed in the length of the alkyl chain of acrylic derivatives (methyl M1, ethyl E2, butyl B4, hexyl H6, octyl O8 and dodecyl D12), resulting in a change in hydrophobicity and a change in the coating structural integrity. A steel substrate corrodes rapidly in a chloride environment and is difficult to protect using relatively thin coatings (less than 10 μm). The laboratory corrosion test of artificially damaged coatings under harsh corrosive conditions (5 wt. % NaCl and 35 °C) for 15 days revealed that the coatings with ethyl and butyl acrylate derivatives showed the best corrosion performance of the surface and no delamination.

Four months of field-testing results in the port of Koper in the Adriatic Sea show that ethyl and butyl-based derivatives provided the most satisfactory corrosion and biofouling protection of structured steel. After four months in the Adriatic Sea, the fouling was visibly present at the surface but could be detached by sonication (simulating the movement of a sailing ship). Commercially available paint based on silicone, much thicker than synthesised coatings, did not show any attachment of macroorganisms but only microorganisms that could barely be visible to the naked eye. In the freshwater of the Ižica River, corrosion and fouling were not as evident, and synthesised coatings exhibited efficiency comparable to that of the commercially available paint.

The ecotoxicity test results for microcrustaceans and microalgae showed that the most promising hybrid coatings included E2 and B4, having the least ecotoxic properties. All three coating leachates were slightly toxic regarding the immobilisation of microcrustacean *Daphnia magna* but still considerably less toxic when compared with the commercial paint containing biocide (Figure 8). Similar results were obtained with the microalgae test. Hence, the hybrid coatings showed promising field-testing results, representing a good basis for further development of the paint system as non-biocide coatings, primary enabling easy detachment of biofouling once the ship is in motion (the so-called biofouling release principle).

Another field test in the Adriatic Sea was conducted using cast aluminium alloys, non-coated and coated with two sets of hybrid coatings. Aluminium-silicon cast alloys are increasingly used in various applications, including marine ones. Two Al-Si cast alloys were investigated as materials for marine exposure: Al-Si9-Cu3 and Al-Si7-Mg0.3. The microstructures, chemical compositions and electrochemical properties of non-immersed alloys were studied, revealing their heterogeneous nature. Eight-month field testing by immersion in the Adriatic Sea was performed to test long-term corrosion and biofouling resistance. Morphological and chemical changes in the
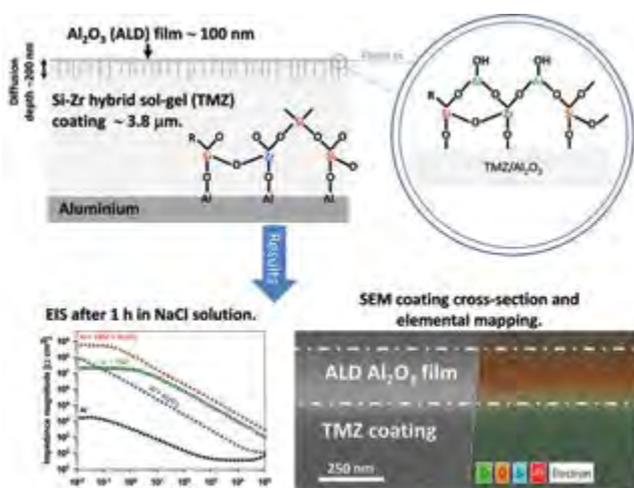
Figure 7: (top) Schematic presentation of the hybrid sol-gel TZM coating sealed with an Al_2O_3 layer prepared with atomic layer deposition. (low left) EIS spectra for uncoated Al samples and samples coated with TMZ and Al_2O_3 coatings and multilayer TMZ-Al_2O_3. (low right) SEM image and EDS mapping of multilayer TMZ-Al_2O_3
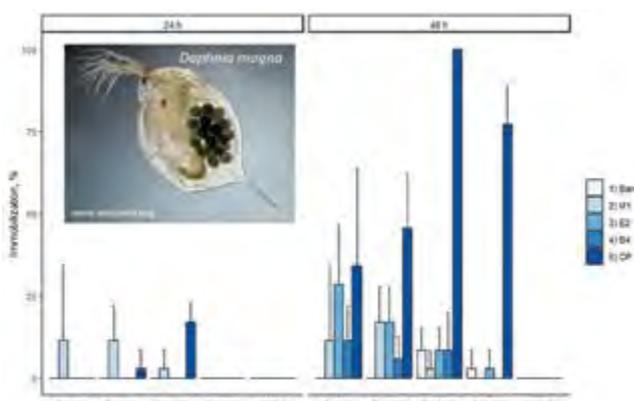
Figure 8: Immobilization of microcrustacean Daphnia magna (inset photo) determined in the leachates after 24 h and 48 h immersion of bare steel; samples are coated with hybrid sol-gel coatings M1, E2 and B4, and with commercial paint Seajet 034 Emperor (CP). The control liquid is the ADaM medium (artificial fresh water for zooplankton culture). Standard deviations are indicated by bars.
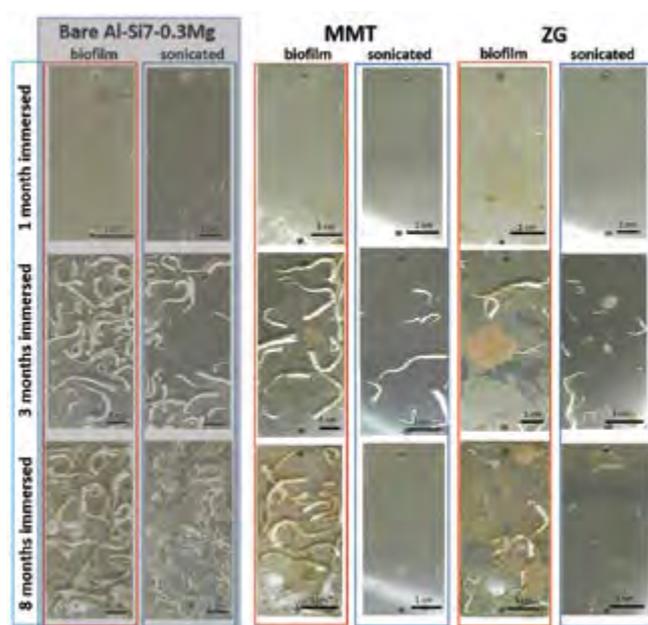
Figure 9: Photographs of uncoated steel samples and steel samples coated with MMT and ZG coatings after 1, 3 and 8 months of immersion in the Adriatic Sea, and after removal of biofouling by sonication.

surface induced by immersion were investigated using surface analytical techniques. Electrochemical measurements of the samples immersed in artificial seawater revealed that alloys were re-passivated by micrometre-thick oxide layers. The Al-Si9-Cu3 alloy formed a layer rich in magnesium, while the one formed on Al-Si7-Mg0.3 was rich in silicon. Electrochemical results indicated that both alloys are suitable for use in marine environments, where Al-Si7-Mg0.3 is more resistant than Al-Si9-Cu3. The biofouling formed up to one month of immersion could be removed by sonication. At the end of the immersion period, macro biofouling was firmly attached to the alloy surface, as evidenced by SEM.

The samples were coated with two sets of hybrid coatings to improve the biofouling behaviour of cast Al alloys (Figure 9). Both coatings were hybrid, i.e., they contained an inorganic part of the sol-gel network and an organic, polymerised part of the network. The coatings were prepared in two steps using two separately prepared solutions. The MMT acrylate-based coating contained the inorganic part of Si-O-Si siloxane bonds intermixed with an organic polymerised acrylate network. The ZG epoxy-based coating contained the inorganic part of Zr-O-Zr and Zr-O-Si bonds intermixed with a polymerised organic network. X-ray photoelectron spectroscopy (XPS) confirmed that the coatings were mainly organic, containing Si(IV) oxide in MMT, and Si(IV) and Zr(IV) oxides in ZG. The coatings decreased the surface wettability; they were homogeneous, dense, having a nanostructured morphology.

After eight months of immersion in the Adriatic Sea, a biofouling layer was formed, but it was removed to a significant extent by sonication, especially from the Al-Si7-Mg0.3 alloy. The coatings remained shiny and virtually intact. The XPS analysis revealed that Al was detected at the coating surface after immersion, indicating some dissolution through the pores. However, the coating structure was preserved.

Electrochemical measurements confirmed that both hybrid sol-gel coatings, MMT and ZG, deposited on cast Al-Si alloys acted as barriers, but better characteristics were obtained when they were deposited on the Al-Si7-Mg0.3 alloy. Based on the results obtained, we can corroborate that these coatings are promising candidates for marine applications, acting on the fouling-release principle, i.e., the attached biofouling can be removed once the ship is in motion.

3 Cerium and zirconium compounds in corrosion protection

In corrosion protection, cerium and zirconium coatings are alternatives to chromate coatings, which are known to be toxic for humans and environmentally inadequate. Ce and Zr compounds have been the focus of our investigation for over a decade. These compounds are environmentally friendly and can achieve a high level of corrosion protection.

Cerium-based inhibitors were studied on aluminium alloy (AA) 7075-T6. Because of its suitable physical and chemical properties combined with a relatively low weight, AA7075-T6 has many applications in the automotive and aircraft industries, various household appliances, and other technical fields. Due to intermetallic particles consisting mainly of Al, Zn, Cu, Fe, and Mg, the mechanical properties are improved compared to the Al metal. However, the IMPs may dissolve or produce galvanic currents with the surrounding matrix due to the differences in electrochemical potential, leading to severe localised types of corrosion. Such corrosion processes generally occur in environments containing a relatively high concentration of chloride ions (Cl^-). Further, the electrochemical behaviour of aluminium alloys depends on the corrosive medium temperature, pH value, dissolved oxygen content, etc. Regarding the composition of the corrosive medium, Cl^- is not the only pollutant in industrial and urban areas. In addition, major inorganic species such as ammonium (NH_4^+), sulphate (SO_4^{2-}) and nitrate (NO_3^-) ions found in the forms of NH_4NO_3 and $(NH_4)_2SO_4$ (or NH_4HSO_4) should be considered as well because they represent corrosive agents for many aluminium alloys. Corrosive conditions may be thus better simulated by the so-called dilute Harrison's solution (DHS) (0.35 wt.% $(NH_4)_2SO_4$ + 0.05 wt.% NaCl), which, in addition to Cl^-, also contains SO_4^{2-} and nitrate NO_3^- reflecting the environmental and atmospheric conditions.

The studies of aluminium alloys in DHS are relatively scarce. Our study addressed the behaviour of an aluminium alloy and its components in conditions simulating the presence of atmospheric salts. The corrosion of synthetic

intermetallic compounds (IMCs) Al_2Cu, Al_2CuMg, Al_7Cu_2Fe, $MgZn_2$, and bulk aluminium alloy 7075-T6 was studied in dilute Harrison's solution. For IMCs, electrochemical measurements were performed using a microcell, and a standard electrochemical cell was used to study the bulk alloy. Separately measured cathodic and anodic potentiodynamic polarisation curves were recorded, and prolonged immersion was character-ised using electrochemical impedance spectroscopy. Bulk AA7075-T6 was less susceptible to corrosion in DHS than in a chloride solution, stemming from the beneficial presence of sulphate ions and a lower chloride concentration. The susceptibility of IMCs to corrosion in DHS increased in the order $Al_2Cu <$ $Al_7Cu_2Fe < Al_2CuMg < MgZn_2$ due to the increased dissolution of Mg in the presence of ammonium ions. The relative nobility of IMCs in respect of the bulk alloy was determined based on the galvanic current density. Further, the use of cerium chloride, nitrate and acetate salts as corrosion inhibitors in DHS was evaluated (Figure 10). Ce salts acted as inhibitors for the alloy during 14-day testing, forming a Ce hydroxide layer. The degree of protection depended

The expression for the synergistic parameter in corrosion inhibition was generalized and extended to multicomponent inhibitor mixtures.

on the type of anion, with acetate Ce salt giving the most efficient protection. For the IMCs, however, no inhibition by Ce salts occurred during short measurements in the microcell, which was due to a relatively short duration of the measurements, reflecting only the initial step of the activation but not the second step of the deposition of Ce layers.

Figure 10: Schematic presentation of the (a) mechanism of the dissolution of 7075 aluminium alloy in dilute Harrison's solution (0.35 wt.% $(NH_4)_2SO_4$ + 0.05 wt.% NaCl), (b) interaction of cerium cations with different anions and (c) corrosion inhibition due to the deposition of a Ce layer.

Limited knowledge of zirconium conversion coating (ZrCC) chemistry is directly due to limited understanding of Zr aqueous chemistry. The high tendency of zirconium to hydrolyse, along with a rapid exchange in geometry, coordination, and sensitivity to solution composition, significantly impedes the study of the composition and geometry of Zr compounds. The primary function of hexafluorozirconate (ZrF_6^{2-}) is to provide an activated metal surface while also adjusting pH from severely acidic to that acceptable for the conversion of hexafluorozirconate to zirconium hydroxide. In our latest study, revised predominance areas for Zr-OH and Zr-F aqueous speciation concerning the Zr amorphous phase were established as the foundation for describing the ZrCC formation mechanism (Figure 11). The tetramer, $Zr_4(OH)_8^{8+}$, was used to represent all other polynuclear species and the fundamental building block of the solid phase. Revised Zr equilibria were the basis for the updated E-pH (Pourbaix) diagram, comprising $ZrOH_3^+$ and $Zr_4(OH)_8^{8+}$ instead of formerly employed ZrO_2^+. H_2ZrF_6 acts as the source of fluoride and also serves to adjust the pH, making it suitable for conversion. Therefore, it acts as a "two-in-one" agent.

We believe this study can serve as the starting point for future extensions to other additives utilised in ZrCC baths, as well as the elucidation of their effects and interactions. This could, at the very least, direct field researchers to focus on the final coating and the solution chemistry behind Zr-conversion bath components. The electrochemical nature of the conversion process is reflected in its initiation; however, the core of the process is based on hydrolysis and condensation. Thus, future efforts to identify ways of controlling electrochemical and sol-gel chemistry could be critical in increasing the overall performance of ZrCCs.

Figure 11: Updated predominance diagram for Zr(IV) (left) and Zr-F (right) species (with varying ionic strength in NaCl) at 25 °C.

4 Modelling barium hexaferrite nanoplatelets

With the aid of DFT-based modelling, we focused on providing an insight into the physico-chemical properties of the unique barium hexaferrite (BHF) nanoparticles. In particular, these nanoparticles grow in the form of platelets, with a low thickness along the principal magnetization axis and the larger width in the other directions.

Figure 12: Schematic summary of the main results of our first-principles-based investigation of the surface morphology of BHF nanoplatelets in a wide range of chemical conditions

They display a uniaxial magnetic anisotropy with the easy axis pointing perpendicularly to the platelet. This unique property of BHF nanoplatelets has led to a variety of novel applications. However, it has been observed that the nanoplatelets display two different surface morphologies depending on the stage/conditions of the preparation. To ground these experimental observations, we employed an *ab initio* thermodynamics framework to systematically investigate the thermodynamic stability of BHF bulk terminations under a wide range of chemical conditions. We calculated the surface phase diagrams of pristine and hydroxylated bulk terminations along the crystalline *c*-axis (which corresponds to the magnetic easy axis). We found that, for pristine terminations, two types dominate: a barium-containing termination (in Ba-rich conditions) and an iron-terminated surface (in Ba-poor conditions). In the presence of water, hydroxylated oxygen-terminated surfaces were identified as the most stable under Ba-poor conditions and low pH values, whereas a hydroxylated barium-containing surface was preferred under high-pH and Ba-rich conditions. Our findings (graphically summarized in Figure 12) are in good agreement with the above-mentioned experimentally determined surface morphologies of nanoplatelets.

Some outstanding publications in the past year

1. Kraš A, Milošev, The aqueous chemistry of zirconium as a basis for better understanding the formation of zirconium conversion coatings: updated thermodynamic data, J. Electrochem. Soc., 2023, **170**, 021508
2. Milošev I, Scully JR, Challenges for the corrosion science, engineering, and technology community as a consequence of growing demand and consumption of materials: A sustainability issue, CORROSION, 2023, **79(9)**, 988–996
3. Rodič P, Milošev I, Frankel GS, Corrosion of synthetic intermetallic compounds and AA7075-T6 in dilute Harrison's solution and inhibition by cerium(III), J. Electrochem. Soc., 2023, **170**, 031503
4. Hamulić D, Medoš G, Korte D, Rodič P, Milošev I, The effect of curing temperature and thickness of polybutyl methacrylate siloxane coatings on the corrosion protection of structural steel S355, Coatings, 2023, **13**, 675
5. Kokalj A, On the use of the Langmuir and other adsorption isotherms in corrosion inhibition, Corros. Sci., 2023, **217**, 111112
6. Chiter F, Costa D., Poberžnik M., Milošev I, Marcus P, Kokalj A, DFT study of Cl^- ingress into organic self-assembled monolayers on aluminum, J. Electrochem. Soc., 2023, **170**, 071504
7. Poberžnik M, Herrero-Saboya G, Makovec D, Lisjak D, Martin-Samos L, Surface phase diagrams of pristine and hydroxylated barium hexaferrite surfaces from first-principles atomistic thermodynamics, Appl. Surf. Sci., 2023, **637**, 157890
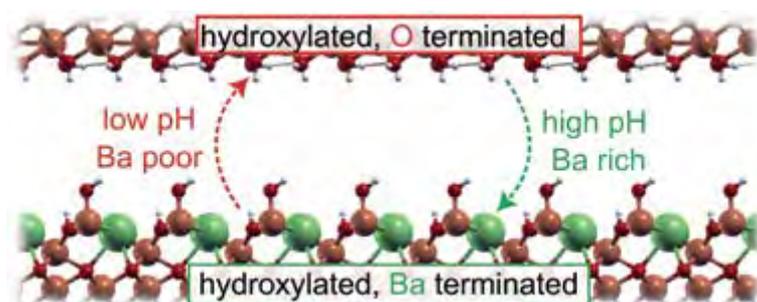
Awards and Appointments

1. Asst. Prof. Peter Rodič mentored several project tasks, which were carried out by high school students and awarded in various competitions: Mija Kapun and Daniil Gainullov (Jože Plečnik Grammar School) – 53rd Krka Award and a silver medal at the ZOTKS competitions; Ela Podboršek and Tim Strnad (Vič High School) – 53rd Krka Award, the gold medal at the Genius Olympiad in the USA, and gold medal at the Olympics Vilnius International Project.

Organization of conferences, congresses and meetings

1. Prof. Ingrid Milošev, Prof. Noel D. Buckley (University of Limerick, Ireland), Prof. Petr Vanysek (Brno Technical University, Czech Republik) and Dr Oumaïma Gharbi (Sorbonne University, France) organised "Young Researchers in Europe: A Special Symposium and Workshop" at the Electrochemical Society (ECS) Meeting in Gothenburg, Sweden, in October 2023. The symposium was a two-day event organised by the ECS Europe Section and sponsored by all divisions. A unique feature of the symposium was three-minute "elevator pitches" where early career professionals in electrochemistry could highlight their work. The program was supplemented by six 40-minute invited talks by authors with experience in grant institutions, international research consortia and collaboration. The purpose was to facilitate connections between scientists and engineers in the field and also to allow early carrier researchers to present their excellence in the field. The symposium was very successful, attracting over 400 submissions. Of these, 100 were chosen for oral "elevator pitches", primarily based on diverse representations of various regions of Europe. The symposium was very well attended, with an estimated several hundred participants.

INTERNATIONAL PROJECTS

1. H2020 - ATHENA; Implementing Gender Equality Plans to Unlock Research Potential of RPOs and RFOs in Europe
   Prof. Ingrid Milošev
   European Commission
2. The Role of Corrosion Protection of Metals in Sustainable Development
   Prof. Ingrid Milošev
   Slovenian Research Agency
3. Atmospheric Pressure Plasma Deposited Coatings: Synthesis and Characterization
   Asst. Prof. Peter Rodič
   Slovenian Research Agency
4. HE - MaX; MAterials design at the eXascale
   Prof. Anton Kokalj
   European Commission
5. COST CA22154; DAEMON - Data-driven Applications towards the Engineering of functional Materials: an Open Network
   Prof. Anton Kokalj
   COST Association Aisbl

RESEARCH PROGRAMMES

1. Chemistry for sustainable development
   Asst. Prof. Peter Rodič
2. Advanced materials for low-carbon and sustainable society
   Prof. Ingrid Milošev

R & D GRANTS AND CONTRACTS

1. Development of advanced nanostructured catalysts for hydrogenation of carbon dioxide to methanol
   Prof. Anton Kokalj
2. Structures of elusive noble-gas compounds elucidated by 3D electron diffraction
   Prof. Anton Kokalj
3. 4D STEM of energy related materials down to quantum level
   Prof. Anton Kokalj
4. Antibacterial alloys: development by additive 3D manufacturing, characterization and clinical applications
   Prof. Ingrid Milošev
5. ChlorideSAM; A DFT Study of the Mechanism of Cl- Penetration into Organic Self-Assembled Monolayers on Aluminium
   Prof. Anton Kokalj
   CNRS

NEW CONTRACT

1. Studies of corrosion processes of rotor and stator components of electric motor drives for automotive applications as part of the Gremo i-Motion mission
   Prof. Ingrid Milošev
   Kolektor Mobility d. o. o.

VISITORS FROM ABROAD

1. Dr Simon Chwatal, Mirjam Spuller, Joanneum Research, Austria (22–24 March 2023 and 15 June 2023)

2. Prof. Daniel Lyons, Center for Marine Research, Ruđer Bošković Institute, Croatia

STAFF

Researchers
1. Prof. Anton Kokalj
2. **Prof. Ingrid Milošev, Head**
3. Asst. Prof. Peter Rodič

Postdoctoral associates
4. Dr. Njomza Ajvazi
5. Dr. Matjaž Dlouhy
6. Dr. Matic Poberžnik
7. Dr. Terezija Poženel Kovačič

8. Dr. Denis Sačer

Postgraduates
9. Lea Gašparič, B. Sc.
10. Erik Gregori, B. Sc.
11. Ana Koblar, B. Sc.
12. Nina Kovač, M. Sc.
13. Ana Kraš, B. Sc.

Technical officer
14. Barbara Kapun, B. Sc.

ELECTRONIC CERAMICS DEPARTMENT

The Electronic Ceramics Department is active in researching the synthesis, properties and applications of ceramic materials for electronics and the energy sector, mainly complex multifunctional materials and structures that can perform multiple functions (multifunctional materials). The materials of interest include piezoelectrics, ferroelectrics, relaxors, multiferroics, conductive oxides, low-dimensional magnets and cuprate superconductors. The emphasis is on the creation of properties with the synthesis and structure being on the nano-, micro- and macro-levels. The group also works on the principles of basic technologies of ceramic pressure sensors, ceramic MEMS and flexible electronics.

Head:
Prof. Barbara Malič

We continued the work on **lead-free ferroelectrics**. We investigated the voltage-driven response of the mobile, needlelike domains and domain walls of a $(K,Na)NbO_3$ single crystal using in situ biasing TEM in a capacitor-like configuration. We showed that domain growth and coalescence are not always continuous but can be interrupted at a certain voltage in favor of fine domain splitting and the formation of nanoscale domains. Other discontinuities are generated when needlelike domains meet and soft-pinning events occur. The study was published in Appied Physics Letters.

With colleagues from Technical University of Darmstadt, Germany, we assessed $Na_{0.5}Bi_{0.5}TiO_3$-based multilayer ceramic capacitors (MLCCs) with Ag/Pd internal electrodes. Optimizing the microstructure of MLCCs included designing ceramic suspensions, tape-casting, electrode screen-printing, lamination and dicing processes, and adapting the heating profile to remove organic additives efficiently. The MLCCs exhibited capacitance stability with a variation of $\leq \pm 10\%$ in a wide temperature (-67–375 °C) and voltage interval (up to 1.5 kV) making them suitable lead-free candidates for high-temperature and power electronics. The study was published in the Journal of the European Ceramic Society.

We continued our investigations on $BiFeO_3$-based ceramics, currently in focus due to their promising properties, appropriate for applications in energy conversion and storage; however, the fundamental structure-property relations in these materials are still poorly understood. With this motivation, we performed a set of analyses on $BiFeO_3$–$SrTiO_3$ (BFO–ST) ceramics using in situ X-ray diffraction with our colleagues from the Technical University of Denmark. In particular, we identified a non-ergodic-to-ferroelectric phase transition induced by electric-field cycling, often referred to in the literature as the "wake-up" process. The increased degree of random multi-site occupation, and thus charge disorder, resulting from the increased content of ST in BFO–ST solid solution, was found to correlate with the increase in the critical field needed to induce the transition. This provided a degree of freedom in controlling the ergodicity of the system, which is the key aspect in engineering materials for energy storage. Our paper on this topic was marked as "hot paper" for 2023 by the Editorial Board of the Journal of Materials Chemistry C.

In the quest for piezoelectric materials as an alternative to lead-based perovskites such as PZT, the large piezoelectric effect of $0.5Ba(Zr_{0.2}Ti_{0.8})O_3$-$0.5(Ba_{0.7}Ca_{0.3})TiO_3$ or BZT-BCT in a bulk form has been reported. BZT-BCT in the thin-film form is an effective approach to device miniaturization. One of the parameters needed for designing thin films on different substrates is the data on linear thermal expansion. The BZT-BCT bulk ceramic was prepared with a solid-state synthesis and consolidated by sintering at 1450 °C. Dielectric permittivity (ε') versus temperature measurement revealed the ε' peak at about 85 °C, indicating the transition from a low-temperature polar ferroelectric phase to a high-temperature nonpolar phase, or Curie temperature. The thermal expansion coefficients of the polar and nonpolar cubic phases of BZT-BCT are 7.69×10^{-6} K^{-1} (40°C – 80°C) and 12.39×10^{-6} K^{-1} (100°C – 600°C), respectively. The results were published in Inf. MIDEM. [Fig.1]

In February 2023 we published a perspective paper in Communication Materials covering the most updated aspects of highly performant **Pb-based relaxor-ferroelectric** perovskite materials. The review provides a critical assessment of the current understanding of these complex materials, particularly in relation with their high piezoelectric responses. The paper reviews in detail

Mojca Otoničar, Mirela Dragomir and Tadej Rojac received the Edward C. Henry Award for the paper titled "Dynamics of domain walls in ferroelectrics and relaxors". The award is given annually by the American Ceramics Society for the best contribution published in the Journal of the American Ceramic Society and Bulletin.

Figure 1: Microstructure, dielectric and ferroelectric properties of the lead-free piezoelectric ceramic $0.5Ba(Zr_{0.2}Ti_{0.8})O_3$-$0.5(Ba_{0.7}Ca_{0.3})TiO_3$

the polar structure of $Pb(Mg_{1/3}Nb_{2/3})O_3$–$PbTiO_3$-based (PMN–PT) ceramic compositions and its implications in the macroscopic piezoelectric response, providing guidelines for the next research steps to be done in this exciting area.

In collaboration with colleagues from the Reactor Physics Department, JSI, and Colorado School of Mines, USA, we continued the investigation of defect-engineered $0.9Pb(Mg_{1/3}Nb_{2/3})O_3$–$0.1PbTiO_3$ (PMN–10PT) **electrocaloric (EC) material** in applications where the material is exposed to high neutron and γ-radiation. Manganese doping of PMN-10PT (0.5 mol % and 1 mol%) contributed to the broadening of the maximum EC-temperature range compared to the undoped PMN-10PT, which could be useful for cooling applications. PMN-10PT and Mn-doped PMN-10PT ceramics were exposed to a 1 MeV equivalent neutron fluence for silicon of 10^{16} cm^{-2} (10^{17} cm^{-2}) and a γ-ray dose of 145 kGy (1200 kGy). The neutron and γ-radiation caused a decrease in the saturated polarization, an increase in the internal bias field and a reduction in the EC temperature change. The respective properties of the undoped PMN–10PT remain almost unchanged upon exposure to both radiations. This radiation-induced degradation of the EC response was attributed to the presence of acceptor (Mn)-oxygen-vacancy defect complexes and their interaction with the irradiation-induced defects. Annealing at 450 °C partially healed the radiation-induced changes in the electrocaloric response of the Mn-doped PMN-10PT. The study was published in the Journal of Physics: Energy.

As part of our ongoing research on **low-dimensional magnetism**, we extended our investigations into **transition-metal oxides**, focusing on the chemical doping of strontium copper orthoborate, $SrCu_2(BO_3)_2$. We investigated substitutions both on the A-site, by replacing Sr with aliovalent La^{3+} and Na^+, and on the B-site, by introducing magnetic dilution through Mg^{2+} substitutions on the Cu site. Although the actual concentrations of the dopants incorporated into the $SrCu_2(BO_3)_2$ structure were lower than our target values, we obtained convincing evidence that these dopants alter the magnetism of the parent system. In collaboration with the Condensed Matter Physics Department and researchers from Tohoku University, Japan, we also performed high-field magnetic measurements which revealed evidence for an additional magnetic structure that is stabilized at high magnetic fields.

We also advanced the **research on quantum spin liquid candidates**. In the frame of collaboration with the Condensed Matter Physics Department, we investigated the crystal growth of other members of the RTa_7O_{19} series (R = Er, Gd), analogues to the Ising triangular-lattice antiferromagnet $NdTa_7O_{19}$. Using the flux growth, we have recently grown $ErTa_7O_{19}$ and $GdTa_7O_{19}$ single crystals. [Fig.2]

In addition, we expanded our **research on silver(II) compounds**, investigating novel systems such as $K/Na/Rb/CsF$–AgF_2 and Bi/YF_3–AgF_2. In collaboration with researchers from the Czech Republic, we successfully determined the crystal structures of these new phases using 3D electron diffraction techniques. We also made efforts to understand the magnetic ground state of these materials by utilizing neutron powder diffraction at the Institut Laue Langevin in Grenoble, France. Moreover, we reinvestigated the crystal structure of AgF based on a low-temperature high-resolution single-crystal X-ray diffraction data.

Figure 2: Single crystals of $ErTa_7O_{19}$ (left) and $GdTa_7O_{19}$ (right) grown using the flux method developed at K5.

Mojca Otoničar organized a Women in Engineering event at the International Conference on Ferroelectric Materials and Applications in Cleveland, Ohio, USA, on gender barriers that young women in science and academia face and the approaches that researchers can adopt to minimize those barriers.
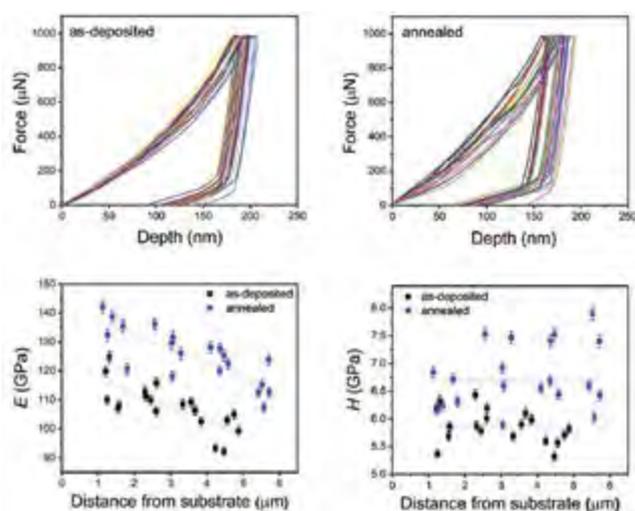
Figure 3: Force-depth curves of the as-deposited and annealed PMN-PT thick film measured with in situ SEM nanoidentation. The hardness (H) calculated from individual measurements plotted against the indentation position for both films and Young's modulus (E) calculated from individual measurements, plotted against the indentation position for both films. The error bars represent the uncertainty of the method, as determined from measurements on the fused-silica standard.

In collaboration with colleagues from the Condensed Matter Physics Department as well as colleagues from Morocco, France, Czech Republic and Ukraine, we studied piezoelectric properties of multiferroic $CoFe_2O_4$–$Ba_{0.95}Ca_{0.05}Ti_{0.89}Sn_{0.11}O_3$ nanowires. Piezo-response force microscopy (PFM) was used to detect the piezoelectric response and determine the piezoelectric coefficient ($d_{33} \sim 40$ pm·V^{-1}) of a single nanowire, as reported in RSC Advances. Furthermore, we investigated the piezoelectric and ferroelectric properties of $BaTi_{0.89}Sn_{0.11}O_3$ nanoparticles in a piezoelectric polymer matrix using PFM. The work was published in ACS Applied Nano Materials.

We continued our research on detecting hazardous substances in the environment within the ARIS project MISSPES, in collaboration with the Faculty of Chemistry and Chemical Technology, University of Ljubljana. Our aim was to achieve rapid on-site detection of the neonicotinoid pesticide with low sensitivity and high selectivity. We developed a fluidic platform using a low-temperature co-fired ceramic and multilayer ceramic technology, allowing
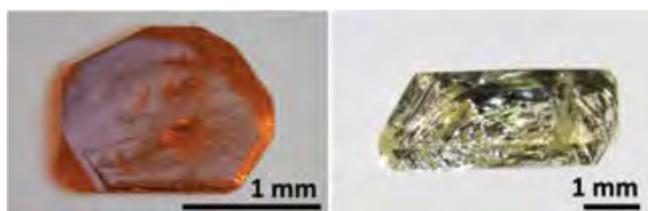
for the integration of a miniature three-electrode electrochemical sensor (ES). We validated the electrochemical response of the ES within the fluidic platform, indicating its proper functioning as an electrochemical cell.

We continued with the preparation of **thick films with the aerosol deposition method**. The aerosol deposition facility is a part of the laboratory for the ultracool preparation of complex oxides, for which financial support was granted by **the Director's Fund for the ULTRACOOL project**. In collaboration with colleagues from the Luxembourg Institute of Science and Technology, and Mechanical Engineering Faculty, University of Ljubljana, we focused on the preparation and characterization of multifunctional $0.65Pb(Mg_{1/3}Nb_{2/3})O_3–0.35PbTiO_3$ (PMN–35PT) thick films deposited on flexible polymer substrates. The thick films exhibited multifunctional properties including flexibility, electrocaloric cooling, and energy storage capability, as well as piezoelectric performance. A paper on this development was included in the 2023 Journal of Materials Chemistry C Most Popular Articles collection.

A thermal treatment is commonly employed in the preparation of electromechanically active thick films using aerosol deposition (AD) to enhance their electrical and electromechanical properties. We investigated the impact of post-annealing in air on the distinctive cross-sectional microstructure and mechanical characteristics of $0.9Pb(Mg_{1/3}Nb_{2/3})O_3–0.1PbTiO_3$ thick films fabricated via AD. While annealing induced microstructural changes at the nanoscale, the mechanical properties, i.e., the hardness and Young's modulus, were significantly affected, as evidenced by an increase in both values after annealing. [Fig. 3]

In collaboration with colleagues from the Luxembourg Institute of Science and Technology, we prepared $0.9Pb(Mg_{1/3}Nb_{2/3})O_3–0.1PbTiO_3$ (PMN–10PT) thick-film structures with a high electrocaloric effect. At room temperature, we observed the highest electrocaloric temperature change of 1.5 °C at an electric field of 600 kV/cm, while this change was 2.4 °C at an ambient temperature of 100 °C. Such excellent electrocaloric properties of the thick-film structures were achieved by depositing functional layers on thermally insulating polymer substrates. [Fig.4] The functional films were prepared using the aerosol deposition method that enables the preparation of dense ceramic films at room temperature, compatible with the low melting temperature of polymer substrates. The results were published in Small Methods.

In collaboration with the Colorado School of Mines from the USA, we prepared Al_2O_3/Al composite thick films. They were prepared using the aerosol deposition method, which allows simultaneous deposition of two powders. Films with 27 vol.% of aluminum exhibited eight times higher dielectric permittivity compared to films without aluminum, i.e., 800 versus 12. However, dielectric losses of the films also increased by a factor of about five. By measuring dielectric properties, modelling and locally measuring electrical conductivity with an atomic force microscope, we found that the percolation threshold occurs at an aluminum content of about 27 vol.% within the alumina matrix.

The development of functional ceramics using the **cold sintering process (CSP)** was governed by optimizing the cold-sintering parameters of $BiFeO_3$ and $K_{0.5}Na_{0.5}NbO_3$-based ceramics, especially the compounds and quantities of the transient liquids used for cold sintering of different ceramic compositions. The electrical and electromechanical properties of cold-sintered ferroelectric ceramics show a great potential of these materials for transducer and energy storage applications, with high dielectric breakdown strength and reduced dielectric losses. The cause of these properties was found in the peculiar and distinctive microstructures of cold-sintered materials, induced by the pressure-dissolution process during their formation, studied with scanning transmission electron microscopy. [Fig. 5] Their unique structural features include strongly etched grain-boundary contacts with interlocking grains, crystal-lattice defects (i.e., lattice bending, edge and screw dislocations and faults), dynamically stable open-pore-channel frameworks, nanometre-sized closed pores that are bound to kinked grain boundaries and dislocations, possible undesired nanosized precipitates, and changed oxidation states with likely reduced ionic

The K5 department takes part in the SCUALE (Sustainable Components for Underwater Acoustics using Lead-free materials in Europe) project. It is coordinated by Thales, and brings together 14 industry players and research institutes from 8 European countries. The project aims to study, develop and produce advanced lead-free materials and components with improved performance to replace existing piezoelectric ceramics for underwater military acoustic applications.
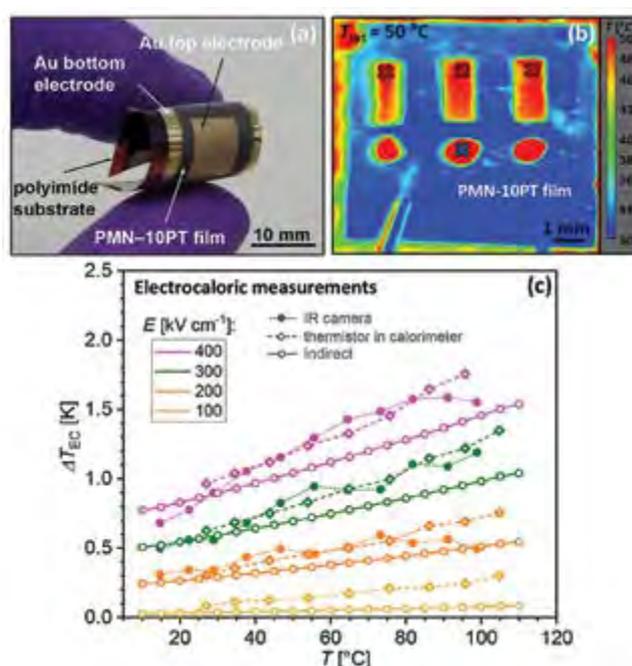
Figure 4: (a) Electrocaloric PMN–10PT thick film prepared with aerosol deposition on a flexible polymer substrate. (b) View of the PMN–10PT electrocaloric thick film captured with a thermal imaging camera. (c) The electrocaloric temperature change of the layer as a function of the external temperature. Electrocaloric measurements were carried out using three different methods.

The MSCA-IF project QMatCh, led by Mirela Dragomir, was highlighted as a Success Story in the MSCA Widening Countries Inspirational Stories.
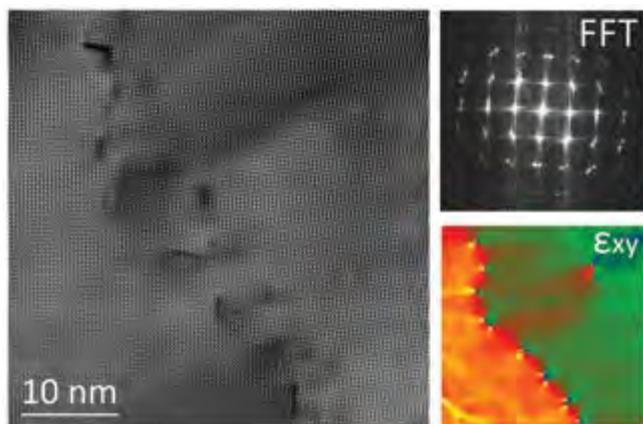
Figure 5: Scanning transmission electron microscopy image showing a set of crystal-lattice dislocations in a $K_{0.5}Na_{0.5}NbO_3$ ferroelectric-ceramic grain, deformed during cold sintering. On the right-hand side are the fast Fourier transform (FFT) of the atomically resolved image and geometric phase analysis, showing deformation and strain in the lattice, respectively.

species. While the main purposes of developing the CSP method are energy savings due to the low-temperature processing and combining chemically different materials into composites, the cracking induced by pressure during sintering and sensitivity of samples to moisture remain the bottleneck in producing cm-scale electroceramic components. For this reason, a better understanding and further development of the CSP method are needed, thus, our studies will continue.

In collaboration with colleagues from the Luxembourg Institute of Science and Technology, we prepared $Pb(Zr,Ti)O_3$ (PZT)-based thick films using the **screen printing** method. The piezoelectric structures on alumina substrates exhibited good properties for a power-efficient haptic actuator. At the limit of touch detection (1 μm out-of-plane deflection), the device consumes only 5 mW at a unipolar voltage of 20 V. At a unipolar voltage of 150 V, the peak-to-peak out-of-plane displacement reaches nearly 10 μm. The study was published in Sensors and Actuators A: Physical.

In collaboration with the National Institute of Chemistry from Ljubljana and RC eNeM we investigated the integration of transparent electronics onto an industrial glass product for the next generation of transparent electronics. The research focused on the development of cost-efficient, environmentally friendly, solution-based manufacturing in an industrial environment. Using non-toxic alcohol-based solutions, we successfully spin-coated transparent thin films of gallium-doped ZnO and indium zinc oxide (IZO) on glass. After annealing at 600 °C in air these films did not exhibit long-range ordering, having a uniform microstructure and smooth surfaces. After annealing in an Ar/H_2 atmosphere, the sheet resistance of the films decreased significantly to a value of a few hundred W/ . These properties are very promising for transparent electronic applications.

Some outstanding publications in the past year

1. Prah, Uroš, Šadl, Matej, Torello, Alvar, Lheritier, Pierre, Kovacova, Veronika, Uršič Nemevšek, Hana, Defay, Emmanuel. Direct electrocaloric characterization of ceramic films. *Small Methods*. 2023, vol 7, iss. 9, [article no.] 2300212, pp. 1–8, illustr. ISSN 2366-9608. https://onlinelibrary.wiley.com/doi/10.1002/smtd.202300212 DOI: 10.1002/smtd.202300212 [COBISS.SI-ID 153049859]

2. Stojanoska, Izabela, Okorn, Miha, Kmet, Brigita, Uršič Nemevšek, Hana, Gradišnik, Vera, Čakara, Duško, Kovač, Janez, Kuščer, Danjela. Indium-zinc-oxide thin films produced by low-cost chemical solution deposition: Tuning the microstructure, optical and electrical properties with the processing conditions. *Heliyon*. 2023, vol. 9, iss. 9, pp. 1–13, DOI: doi.org/10.1016/j.heliyon.2023.e19744. [COBISS.SI-ID 163179779]

3. Salmanov, Samir, Koblar, Maja, Kmet, Brigita, Malič, Barbara, Rojac, Tadej, Kuščer, Danjela, Otoničar, Mojca. Structure and electrical properties of cold-sintered strontium-doped potassium sodium niobate. *Journal of the European Ceramic Society*. [Print ed.]. 2023, pp. 7516–7523, illustr. ISSN 0955-2219. https://www.sciencedirect.com/science/article/pii/S0955221923005964?via%3Dihub#ec0005, DOI: 10.1016/j.jeurceramsoc.2023.07.069. [COBISS.SI-ID 160125699]

4. Sarkar, Ankita, Šadl, Matej, Jazbec, Anže, Snoj, Luka, Drnovšek, Silvo, Rojac, Tadej, Brennecka, Geoff, Uršič Nemevšek, Hana, Malič, Barbara. Influence of neutron and gamma irradiation on the electrocaloric properties of Mn-doped $0.9Pb(Mg_{1/3}Nb_{2/3})O_3$–$0.1PbTiO_3$ ceramics. *JPhys Energy*. 2023, vol. 5, no. 4, [article no.] 045006, pp. 1–12, illustr. ISSN 2515-7655. https://iopscience.iop.org/article/10.1088/2515-7655/acf61b, DOI: 10.1088/2515-7655/acf61b. [COBISS.SI-ID 164507907]

5. Rojac, Tadej. Piezoelectric response of disordered lead-based relaxor ferroelectrics. *Communications Materials*. 2023, vol. 4, article no. 12, pp. 1–7, illustr. ISSN 2662-4443. https://www.nature.com/articles/s43246-023-00336-9#Abs1, DOI: 10.1038/s43246-023-00336-9. [COBISS.SI-ID 141850883]

6. Condurache, Oana, Dražić, Goran, Rojac, Tadej, Uršič Nemevšek, Hana, Dkhil, Brahim, Bradeško, Andraž, Damjanović, Dragan, Benčan, Andreja. Atomic-level response of the domain walls in bismuth ferrite in a subcoercive-field regime. *Nano Letters*. 2023, vol. 23, iss. 2, pp. 750–756, illustr. ISSN 1530-6992. DOI: 10.1021/acs.nanolett.2c02857. [COBISS.SI-ID 133050115]

Awards and Appointments

1. Barbara Repič, student award "Alessandro de Vita" at the cross-border workshop for doctoral students in the field of nanoscience and nanotechnology CrossNano 2023, organizing committee CrossNano2023

2. Mirela Dragomir, Mojca Otoničar, Tadej Rojac, "Edward C. Henry Award" for outstanding contribution published in the Journal of the American Ceramic Society, Awards and scholarships committee of the Journal of the American Ceramic Society

Organization of conferences, congresses and meetings

1. MIDEM 2023: 58th International Conference on Microelectronics, Devices and Materials with the Workshop on Chemical Sensors: materials and applications, Lipica, Slovenia, September 27-29, 2023

INTERNATIONAL PROJECTS

1. Laboratory Measurements
   Prof. Barbara Malič
   TDK Electronics GmbH & Co Og
2. Laboratory Measurements for TDK
   Prof. Hana Uršič Nemevšek
   TDK Electronics GmbH & Co Og
3. Laboratory Measurements
   Prof. Andreja Benčan Golob
   TDK Electronics GmbH & Co Og
4. Optical Dilatometry Analysis
   Prof. Barbara Malič
   Lithoz GmbH
5. H2020 - ATHENA; Implementing Gender Equality Plans to Unlock Research Potential of RPOs and RFOs in Europe
   Prof. Barbara Malič
   European Commission
6. H2020 - QMatCh; Towards Quantum States of Matter via Chemistry under Extreme Conditions
   Asst. Prof. Mirela Dragomir
   European Commission
7. Realizing In-Situ Studies of Dynamic Mechanisms in Ceramic Oxides in the Reducing Environment in a Transmission Electron Microscope
   Prof. Andreja Benčan Golob
   Slovenian Research Agency
8. ABO3-Type Perovskite Structured Ferroelectric Ceramics for Future Sensors, Actuators and Solid-State Refrigerators
   Prof. Hana Uršič Nemevšek
   Slovenian Research Agency
9. Low Temperature Processing of Piezoelectric Thick Films for Medical Imaging and Energyharvesting Applications
   Prof. Hana Uršič Nemevšek
   Slovenian Research Agency
10. Ferroelectric and Antiferroelectric Ceramic Materials
    Prof. Hana Uršič Nemevšek
    Slovenian Research Agency
11. Single-Crystal Growth and High-Pressure Studies of Low-Dimensional Quantum Magnets
    Asst. Prof. Mirela Dragomir
    Slovenian Research Agency
12. EDF; SCUALE - Sustainable Components for Underwater Acoustics using Lead-Free Materials in Europe
    Prof. Barbara Malič
    European Commission

RESEARCH PROGRAMME

1. Multifunctional materials and devices: from quantum to macroscale
   Prof. Barbara Malič

R & D GRANTS AND CONTRACTS

1. In situ atomic level Quantitative Scanning Transmission Electron Microscopy of Functional Materials
   Prof. Andreja Benčan Golob

2. TCCbuilder: An open-source simulation tool for thermal control circuits
   Prof. Barbara Malič
3. The quest for high-temperature superconductvity and exotic magnetism in fluoridoargentates(II)
   Asst. Prof. Mirela Dragomir
4. Designing functionality of lead-free ferroelectrics through domain wall engineering
   Prof. Andreja Benčan Golob
5. The cool way to polarize
   Asst. Prof. Mojca Otoničar
6. Engineering of relaxor ferroelectric thin films for piezoelectric and energy storage applications
   Prof. Tadej Rojac
7. Structures of elusive noble-gas compounds elucidated by 3D electron diffraction
   Asst. Prof. Mirela Dragomir
8. All in One: Multi-caloric and Multi-scavenging Elements for Green Future
   Prof. Hana Uršič Nemevšek
9. High-pressure stabilization and phase transitions of elusive transition-metal fluorides
   Asst. Prof. Mirela Dragomir
10. Enhanced piezoelectricity via structural disorder in polycrystalline relaxor ferroelectrics
    Prof. Tadej Rojac
11. MIcrofluidic Sensor System for PESticides detection (MISS PES)
    Prof. Danjela Kuščer Hrovatin
12. Flexible elements with multi-physical properties
    Prof. Hana Uršič Nemevšek
13. Antiferroelectric materials for cooling and high power electronic applications
    Prof. Andreja Benčan Golob
14. 4D STEM of energy related materials down to quantum level
    Prof. Andreja Benčan Golob
15. Anisotropic quantum magnetism in novel rare-earth materials
    Asst. Prof. Mirela Dragomir
16. Dislocation imprint by cold sintering to tailor ferroelectric polarization
    Asst. Prof. Mojca Otoničar
17. Process intensification for the continuous synthesis of high purity hydrogen peroxide using a micro-scale electrocatalytic reactor
    Prof. Barbara Malič
18. Advanced materials and technologies for the sustainable printed electronics on glass
    Prof. Danjela Kuščer Hrovatin
19. Battery Thermal Management System Based on High Power Density Digital Microfluidic Magnetocaloric Cooling
    Prof. Hana Uršič Nemevšek
    Ministry of Higher Education, Science and Innovation
20. Minor Services - Foreign Customers
    Prof. Barbara Malič

NEW CONTRACTS

1. Advanced materials and technologies for the sustainable printed electronics on glass
   Prof. Danjela Kuščer Hrovatin
   Razvojni Center Enem Novi Materiali d. o. o.
2. Development of microstructured non-porous bulk ceramics with special properties for possible use in LTCC structures, development and study of materials for use in fuel cells and electrolyzers
   Prof. Barbara Malič
   Keko - Oprema d. o. o. Žužemberk

VISITORS FROM ABROAD

1. Katarina Lubina, Josip Juraj Strossmayer University of Osijek, Osijek, Croatia, January 8 – April 8, 2023
2. Dr Jurij Koruza, Graz University of Technology, Graz, Austria, January 16, 2023
3. Antonio Bartošak, University of Bjelovar, Bjelovar, Croatia, January 23 – April 22, 2023
4. Lovro Pečur, University of Bjelovar, Bjelovar, Croatia, January 23 – April 22, 2023
5. Prof. Dragan Damjanovic, Lausanne, Switzerland, January 30 – February 10, 2023
6. Enrico Maradei, University of Bologna, Bologna, Italy, March 1 – June 1, 2023
7. Meryem Lachhab, University Limoges, France, March 3 – June 3, 2023
8. Paul Derkinderen, IUT de Blois, Blois, France, April 3 – June 16, 2023
9. Anya Geairon, University Orléans, Orléans, France, April 1 – July 1, 2023
10. Luka Nunar, University College London, London, Great Britain, April 3-21, 2023
11. Prof. Andreas Klein, Technical University Darmstadt, Darmstadt, Germany, April 11-13, 2023
12. Dr Shuang Gao, Technical University Darmstadt, Darmstadt, Germany, April 15-22, 2023
13. Floryne Brosse, University Tours, Tours, France, April 11 – June 23, 2023
14. Prof. Alp Sehirlioglu, Case Western Reserve University, Cleveland, Ohio, USA, April 19-21, 2023
15. Gabriel Burghgrave, INETUM Lille, Lille, France, May 22 – August 25, 2023
16. Prof. Vera Gradišnik, University of Rijeka, Rijeka, Croatia, June 5-16, 2023
17. Matthieu Laloyer, Clermont Auvergne INP, Aubriere, France, June 5 – September 15, 2023
18. Prof. Franck Levassort, Tours University, Tours, France, June 8-9, 2023
19. Iana Deldicque, Dassault Aviation, Paris, France, July 1 – September 30, 2023
20. Alexandre Sierk, CFA SUP Nouvelle-Aquitaine, Chasseneuil du Poitou, France, July 3–September 22, 2023
21. Prof. Brakhim Dkhil, CentraleSupélec, Paris, France, August 23-25, 2023
22. Prof. Tileli Vasiliki, Ecole Polytechnique Federale de Lausanne, Lausanne, Switzerland, August 28-30, 2023
23. Aikaterini Spanou, University of Crete, Crete, Greece, October 1 – December 31, 2023
24. Prof. Andrew J. Bell, University Leeds, Leeds, Great Britain, October 16-20, 2023

STAFF

Researchers
1. Prof. Andreja Benčan Golob
2. Dr. Andraž Bradeško*
3. Asst. Prof. Mirela Dragomir
4. Prof. Goran Dražić*
5. Prof. Danjela Kuščer Hrovatin
6. Dr. Kostja Makarovič*
7. **Prof. Barbara Malič, Head**
8. Asst. Prof. Mojca Otoničar
9. Prof. Tadej Rojac
10. Prof. Hana Uršič Nemevšek

Postdoctoral associates
11. Dr. Antonio Iacomini
12. Dr. Soukaina Merselmiz
13. Dr. Alaka Panda
14. Ankita Sarkar, M. Sc.
15. Dr. Aadil Abass Shah
16. Dr. Matej Šadl

Postgraduates
17. Matic Belak Vivod, B. Sc.

18. *Dr. Oana Andreea Condurache, left 01.11.23*
19. Ivana Goričan, B. Sc.
20. Maja Koblar, B. Sc.
21. Sabi William Konsago, M. Sc.
22. Victor Regis De Moraes, M. Sc.
23. Barbara Repič, B. Sc.
24. Samir Salmanov, M. Sc.
25. Lia Šibav, B. Sc.
26. Blaž Velkavrh, B. Sc.
27. Katarina Žiberna, B. Sc.

Technical officers
28. Izabela Čurković, B. Sc.
29. Silvo Drnovšek, B. Sc.
30. Brigita Kmet, B. Sc.

Technical and administrative staff
31. Andrej Debevec
32. Tina Ručigaj Korošec, B. Sc.

Note:
* part-time JSI member

DEPARTMENT FOR NANOSTRUCTURED MATERIALS K-7

The research and development at the Department for Nanostructured Materials are focused on the leading-edge areas of nanotechnology and advanced materials, addressing the most difficult societal challenges that Europe and the world are currently facing. This includes clean and efficient energy, health, environment remediation and critical-raw-materials resource efficiency. A versatile team with synergies across a variety of complementary basic and applied expertise in combination with state-of-the-art research methods enables us to respond promptly to various emerging challenges. The basic and applied research of the Department for Nanostructured Materials includes permanent magnets and intermetallic alloys, engineering and functional ceramics, minerals, sensors, materials for a sustainable and ecologically built environment, biomimetic materials and biomaterials.

Head:
Prof. Sašo Šturm

Magnetic materials

Magnetic materials group is addressing the most pressing European social challenges, which are closely related to the goals of the European Green Deal and the Critical Raw Materials Act. We want to contribute to climate neutrality by developing resource-efficient and environmentally friendly e-mobility and green-energy production. At the same time, we promote a circular economy in the use of materials by recycling them, which reduces the EU's dependence on critical raw materials from foreign sources. Permanent magnets based on critical rare-earth elements (Nd-Fe-B, Sm-Co) have the best performance and highest energy product. They are of particular concern to the EU as they are indispensable for electric mobility and green electricity production in wind turbines. For this purpose, we devise solutions for the design, production and applications of permanent magnets with improved magnetic properties and the efficient use of material resources. With our work, we strive to develop knowledge and create new solutions to contribute to a more sustainable and resilient future for Europe and beyond.

Europe is at the forefront of the Green Transition, but its success depends on sustainable energy and mobility solutions.

Modelling of advanced magnetic devices – One of the alternative approaches to reducing the consumption of critical rare-earth materials in permanent magnets is to optimize their geometry for specific applications, for example, in magnetic generators or so-called magnetic harvesters. This generator converts mechanical work into electrical energy and enables the powering of a smartphone without using an external power source. The proposed concept uses magnets of smaller volumes and more complex shapes. We designed two new permanent magnets for a novel magnetic harvester using the finite-element method. The optimization of the dimensional parameters showed that the proposed solutions are more efficient than the existing standard implementations. A schematic representation of the conversion of mechanical energy during human movement to power smart devices and the constructed magnetic harvester are shown in Figure 1. The research results were published in the magazine *Materials and Technology* in the paper entitled Optimum design of a permanent-magnet-based self-charging device for a smartphone (https://doi.org/10.17222/mit.2023.968).

Rapid consolidation of permanent magnets – Within the framework of the **ARIS Z2-2645** project (https://www.ijs.si/ijsw/ARRSProjekti/2020/Z2-2645) we developed strategies for the rapid consolidation of Nd-Fe-B-type magnets based on the novel approach of intense thermal radiation, i.e., radiation-assisted sintering (RAS). Rapid densification and sintering occur in a modified conventional spark plasma sintering (SPS) furnace, enabling fast and efficient heating. The novel furnace arrangement allows no pressure to be applied to the magnetically oriented green compacts. The

Figure 1: Schematic of the conversion of mechanical energy during human movement (left, middle) for powering smart devices and the constructed magnetic harvester (right)

latter is of decisive importance in preserving the pre-aligned magnetic texture in the final magnet, which leads to higher remanent magnetization values (B_r) and high energy products $(BH)_{max}$, with comparable coercivities (H_{ci}) to conventional sintering. The new RAS strategy enables the densification of standard Nd-Fe-B powders in just 10 minutes, with magnetic properties comparable to magnets prepared in a conventional way. It is important to emphasize that short heating cycles reduce the energy consumption required to prepare advanced Nd-Fe-B magnets by an order of magnitude compared to slow, hours-long, conventional sintering strategies.

In 2023 we finished a project in the scheme **EIT RAW Materials 21043 RECO2MAG** (https://reco2mag.rgf.bg.ac.rs/), whose primary aim was to assist industry in developing Nd-Fe-B permanent magnets with improved properties. We have developed innovative methods that include the improved jet-milling of strip-cast Nd-Fe-B feedstocks. With further additions of NdH_3 and DyF_3 we have raised the magnetic properties denoted as magnetic grades from the current N38M to N48M (Br=1.2T→1.4T). At the same time, we also increased the coercivity from class M to UH (1200 kA/m (M)→1800 kA/m (UH)). We also successfully implemented the electrophoretic deposition of heavy rare earths to industrially produced Nd-Fe-B magnets. With the subsequent process of diffusing heavy rare earths along the grain boundaries, we achieved an increase in coercivity from M grade to SH grade (1100 kA/m (M) to 1750 kA/m (SH)).

We continued our research in the **EIT RAW Materials INSPIRES project** (https://inspires-magnet.eu/). The project focuses on recycling and reprocessing Nd-Fe-B permanent magnets. We conducted jet-milling of hydrogen-processed magnetic scrap (HPMS) received from Pforzheim University, followed by sintering trials incorporating DyF_3 and NdH_3 additives for enhanced coercivity. Both conventional and rapid sintering methods were employed, with RAS showing a 30% increase in coercivity to ~1300 kA/m compared to conventional methods. Using the HPMS process we successfully recycled 10 kg of waste magnets. We produced powders suitable for sensor applications with coercive force H_{ci} = 600 kA/m and remanent magnetization B_r = 0.75 T to be further processed into bonded magnets at our industrial partner Kolektor KFH.

Tailoring the permanent magnets' properties at the level of individual grains - As part of the **MSCA PF OCARINA** project (https://cordis.europa.eu/project/id/101024046) we provided guidelines for developing new permanent magnets of the Nd-Fe-B type by tailoring the magnetic properties at the level of individual grains. The strategy involves the preparation of an input material on which a new microstructure of the magnet is built by adding novel phases. The input material must, therefore, be monocrystalline or single-grain and be based solely on the $Nd_2Fe_{14}B$ matrix phase. The monocrystalline $Nd_2Fe_{14}B$ was obtained by environmentally friendly chemical etching with an organic acid. The latter is selective and preserves the magnetic properties of the $Nd_2Fe_{14}B$ matrix phase, while successfully removing the Nd-rich intergranular phase, proven on fresh and recycled materials.

The work was published in *MDPI Materials* in two manuscripts: Environmentally friendly approach for $Nd_2Fe_{14}B$ magnetic phase extraction by selective chemical leaching: a proof-of-concept study (https://doi.org/10.3390/ma16145181) and in Short-loop recycling of Nd-Fe-B permanent magnets: a sustainable solution for the $Nd_2Fe_{14}B$ matrix phase recovery (https://doi.org/10.3390/ma16196565).

Figure 2: A schematic flow of the selective leaching process of Nd-Fe-B permanent magnets

Our work within the **Horizon EU project 101058598 – REEsilience** (https://reesilience.eu/) continues research on the development of new permanent magnets of the Nd-Fe-B type by tailoring the magnetic properties at the level of individual grains. The latter was obtained through selective chemical leaching based on recycled feedstocks. Adding a low-eutectic Nd-Cu alloy in the range 0–30 wt. % to the single-crystal matrix phase $Nd_2Fe_{14}B$, we introduced a new metallic phase source at the grain boundary. The bulk Nd-Fe-B magnets prepared with an SPS furnace had a high coercivity H_{ci}=826 kA/m and remanent magnetization B_r=1 T. The developed method, which uses $Nd_{70}Cu_{30}$ instead of pure Nd, supports the development of efficient recycled permanent magnets with a reduced content of critical elements and good performance. Furthermore, by applying an electrochemical approach to the $Nd_2Fe_{14}B$ monocrystalline phase, we successfully deposited a 1-µm layer of Cu on the powder particles via chemical reduction. By introducing Cu as a non-critical element into the Nd-Fe-B microstructure, we can further tailor the magnetic properties of Nd-Fe-B magnets at the level of individual grains.

Non-rare-earth-based permanent magnets – We continued research on strengthening ceramic magnets based on ferrites in the permanent magnets segment without critical rare-earth elements. Since rapid densification and sintering play a key role in manufacturing functional materials, it encourages us to explore the consolidation potential of Sr-ferrite-based ceramic magnets further. In the **EU project PASSENGER** (https://passenger-project.eu/) we characterized novel, ferrite-based magnetic powders and condensed magnets.

Bonded permanent magnets - a key goal in this segment is the development of clean-manufacturing technologies that shorten the path between the initial design stages and the finished products. We are dedicated to additive technologies (3D-printing), which enable the rapid production of complex magnetic prototypes, from both fresh and recycled powders. In 2023, the **EIT Manufacturing aProMag project** (www.apromag.eu) was completed. The project aimed to develop innovative rotor prototyping processes for brushless DC motors and actuators using the advanced 3D-printing of permanent magnets.

Key innovations included: i) integration of 3D- printing directly in the magnetic field to produce magnetically orientated magnets with improved magnetic properties, ii) use of powder from recycled Nd-Fe-B magnets and iii) cost/time savings through rapid prototyping. The breakthroughs we achieved are a developed sensor system for
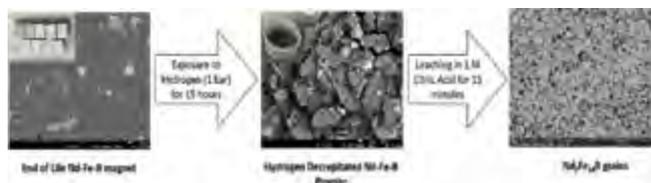
monitoring magnetic filaments and constructing a precision nozzle to produce magnetically orientated magnets with complex shapes.

Furthermore, in the framework of the 3D printing of permanent magnets we produced filaments based on $SrFe_{12}O_{19}$ with polyphenylene sulfide (PPS) with a filling factor of 70 wt. %. We subsequently printed this filament with a 3D printer directly onto a permanent magnet. Upon printing in a magnetic field, we increased the remanent magnetization by 61% due to improved magnetic orientation. The research entitled "**Additive-manufactured anisotropic magnets for harsh environments**" was published in the *Journal of Magnetism and Magnetic Materials* (https://doi.org/10.1016/j.jmmm.2023.171165).

We continued our research on the **M.ERA.NET Addmag project** (https://www.m-era.net/materipedia/2021/addmag) investigating the additive-manufacturing-based production of complex Nd-Fe-B magnets from recycled material. The first attempts to make magnets by 3D printing and sintering showed that the carbon was not completely removed from the polymer and caused the formation of free iron. We are now optimizing the process to remove all the polymer and testing samples with lower polymer content and different polymers that are easier to remove from the sample.

Figure 3: Schematic of printing in a magnetic field (left). Demagnetization curves of the pure Sr-ferrite powder (100%-orange) and the 3D prints (70%-blue), with (solid line) and without (dashed line) an external magnetic field (right) (https://doi.org/10.1016/j.jmmm.2023.171165)

Chemical recycling of permanent magnets – In the **MSCA PF Gyromags** Green Recycling Route for Sm-Co Permanent Magnet Swarf (https://cris.cobiss.net/ecris/si/en/project/19583) we dealt with waste grinding swarf from producing Sm-Co magnets. The primary aim was to clean, recycle and use it as a secondary source of samarium and cobalt. By reducing the carbon content from ~8 wt. % to 0.15 wt. % with chemical and pyrometallurgical processes we gave new guidelines for its efficient recycling.

Complex intermetallic alloys

The International Research Laboratory (IRL), a collaboration between the Jožef Stefan Institute (JSI) in Slovenia and the Jean Lamour Institute (IJL) in France, aims to be a leading European center for developing complex inorganic materials.

Utilising a holistic approach called materiomics, we explore the links between physicochemical material properties and material characteristics and function over relevant length scales. Within this frame, CNRS granted the prolongation of the existing collaboration into a new IRL: *Materiomics of Complex Inorganic Materials.* This new IRL deals with both structurally or chemically complex materials, covering alloys and intermetallic compounds from large-unit-cell crystals to aperiodic materials and high-entropy alloys, as well as new complex oxide phases.

In recent studies we investigated the oxide layer growth and surface topography changes in an $Al_{59}Cu_{25}Fe_{13}B_3$ quasicrystalline (QC) material under various ambient conditions. The boron-rich $AlFe_2B_2$ phase was found to be most susceptible to oxidation, affecting the surface's wettability. The study highlighted the strong dependency of surface energy on the polar component, which is highly sensitive to environmental conditions. These findings were published in *Crystals* (https://doi.org/10.3390/cryst13060859).

Figure 4: Transmission electron microscopy (TEM) images of the QC annealed at 500 °C for 1h in air and high-magnification image of the oxide on the surface of the QC bulk with the diffraction patterns (https://doi.org/10.3390/cryst13060859)

Fusion materials

Plasma-facing structural materials are one of the bottlenecks to successfully and economically implementing fusion as an energy source. Therefore, the development of novel materials within the framework of the European fusion program EUROfusion (2021–2025) is of the utmost importance for technological progress.

During this period we continued our research into $W–W_2C$ composites to improve the long-term resistance of plasma-facing tungsten-based materials. The $W-W_2C$ composite with 4 at. % C in the initial composition exhibits a brittle-ductile transition temperature that is 200 °C lower in comparison to current state-of-the-art tungsten materials foreseen for the divertor application, making it an attractive candidate material.

The continued development is focused on the in-depth investigation of the microstructure-property relationship of this material and the up-scaling capabilities towards the demonstration of industrial-scale manufacturing. Additionally, the additive manufacturing of $W–W_2C$ is being investigated as a prospective path towards more complex-shaped and functionally graded components.
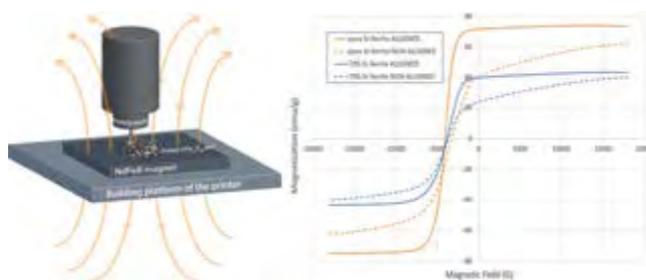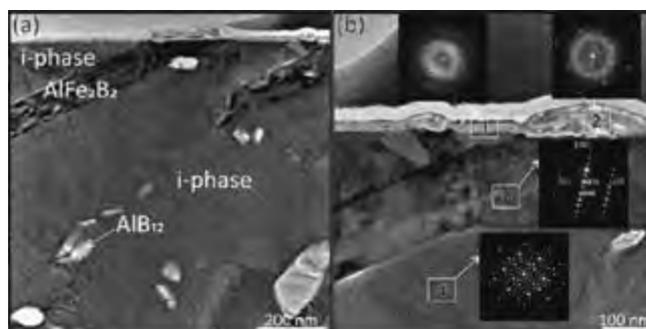
Figure 5: Schematic (left) and analysis of the formation of the interphase layer between W and WC with use of scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD) (https://doi.org/10.1016/j. ijrmhm.2023.106301)

In collaboration with the Department for Low and Medium Energy Physics (F2) we investigated the effect of deuterium retention in tungsten, tungsten carbide, and tungsten-ditungsten carbide composites. The research was published in the *Journal of Nuclear Materials* (https://doi.org/10.1016/j. jnucmat.2023.154455), indicating that the microstructural and crystal lattice form stable functionally graded plasma-facing components in the W-C system. In 2023 we also published our research on the microstructural development of composite structures between W and WC. A study published in the *International Journal of Refractory Metals & Hard Materials* (https://doi.org/10.1016/j.ijrmhm.2023.106301) focused on the ability to design stable functional gradient components in the W-C system suitable for use in components in contact with plasma.

Catalysis

Apart from the knowledge gained from the previous studies on TiO_2, the Catalysis Group successfully continued the research on high-entropy materials (HEMs) for catalytic applications. The past knowledge of anodic oxidation process has been implemented on the high-entropy alloy (HEA) substrate to grow high-entropy oxides (HEOs). The preliminary conversion was tested on refractory TiNbZrHfTa HEA composition.

Our preliminary results showed that anodic oxidation of TiNbZrHfTa resulted in the formation of oxide nanotubes with different diameters by changing the applied potential during HEA anodization (60 V = Ø130 nm, and 30 V = Ø50 nm). This exemplifies how the anodization process itself can tune some morphological features of the nanostructured thin film.

On the other hand, the Cantor HEA alloy showed promising results in the process for the oxygen-evolution reaction (OER). We successfully synthesized a spinel $(CoFeNiMnCr)_3O_4$ HEO thin film by electrochemical modification of equiatomic CoFeNiMnCr HEA and subsequent thermal treatment. This synthesis strategy is advantageous since the formed HEO thin film can be considered a well-defined surface, and the thin-film thickness can be tuned from nanometres to a few micrometres by processing parameters. The $(CoFeNiMnCr)_3O_4$ HEO exhibits a low overpotential for the OER, that is 341 mV at 10 mA/cm^2, a Tafel slope of 50 mV/dec, and an unchanged surface after a long-term stability test in alkaline media. These results are similar (or even better) to those obtained by $(Co,Cu,Fe,Mn,Ni)_3O_4$ synthesized in powder form and loaded in carbon nanotubes (350 mV, 59.5 mV/dec,) and/or to RuO_2 (235 mV, 77.2 mV/dec), thus evidencing the great potential of HEOs for OER.

The research vision of the Catalysis Group is to apply electrochemical oxidation processing techniques on new classes of materials to tailor/modify the morphology, structure, and chemistry of their surfaces, which, in contact with liquid or gaseous media/substances causes desirable catalytic transformations/ degradations of substances via photocatalytic (photoelectrocatalytic, electrocatalytic) processes for various applications in environment and energy.
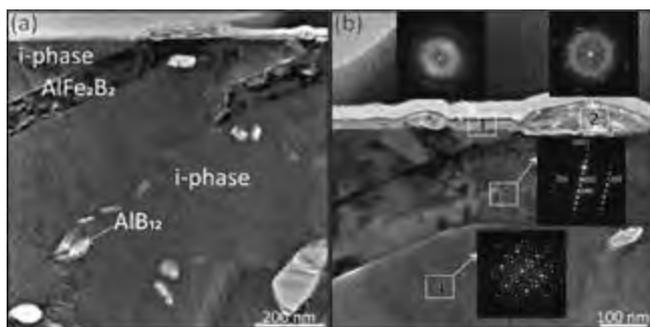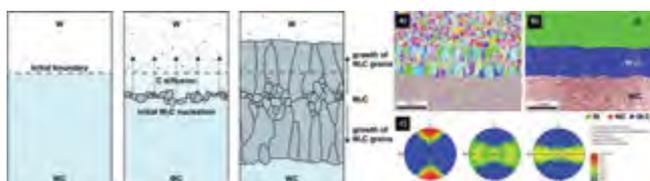

Figure 6: SEM image of anodized TiNbZrHfTa HEA with applied potential of 60 V (upper) and 30 V (lower)

Figure 7: Top-view SEM image of electrochemically treated CoFeNiMnCr HEA (left), $(CoFeNiMnCr)_3O_4$ (middle), and LSV curves (right) for (■) CoFeNiMnCr HEA and (▲) $(CoFeNiMnCr)_3O_4$ HEO

This discovery has far-reaching implications for water-splitting research. It shows how resolving atomistic structure of mineral–water interfaces is crucial for understanding the photocatalytic properties of minerals and can be used as a guide to design mineral-based functional materials.

The interface structure and surface chemistry of rutile fibres were studied in the presence of water by means of advanced high-resolution microscopy and spectroscopy methods combined with the atomistic structure modelling and density functional theory (DFT) calculations. While staying in stable separation throughout their growth, the rutile fibres were shown to adopt a special crystallographic registry that is controlled by strong repulsion forces generated between fully hydroxylated and protonated (110) surfaces. During the relaxation, a turbulent proton transfer and cracking of the O–H bonds was observed, generating a strong acidic character via proton jump from the bridge –OH^b to the terminal –OH^t groups, and spontaneous dissociation of the interfacial water via a transient protonation of the –OH^t groups was observed. Furthermore, it was shown that this particular interface structure can be implemented to induce an acidic response in an initially neutral medium when re-immersed. Our work presents the first demonstration of a quantum confined mineral–water interface capable of memorizing its past and conveying its structurally encoded properties into a new environment.

Our study entitled *Mnemonic rutile-rutile interfaces triggering spontaneous dissociation of water* (https:// doi.org/10.1002/adma.202308027) was immediately recognized as of key importance by the Editorial Board of Advanced Materials (IF=29.2) and received high opinions from the reviewers. Following its publication, the paper

was tagged as Editor's Choice and highlighted as Hot Topic in the Section of catalytic water splitting. The key authors of this article come from the Department of Nanostructured Materials.

Sensors

Within the Sensors Group, we focus on the development of sensitive and selective receptor elements for the electrochemical detection of toxic organic compounds (TOCs), persistent and mobile chemicals (PMCs), biomolecules, and pathogens. The receptor elements are based on three-terminal screen-printed electrodes (SPEs) connected to a portable potentiostat, enabling inexpensive and user-friendly electrochemical sensors for real sample measurements.

Catechol (CC), resorcinol (RS), and hydroquinone (HQ) are benzenediol isomers that are known to pose problems to living beings. HQ is banned in the cosmetic industry, while RS is its replacement. They are electrochemically active molecules, and detection was performed using SPEs where the working electrode was modified by coating with a thin layer of carbon-supported catalyst (Pt/C).

The modified SPEs detected three isomers selectively, reaching a detection limit of 1 µM for CC and HQ and 100 nM for RS with good reproducibility in laboratory conditions. Furthermore, we analysed the modified surface of the SPE using electrochemical impedance spectroscopy (EIS) and the efficacy of modified vs. unmodified

Figure 8: Cover (Adv. Mater. 4/2024)

SPEs when used for detection. The analysis showed that the modification of the SPE using Pt/C noticeably improved the electrical characteristics, resulting in a better sensing element. Also, the unmodified electrodes' electrical characteristics improved as they were being cycled; the improvement is directly proportional to the number of cycles, while the modified electrodes showed higher performance from the beginning, with peak performance lasting a certain number of cycles. Afterwards, degradation was observed. An analysis of the EIS data was performed using equivalent circuit fitting, which gave a deeper insight into the possible electrical model of the SPEs, each element of the circuit representative of a given property.

PMCs are the result of the development of modern organic chemistry, and they are found in tens of thousands of everyday products. On the top of the priority list of PMCs are bisphenols. **Bisphenol S** (BPS) is commonly found in everyday items like thermal paper. It has been identified as easily migrating from paper products onto human skin, subsequently entering the body and disrupting the endocrine system by imitating the estrogen hormone. Given its widespread presence, assessing BPS levels assumes critical significance.

Our study introduces a straightforward, cost-effective electrochemical sensor utilizing SPE-carbon (SPE-C) and SPE-single-wall carbon nanotube (SPE-SWCNT) working electrodes. BPS detection spans a broad linear range from 1 to 400 µM, with limits of detection recorded at 0.73 µM and 0.87 µM for SPE-C and SPE-SWCNT electrodes, respectively. Both sensors exhibit excellent repeatability, even after being utilized sixteen times with a single electrode, underscoring their potential for continuous environmental monitoring in real-time. The practical application of the SPE-C sensors was assessed by detecting BPS extracted from thermal paper receipts gathered from nearby stores.

Another PMC of great concern is **benzisothiazolinone (BIT)**, which serves as an antimicrobial agent incorporated into various products, in-cluding laundry detergents, water-based paints and food packaging paper,

> We are developing receptor elements for the detection of toxic organic compounds (TOCs), such as formaldehyde and benzenediols, persistent and mobile chemicals (PMCs), pathogens, such as SARS-CoV-2, and biomolecules, such as polyamines.
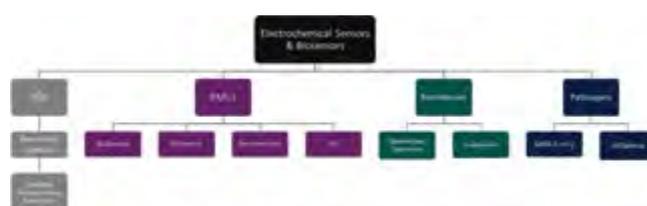
Figure 9: Selected analytes within the separate groups chosen for electrochemical detection

Figure 10: Electrochemical detection of BPS from thermal paper

contributing to the contamination of municipal wastewater. Exposure to BIT through skin contact with such products can result in skin sensitization and allergic reactions. Moreover, the discharge or runoff of BIT-containing substances into water bodies poses a substantial threat to aquatic life. Hence, we are developing fast and reliable electrochemical detection methods utilizing carbon- and gold-based SPEs. The electrodes demonstrated excellent electrochemical responses for BIT detection, exhibiting a linear range of 0.25 to 2000 µM for carbon working elec-trodes and 0.25 to 100 µM for the gold working electrodes. Cyclic voltammetry (CV) and square-wave voltammetry (SWV) were used to detect BIT in solution, revealing differences between the two methods. SWV showed a much lower detection limit compared to CV. For instance, with a carbon working electrode, the detection limit using CV was 0.61 µM, whereas with SWV, it was 0.04 µM. Similarly, with a gold working electrode, the difference was even more pronounced, with CV yielding a detection limit of 6.84 µM compared to 0.07 µM with SWV. To assess the

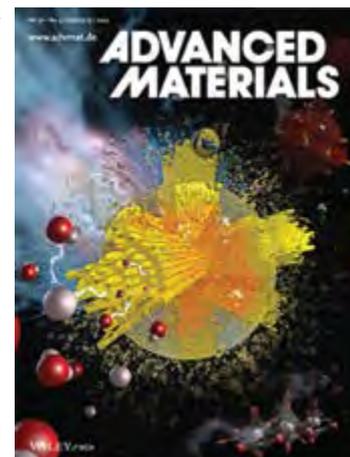potential for implementing the proposed sensor for on-site analysis, it was applied to estimate BIT levels in river samples, indicating its potential suitability for real sample monitoring.

The electrochemical detection of **biomolecules** is a new field we started in 2023 when the joint project between our group and the Italian group from IMEM in Parma (CNR) was accepted. The project SENSE-PA focuses on the development of a new sensor platform based on electrochemical biosensors for the detection of important biological molecules polyamines (PAs), i.e., putrescine, spermidine, and spermine.

They are responsible for numerous cell functions, including cell proliferation, the stabilization of nucleic acid conformations, cell division, homeostasis, etc. The levels of PAs in blood samples in cancer patients are higher than those found in healthy people. Hence, a high level of polyamines is regarded as a biomarker for the timely diagnosis of cancer and other pathophysiological conditions. Therefore, the portable and direct detection in biological fluids is of high interest and the developed portable electrochemical biosensors will allow the fast, sensitive, and selective detection of PAs in water and biological fluids (artificial saliva, artificial urine, and real samples) with limits of detection (LOD) down to the nM range.

In the frame of developing in-house-made miniature, portable, wireless, easy-to-use and inexpensive sensors setup for the detection of TOCs and PMCs, we published in *MDPI Sensors* a paper entitled IoT Electrochemical Sensor with Integrated $Ni(OH)_2$–Ni Nanowires for Detecting Formaldehyde in Tap Water (https://doi.org/10.3390/s23104676). We have constructed a portable, autonomous, IoT electrochemical sensor that detects aqueous formaldehyde (HCHO) in distilled or tap water. The sensor comprises assembled electronics consisting of a photon Internet of Things (IoT) development kit, a USB port for charging, and a miniaturized potentiostat, all enclosed in a small protective case (58 mm × 33 mm). The external part of the sensor can connect to the HCHO detection system via a three-terminal electrode connector. The HCHO detection system based on custom-made Ni $(OH)_2$–Ni NWs SPEs allowed us to rapidly (1 s) detect HCHO in alkaline media. The detection system can detect concentrations of HCHO at 0.8 μM/24 ppb, a linear response over two wide ranges of HCHO concentrations (0.8×10^{-6} to 5×10^{-4} M and 5×10^{-4} to 1×10^{-2} M). It also assembles the basic requirements for real-time applications, including low cost, simplicity, selectivity, and sensitivity, together with reusability and reproducibility. Thus, this study demonstrated that the developed IoT electrochemical sensor, which allows for the easy replacement of an external detection system, can be used as an effective, portable, inexpensive device for testing HCHO and other organic/inorganic pollutants in real-life conditions.

Figure 11: Electrochemical detection of HCHO with a commercial potentiostat vs. our portable IoT sensor system (https://doi.org/10.3390/s23104676)

Nanomedicine

The Nanomedicine Group is working on the development of biomimetic delivery systems for innovative cancer treatment and diagnostics, focusing on the following areas:

- **Contrast agents for magnetic resonance imaging**: we are developing new and safer formulations based on superparamagnetic nanoparticles;
- **Photo-thermal therapy**: a portable NIR laser with adjustable power is used to irradiate suspensions, cells and animal models. We test many nanomaterials and molecules that exhibit a photo-thermal effect;
- **Gene therapy:** free nucleic acids are very unstable, so we are developing delivery systems for efficient and safe introduction of nucleic acids into cells. For this purpose, we use vesicles from erythrocyte membranes and polyamine-genipin polymer particles;
- **Active targeting of cancer cells:** through active targeting of receptors that are overexpressed on cancer cells and, to a lesser extent, on normal ones, we want to improve the specificity of therapies and, at the same time, reduce side effects. For this purpose, we are developing peptide analogues with a high affinity for these receptors.

One of the most revolutionary achievements in this new era is gene therapy, which focuses on the use of therapeutic delivery of nucleic acids into the patient's cells (so-called transfection). Despite the great potential for therapy, the biggest challenges are related to the efficient delivery of nucleic acids to the target site and immunogenicity. Therefore, the development of new, safer and, at the same time, highly effective transfection agents is crucial for progress in this field. In 2023 we carried out a breakthrough study where we developed a new and efficient procedure for the preparation and purification of vesicles from erythrocyte membranes as a delivery system for nucleic acids for the purpose of gene therapy (Figure 12). The entire process is completed in four hours, representing an important step forward in realising personalised medicine therapies, which remains the greatest challenge of the 21st century.

We performed a detailed characterisation of these vesicles using advanced electron microscopy methods in collaboration with the National Institute of Chemistry, Ljubljana, and the Institute for Cell Biology, Faculty of Medicine, University of Ljubljana. We have proven that the vesicles effectively protect nucleic acids from enzymatic degradation with high stability for up to one month.

The study was carried out in collaboration with the Oncology Institute of Ljubljana. The article has been submitted for peer review by the *Journal of Controlled Release*.

As an extension of this study, we started with an active method of targeting breast-cancer cells in order to improve the selectivity and efficiency of siRNA delivery to these cells. For this purpose, we use molecular modeling methods to determine the optimal sequence of peptides that demonstrate high selectivity and affinity to target receptors. We have successfully bound the selected peptide to the surface of the vesicles and will continue testing on cell models in 2024.

In addition to the use of vesicles from erythrocyte membranes, we also developed innovative, cationic polyamine nanoparticles from natural ingredients (genipin and polyamines) as a safe and efficient delivery system for RNA molecules (Figure 13). The proposed nanoparticles also exhibit fluorescent properties, which can be advantageously used for imaging purposes.

In addition we tested this system on a number of cell models, including those where the uptake of nucleic acids is particularly difficult (lymphoblasts). We have demonstrated that genipin-polyamine nanoparticles are an extremely efficient and much safer transfection agent than commercially available reagents (e.g., Lipofectamine), which indicates a great potential for continuing pre-clinical experiments and also transfer towards higher levels of technological development. The results of this study are currently in peer review in the *Journal of Nanobiotechnology* (impact factor 10.2).

In the field of photo-thermal therapy, we test many nanomaterials, i.e., magnetic nanoparticles, gold nanostructures, carbon dots, and bismuth-selenide structures. We published two articles. The first one, in collaboration with the University of Nova Gorica, entitled *Silica coated Bi$_2$Se$_3$ topological insulator nanoparticles: an alternative route to retain their optical properties and make them biocompatible* in the journal *Nanomaterials* (https://doi.org/10.3390/nano13050809). Another article was a result of a collaboration with the Politecnico di Torino, Italy, entitled *Tannic-acid-mediated synthesis and characterisation of magnetite–gold nanoplatforms for photothermal therapy*, published in *Nanomedicine* (https://doi.org/10.2217/nnm-2023-0134).

Besides excellent research, our mission is also to present our research findings to the general public. For this purpose, Dr. Nina Kostevšek conducted a radio interview on the Podobe znanja broadcast, ARS, entitled How red blood cells can deliver medicines instead of oxygen (https://365.rtvslo.si/arhiv/podobe-znanja/174962029). And then a video interview and a podcast for the Slovenian Press Agency entitled Slovenian researcher with nanotechnology for more effective cancer treatment (http://znanost.sta.si/3203860/slovenska-raziskovalka-z-nanotehnologijo-do-bolj-ucinkovitega-zdravljenja-raka).

Microplastics

The Microplastics Group is seeking a major breakthrough in methods to effectively remove environmental micro- and nanoplastics near the source of pollution. Our research work is devoted to photocatalyst synthesis, photodegradation, biodegradation, and characterization of photocatalysts and analysis of changes in micro/nanoplastics. Efficient metaloxide (ZnO, TiO$_2$, etc.) photocatalysts have been developed using hydrothermal or solvothermal synthesis and atomic layer deposition (ALD). ZnO thin films doped with copper atoms, as published in *Ceramics International* (https://doi.org/10.1016/j.ceramint.2023.08.196) and nanocomposites based on TiO$_2$ and reduced graphene oxide, as published in *MDPI Molecules* (https://doi.org/10.3390/molecules28217326), were explored for the removal of methylene blue dye under visible light, work has been started as part of the **ARIS bilateral project BI-HR/20-21-017**. Within the **ARIS project J4-2549**

In cell models and then in animal models, we demonstrated the effectiveness of target gene silencing with our vesicles containing encapsulated siRNA.
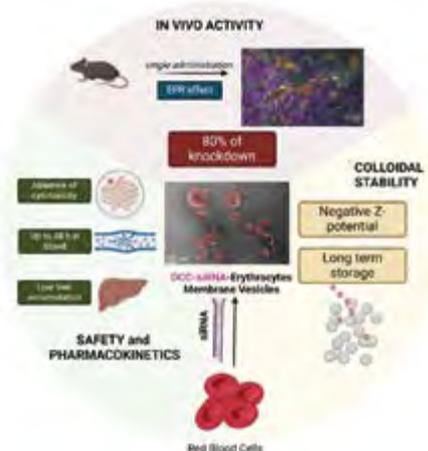
Figure 12: Schematic sum-up of siRNA-loaded erythrocytes membrane vesicles (EMVs). EMVs retained parental erythrocytes zeta-potential and they were stable up to 4 weeks at 4°C. We tested their gene-silencing ability in vitro on B16F10 murine melanoma cell line and in tumor-challenged mice. We also determined their biodistribution and pharmacokinetic properties and found that the vesicles increase the circulation time (a few minutes for free siRNA to 48 for encapsulated in vesicles).

Fluorescent genipin-polyamine nanoparticles as carriers of nucleic acids represent a complete innovation in the field of transfection and delivery of nucleic acids.
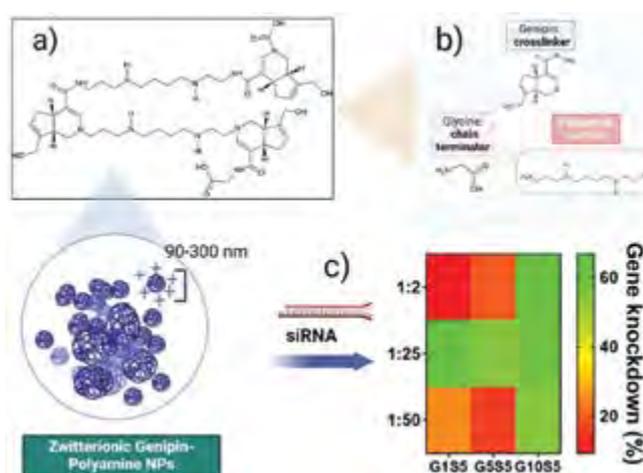
Figure 13: a) General structure of genipin-polyamine polymeric nanoparticles (NPs) with size 90–300 nm. For the sake of simplicity, some chemical bonds were elongated and the picture is not representative of the structural arrangement of the polymer in water or buffer. b) Components of polymers and their function in the synthesis process; c) Gene knockdown efficacy (%) upon incubation of B16F10 cell with siRNA-containing polymeric NPs, as determined via qRT-PCR analysis.
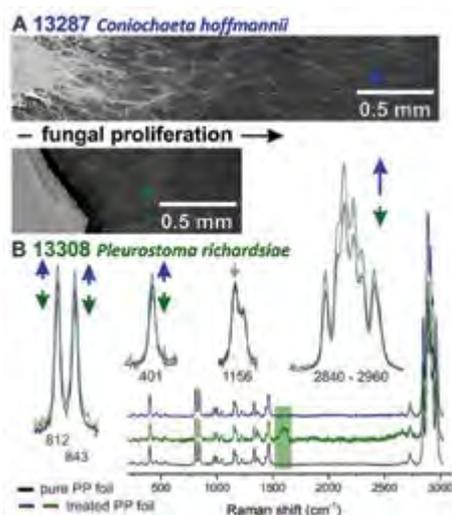
Figure 14: The selected fungi C. hoffmannii and P. richardsiae grow on pure polypropylene (PP) film. SEM images show that C. hoffmannii (A) spreads across the surface more than P. richardsiae (B). Raman spectroscopy reveals PP bond damage due to overgrowth of each fungus on the surface of the film (https://doi.org/10.1016/j.micres.2023.127507).

Our research focuses on the core principles of solid-state physics and chemistry to develop ZnO-based ceramics and thick-film structures with improved properties for use in overvoltage protection and thermoelectric technologies.

(https://cris.cobiss.net/ecris/si/sl/project/18312) we identified two fungi, *Coniochaeta hoffmannii* and *Pleurostoma richardsiae*, capable of colonizing the polypropylene (PP) fibres. The study is published in *Microbiological Research* (https://doi.org/10.1016/j.micres.2023.127507). All our research topics, synthesis of photocatalyst, photodegradation, biodegradation and characterization of photocatalysts and analysis of changes in micro/nanoplastics, come together in analysing large hailstones that fell down in Slovenia, in 2019, where we found diverse microorganisms and fibres of natural and anthropogenic origin, as it is published in *Science of The Total Environment* (https://doi.org/10.1016/j.scitotenv.2022.158786, IF 9.8).

Semiconducting ZnO-based ceramics

As non-toxic and low-cost n-type semiconducting oxide with direct wide bandgap of 3.4 eV and high energy absorption capability, ZnO is already widely used in overvoltage protection, while it also has also great potential for piezoelectric, pyroelectric, thermoelectric, optical, luminiscence and photocatalytic applications. High amenability for doping is ann additional advatnage of ZnO for use in these technological applications, enabling fine tuning of the physical properties of ZnO-based ceramics in accordance with the required characteristics.

In ZnO-based ceramics for both areas of application, varistors and thermoelectrics, the same dopants can be used to affect microstructure development, point and planar defects in the grains, electronic states in grains and at the grain boundaries, charge-carrier concentration and mobility, and transport of charge and heat, thus tailoring their characteristics.

ZnO-based varistor ceramics for overvoltage protection - Exceptional current-voltage (I-U) nonlinearity of the ZnO-based varistor ceramics results from the electrostatic double Schottky barriers at the grain boundaries and their formation is primarily attributed to the so-called varistor formers like oxides of Bi, Pr and V. However, for high I-U nonlinearity, other dopants like oxides of Sb, Ti, Sn, Co, Mn, Ni, Cr and Al have to be added to the ZnO; they affect electronic states at the grain boundaries, and at the same time, some of them (oxides of Co, Mn, Ni) also incorporate into the ZnO grains as donors and increase their conductivity. Dopants like Sb, Ti and Sn also result in the formation of planar defects in ZnO grains, so-called IBs, and our previous research showed that IBs have a key influence on the ZnO grain growth and, thus, on the breakdown voltage of varistor ceramics. Such compositions with numerous dopants added to ZnO in total amount of 7 to 12 wt.% result in a complex microstructure for ceramics with several types of secondary phases at the grain boundaries of ZnO, thus reducing the effective electrical contact among them.

Our research aims to understand the complex interplay of dopants on the electronic states in grains and at the grain boundaries, as well as on grain growth and microstructure development. This is a key to optimising the composition's electrical and energy characteristics of the ZnO-based varistor ceramics, possibly with a much lower addition of dopants to ZnO (i.e., 3 to 5 wt.% total) to minimise or eliminate redundant secondary phases.

Our research, conducted in collaboration with the Shanghai Institute of Ceramics, Chinese Academy of Science (SICCAS), on the influence of selected dopants and process parameters on the formation of electrostatic Schottky barriers at the grain boundaries and on the electrical/thermoelectric characteristics of ZnO ceramics, resulted in the discovery of a novel type of ZnO-Cr_2O_3-based varistor ceramics. The study was published in *ACS Applied Materials & Interfaces* (https://doi.org/10.1021/acsami.1c07735).

Compared to the currently known standard varistor ceramics based on ZnO, these novel varistor ceramics do not contain volatile (Bi_2O_3), expensive (Pr_6O_{11}) and toxic (V_2O_5) dopants, have a simple and cheaper chemical composition with less than 5 wt% of dopants and is practically single-phase. In the ZnO-Cr_2O_3-based varistor ceramic, the formation of electrostatic Schottky barriers is induced by the addition of Cr_2O_3, while the addition of small amounts of Ca, Co and Sb oxides further improves the I-U nonlinearity.

The optimal amount of added Cr_2O_3 was determined to be about 0.1 mol.%, as published in the journal *Materials Research Bulletin* (https://doi.org/10.1016/j.materresbull.2022.112111), while for larger additions, the secondary $Ca_3(CrO_4)_2$ phase starts to form, which leads to a decreased barrier height and degradation of the nonlinear I-U characteristics. The addition of CaO has a positive effect on the height of the electrostatic Schottky barriers and the nonlinear I-U characteristics within the limits of solid solubility in ZnO, which is about 2 mol.%. In regard to the Co_3O_4-doping, the best characteristics were obtained for the addition of 0.5 mol.% Co_3O_4, while at higher additions, the excess Co^{3+} ions enter the grain boundaries as donors, increasing the carrier concentration in the grain-boundary region and consequently decreasing the height of electrostatic barriers and the nonlinearity of the ZnO-Cr_2O_3-based varistor ceramics, as published in the journal *Materials Science in Semiconductor Processing* (https://doi.org/10.1016/j.mssp.2023.107570). In the field of varistor ceramics and surge protection, we collaborated

with the companies Bourns and Raycap in the development of varistors for various fields of application and the optimisation of their production.

The recent start of collaboration in the field of atomistic study of inversion boundaries in ZnO with Materials Center in Leoben (MCL), Austria, has evolved in a new postdoctoral Research project ARIS **Z2-50056**, called "Stability and formation of inversion boundaries in ZnO: DFT and experimental screening for new IB–forming dopants.

The collaborating scientists are developing a new theoretical approach for ab-initio calculation of the stability of chemically induced domain walls in diverse electronic and functional materials across different chemistries, which has not yet been attempted before for interfaces. The research within this project is focused on the spontaneous formation of inversion boundaries (IBs) that appear to be triggered by the addition of specific transition-metal dopants. The research involves a theoretical investigation of atomistic-scale mechanisms that lead to the formation of IBs, whereas experimental studies (diverse synthesis methods, electron microscopy and atomistic modelling) are directed to the confirmation of identified formation mechanisms. Dopants that were predicted to spontaneously form IBs in ZnO are currently experimentally tested.

ZnO-based thermoelectric ceramics - Enhancing the thermoelectric characteristics of the ZnO ceramics expressed by the figure of merit (ZT = sS²T/k), primarily demands a significant increase in electrical conductivity (s), while preserving a very high Seebeck coefficient of (S) -400mV/K (S) and a drastic decrease of a much too high thermal conductivity (k), due to a simple crystal structure composed of light elements.

Electrons along the planar defect, which is limited in width to one layer of atoms and practically infinite in the other two dimensions, switch to a ballistic transport mode (s_b).

At the same time, the 2D structural and chemical anisotropy of IBs induces scattering of phonons transversely crossing the planar defect, which lowers the thermal conductivity of ZnO ceramics. The research is carried out in collaboration with the Shanghai Institute of Ceramics, Chinese Academy of Science (SICCAS), CRISMAT Laboratory (Caen, France) and the National Institute for Materials Science (NIMS, Tsukuba, Japan).

Some of the key problems for an increase in the electrical conductivity of ZnO are related to the very limited solid solubility of donor dopants (i.e. Al^{3+}) in ZnO and the formation of electrostatic Schottky barriers at the grain boundaries due to intrinsic acceptor states, i.e., oxygen interstitials (O_i), and zinc vacancies (V_{Zn}). Our results showed that sintering in a reductive atmosphere mostly prevents the formation of Schottky barriers at grain boundaries and simultaneously greatly increases the solid solubility of Al in ZnO, resulting in an increase in the electrical conductivity of ZnO ceramics by several orders of magnitude while the thermal conductivity decreases due to the high concentration of point defects in ZnO grains. At the same time, the question of the stability of such thermoelectric ceramics under oxidative operating conditions is raised. Further studies showed that subsequent prolonged annealing in air at temperatures up to 1000°C does not affect the enhanced solid solubility of the donor dopants (i.e., Al) in the ceramics by sintering in a reducing atmosphere; however, it lowers the concentration of intrinsic donor defects, i.e., zinc interstitials (Zn_i) and oxygen vacancies (V_O), thus decreasing the concentration of charge carriers. Nevertheless, the power factor, PF (PF=sS²), of air-annealed ceramics was still 8-times higher than that of ZnO ceramics prepared only by sintering in air, which provides good guidelines for the further development of thermoelectric ZnO ceramics, as published in the *Journal of Materials Research and Technology* (https://doi.org/10.1016/j.jmrt.2022.11.091).

The aim of this research is to understand the influence of donor dopants (M^{3+}) on charge-carrier concentration and mobility and the interfaces, such as grain boundaries (GBs) and specific inversion boundaries (IBs) in grains, on charge and heat transport. Special attention is given to the role of multiple IBs, which are induced by dopants such as In^{3+} and Ga^{3+} and act as an energy filter where phonon and electron pathways split.
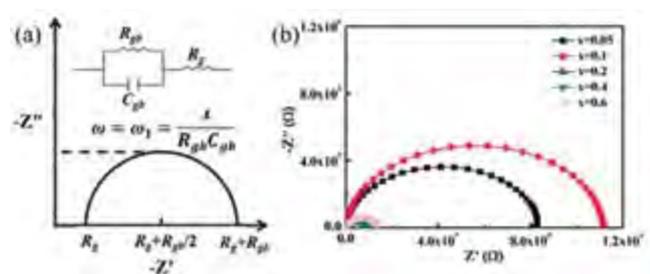
Figure 15: (a) Typical equivalent circuit and ideal Nyquist plot for ZnO-Cr$_2$O$_3$-based varistor ceramics (R_{gb}, C_{gb} for grain boundaries, R_g for grains). (b) Impedance diagrams measured at 200°C for ZnO–Cr$_2$O$_3$-based varistor ceramics with different Cr$_2$O$_3$ contents (x = 0.05, 0.1, 0.2, 0.4, 0.6) showing much higher resistivity of grain boundaries (R_{gb}) at optimal additions of Cr$_2$O$_3$ up to 0.1 mol.%. (https://doi.org/10.1016/j.materresbull.2022.112111)
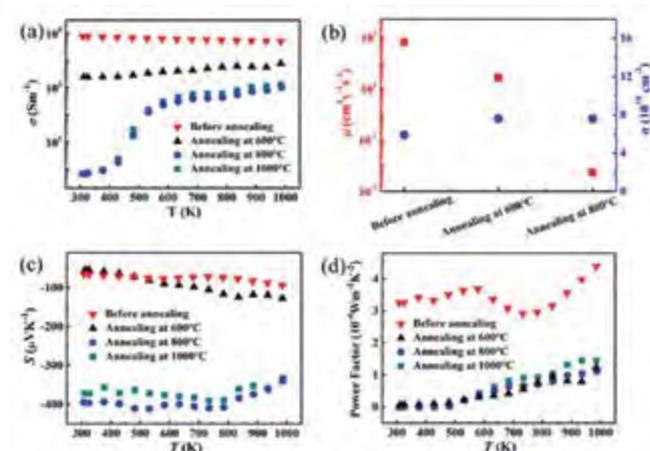
Figure 16: Temperature dependence of (a) electrical conductivity (σ), (b) the Hall measurement of charge carrier concentration (n) amd mobility (μ), (c) Seebeck coefficient and (d) Power factor of the ZnO-based thermoelectric ceramics prepared by sintering in reducing atmosphere before and after annealing in air at different temperatures. (https://doi.org/10.1016/j.jmrt.2022.11.091)

Engineering Ceramics

Additive manufacturing (AM) and rapid sintering – We evaluated the effect of infill strategies of thermoplastic 3D-printing (T3DP) on the flaw-type population and bending strength of 3 mol.% yttria partially stabilized zirconia (3Y-TZP) bars as published in *Open Ceramics* (https://doi.org/10.1016/j.oceram.2023.100367)*,* a sister open-access version of the *Journal of the European Ceramics Society*. The T3DP rapidly deposits micron-sized droplets, which fuse and solidify to form lines and layers, where we showed that, unlike in fused-filament fabrication (FFF), the flaw-type population determining the strength is less affected by the infill strategies. In relation to FFF, a systematic investigation was carried out for the development of in-house alumina feedstock formulation by an extrusion process. The printing parameters and the quality of the printed parts, the debinding and the sintering processes were influenced by the ratio between ethylene vinyl acetate and paraffin-wax binder phase in the feedstock. The study was published in *Open Ceramics* (https://doi.org/10.1016/j.oceram.2023.100496).

In collaboration with Montanuniversität Leoben, Austria (MuL) we demonstrated the feasibility of texturing lithography-based, additively manufactured (LCM) alumina ceramics within minutes by combining rapid radiation heating ($\sim$450 °C/min) and short dwell times (<20 min), opening the path for tailoring the microstructure of 3D-printed ceramics using pressure-less rapid-sintering protocols. The study was published in *Open Ceramics* (https://doi.org/10.1016/j.oceram.2023.100428). Textured microstructures in ceramics have gained interest due to their beneficial effect on structural properties, such as increasing damage tolerance. Textured alumina may be otherwise conventionally achieved through templated grain growth (TGG) occurring when sintering at high temperatures and with very long dwell times.

Dental Ceramics - in the field of dental ceramics, we have been traditionally involved in the interdisciplinary translational research of zirconia dental ceramics in collaboration with Department for Prosthetic Dentistry, Medical Faculty, University of Ljubljana (DPD-MF-UL), where numerous *in vitro* and *in vivo* clinical studies have been conducted. Rapid sintering and AM are also becoming interesting in the dental ceramic material processing workflow. In 2023 we were invited to contribute to the special issue of the Current Oral Health Reports journal, where we published a review paper entitled "*Sintering Strategies for Dental Zirconia Ceramics: Slow Versus Rapid?*" (https://doi.org/10.1007/s40496-023-00355-y). The review was made in collaboration with professor Mutlu Özcan, director of Clinic for Masticatory Disorders and Dental Biomaterials, Center for Dental Medicine, University of Zurich, Switzerland.

On the other hand, in collaboration with Montanuniversität Leoben in Lithoz GmbH, Vienna, Austria, we have studied the effect of airborne particle abrasion and regeneration firing on the subsurface damage and strength distribution of 3D-printed zirconia parts for dental applications. A study published in the leading *Dental Materials* journal shows how LCM technology is a viable approach for the future manufacturing of dental restorations with potential clinical applications (https://doi.org/10.1016/j.dental.2023.10.025). Debonding of zirconia cantilevered resin-bonded fixed dental prostheses remains the main treatment complication. In a short-term randomized clinical trial, nanostructured alumina coating has been shown to be a promising pre-treatment for the bonding surface of zirconia, as published in *The Journal of Prosthetic Dentistry* (https://doi.org/10.1016/j.prosdent.2021.07.003).

Furthermore, the *in vitro* simulation of prostheses' long-term exposure to oral conditions further confirmed the coating's long-term effectiveness. The experimental model was also successfully validated by finite-element analysis (FEA), as published in *Science Materials* (https://doi.org/10.3390/ma16072646).

In an established collaboration with the Department of Prosthetic Dentistry, Center for Dental Medicine, Faculty of Medicine, University of Freiburg, Germany, we have provided expertise on the zirconia ceramics and advanced characterization in a common study, entitled *Long-term stability of hydrothermally aged and/or dy-*

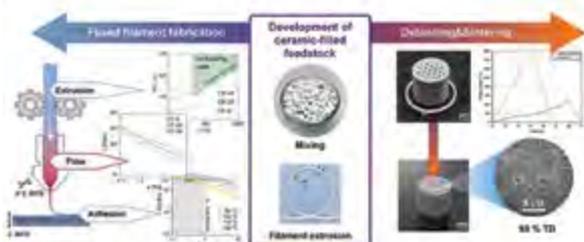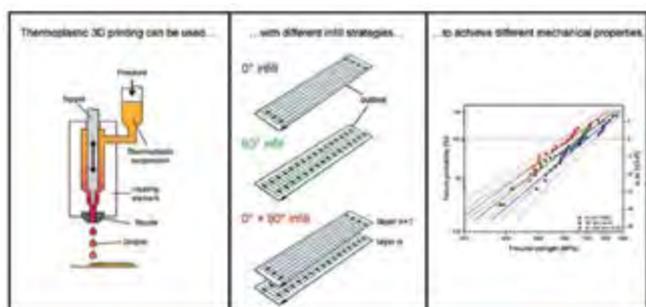*Figure 17: Graphic representation of feedstock preparation and FFF additive manufacturing followed by debinding and sintering of 3Y-TZP ceramics (https://doi.org/10.1016/j.oceram.2023.100367), (https://doi.org/10.1016/j.oceram.2023.100496)*
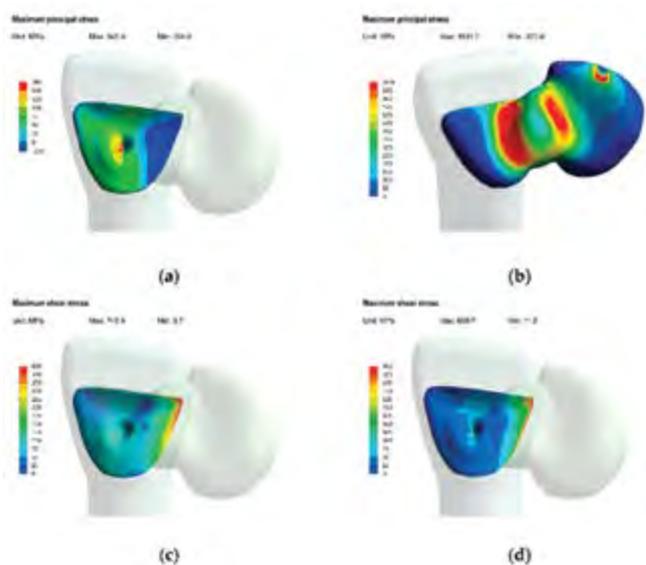

Figure 18: Calculated stresses represented in colorimetric stress maps (MPa) for a resin-bonded fixed dental prosthesis (https://doi.org/10.3390/ma16072646)

namically loaded one-piece diameter reduced zirconia oral implants, which showed higher fracture strength than conventionally milled counterparts, that was published in *Journal of Functional Biomaterials* (https://doi.org/10.3390/jfb14030123).

In collaboration with Charité-Universitätsmedizin Berlin we have performed a fractographic analysis of the 3D-printed and milled composite resins for definitive restorations, published in the *Journal of Esthetic and Restorative Dentistry* (https://doi.org/10.1111/jerd.13132).

Bioceramic materials

Genuine Technologies d.o.o. (GenTech), a start-up company co-founded by several department members, is using JSI`s licensed knowledge for the manufacturing of Ca-silicate-based cement (RS+) for endodontic treatment of teeth. In collaboration with Endodent d.o.o., a study was published in the journal *Materials* (https://doi.org/10.3390/ma16083174), where we compared rheological properties and setting kinetics of bioceramic hydraulic cement RS+ and commercially available benchmark ProRoot MTA. In 2023, GenTech released a new class-I medical device, an amorphous bioactive glass formulation for treating the hypersensitivity of teeth.

Mineralogy

The team involved with the studies of aragonite twinning under the NKFIH–ARRS bilateral project 'Aragonite: Structure and formation' (https://www.ijs.si/ijsw/ARRSProjekti/2022/Aragonit%3A%20struktura%20in%20nastanek) in collaboration with the University of Pannonia in Veszprém, Hungary, was involved in studying the formation of aragonite from Mg-bearing solutions. The results showed that aragonite nucleates as twinned from its initial stages of growth.

Furthermore, we have shown in collaboration with our external project partner from Sobolev Institute of Geology and Mineralogy in Novosibirsk, that all low-temperature aragonites of inorganic origin display twinning and twisting and that the origin of these structural features is not understood. Further studies were conducted on resolving the origin Hiragi–Makovicky reflections and their relation to the twinning of aragonite.

In collaboration with the Department for Litospheric Research of Vienna University in the frame of FWF–ARRS bilateral project Mineral inclusions in garnets from macroscopic to atomic scale – opening the petrogenetic archive (https://www.ijs.si/ijsw/ARRSProjekti/2019/Vklju%C4%8Dki%20v%20granatih%20od%20makroskopskega%20do%20atomarnega%20nivoja%3A%20Odpiranje%20petrogenetskega%20arhiva) a potentially new mineral from the apatite group was identified as inclusion in pegmatitic garnets by electron diffraction, energy dispersive X–ray spectroscopy, powder XRD and Rietveld refinement methods. The new mineral is currently under investigation and its structural, mineralogical and physical properties are being determined in collaboration with different research groups.

In collaboration with the Faculty of Natural Sciences and Engineering, we prepared samples of natural micro-diamond inclusions in garnet grains from Pohorje gneiss for transmission electron microscopy (TEM) analysis. We preliminarily identified the relevant diamond inclusions using Raman spectroscopy and SEM techniques. Lamella preparation with a focused ion beam (FIB) proved challenging due to various factors, particularly the tendency of the diamond phase towards amorphisation upon interaction with the ion beam, and the presence of different mineralogical phases hindering uniform thinning of the lamella to the appropriate thickness for TEM analysis.

The obtained electron-diffraction patterns, atomic-resolution images and spectroscopic results through EDS and Electron Energy-loss Spectroscopy (EELS) analyses all confirm the existence of natural diamonds in the Pohorje region.
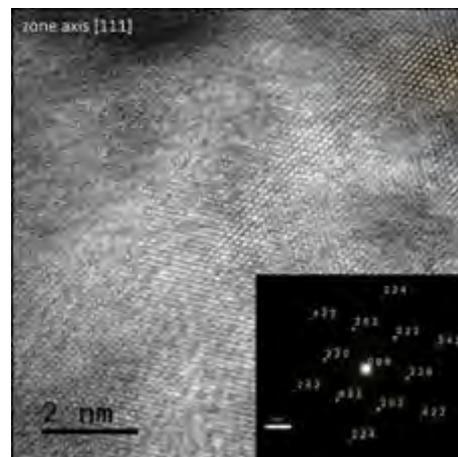
Figure 19: TEM image of nanodiamond grain at atomic resolution in the [111] zone axis. In the top right corner, the crystal structure at [111] is displayed. In the bottom right corner, the indexed electron diffraction pattern of this area is shown.

Advanced Electron Microscopy

Our approach creates a seamless integration between material synthesis, atomic-scale structural and chemical characterisation, and the resulting physical properties, supported by atomic-level modelling based on density-functional theory (DFT). We employ diverse electron microscopy (EM) techniques for advanced nanomaterial characterisation, focusing on extracting detailed information from the material's interfaces. Recently, we focused on 4D scanning transmission electron microscopy (STEM/4D-STEM) and electron ptychography to reconstruct the electron exit wave, coupled with computational microscopy for high-data, high-speed processing and smart automation of microscopy procedures. In experimental microscopy, we employ in-situ TEM techniques to study materials in their natural environments and under dynamic conditions, in-opreando. Additionally, we continuously innovate specimen preparation routines using focused ion-beam technology to support advanced TEM analysis.

The Advanced Electron Microscopy Group develops and implements cutting-edge electron microscopy techniques for materials characterisation.

High-resolution STEM - We studied RE-Au-Si systems, which are 1/1 Tsai-type quasicrystalline approximants with cluster center decoration, which can be distorted tetrahedrons, rare earth atoms or intermediate clusters of randomly distributed distorted tetrahedrons and rare earth atoms. We showed that by correlating line-intensity profiles extracted from experimentally obtained, high-angle annular-dark-field STEM (HAADF-STEM) images with line-intensity profiles extracted from corresponding simulated images, it is possible to determine which kind of cluster centre decoration is present in studied materials. In particular, we found that due to probe channelling in scanning direction coinciding with the (Figure 20) crystallographic plane across the center of the cluster, the presence of distorted tetrahedron results in intensity broadening while rare-earth atom at the center results in sharp intensity. The results of this study were published in the *Israel Journal of Chemistry* (https://doi.org/10.1002/ijch.202300117).

Figure 20: Combining scanning transmission electron microscopy images and their simulations with X-ray diffraction allows (https://doi.org/10.1002/ijch.202300117)

In-situ liquid TEM (LTEM) - Recent development of liquid-cell TEM holders allows for in-situ study of materials reactions. Such specialised holders contain liquid cells that can withhold liquid in a confined environment, facilitating the imaging and spectroscopy of samples in reaction media.

One of the most studied chemical processes in liquid TEM is related to studies of nucleation, growth, and dissolution processes of nanoparticles and nanostructures. Moreover, combining the capabilities of liquid-cell TEM holders with microsize electrodes printed on a chip, i.e. the in-situ electrochemical liquid transmission electron microscopy (EC-LTEM), enables us to study dynamic phenomena during electrochemical reactions at high spatial and temporal resolution.

This is also the subject of a SLO-FWO joint project where we use the EC-LTEM to investigate the dynamics of the electrochemical deposition and dissolution of metallic nanoparticles (NPs) such as Au, Ag, Pt, and Pd by directly visualising them during the process. In our recent study, we tackled the dissolution process of Au NPs under electrochemical biasing. In-situ EC-LTEM observations showed that upon potentiostatic polarisation, Au NPs dissolve at different stages, revealing a core-shell structure during the dissolution. The shell, which is more resistant, leads to a delayed, particle-by-particle dissolution process once broken down. This phenomenon can be seen in Figure 21, where coloured dotted circles mark various Au NP's stagewise dissolution. These findings contribute to understanding the complex, stochastic behaviour of gold NP dissolution, which cannot be elucidated only with traditional electrochemistry methods. For more information on the subject, the reader is encouraged to follow the webinar presented by our group member organised within the ESTEEM3 project (https://www.youtube.com/watch?v=m4ZHW7JXoks&t=1472s&ab_channel=ESTEEM3Project).

We are actively involved in the ESTEEM consortium within the ESTEEM3 project (Enabling Science and Technology through European Electron Microscopy - https://www.esteem3.eu/) in the development of various state-of-the-art transmission electron microscopy techniques (TEM) and materials

Figure 21: Dissolution of Au NPs under an electrochemical potentiostatic bias observed via in-situ EC-LTEM. Coloured dotted circles mark the dissolution of various NPs at various stages.

characterisation. The Microscopy research group stays strongly connected with the activities within the Center for Electron Microscopy and Microanalysis (CEMM), mainly through the implementation of various electron microscopy analytical techniques and the possibility for the researchers to access research infrastructure for electron microscopy.

Education and outreach activities

The department members participated in science promotion activities within the framework of the Science on the Street project (ZnC) (https://znc.si/). The year 2023 marked the celebration of the 10th anniversary of Science on the Street, which ended with an event in the ZRC Atrium. We organised a total of 17 public events, of which 13 were popular-science lectures. The lectures were held live and online from the ZRC Atrium, the Library in Kranj, the Library in Izola, the Lanthieri Palace in Vipava, the Xcenter in Nova Gorica, the Right Atrium of the Ljubljana City Hall and the garden of the Bohinj Hotel in Ribčev Laz. On the ZnC website, we have published 14 blogs of researchers and 3 competitions. In cooperation with the Department for Nanostructured Materials, within the framework of the SUSMAGPRO project (https://www.susmagpro.eu/) and the City Municipality of Ljubljana we organised an exhibition entitled "Make a new magnet by recycling old magnets" in the Atrium of the Ljubljana City Hall.

Strategic Research and Innovation Partnership of the Factories of the Future (SRIP ToP) activities, vertical value chain Advanced Green Technologies

Within the vertical value chain Advanced Green Technologies, which covers sensors and magnetic materials, we carried out activities related to the preparation of new action plans for 2024. We organised meetings with company representatives and other SRIPs.

Awards and Appointments

1. **Dr Nina Kostevšek** was the recipient of the award for the best presentation entitled Magneto-Erythrocyte Membrane Vesicles as T2 MRI Contrast Agents at the lecture Nanotechnology for Imaging, Sensing and Diagnostics at the BioNanoMed2023 conference in Graz, Austria. The award is given by NanoMedicine-Austria and BioNanoNet Forschungsgesellschaft mbH (BNN), Austria.

2. **The recipient of the Jean-Marie Dubois Award** (named after our colleague from the K7 department) for significant, sustained research on any aspect of quasicrystals was Prof. Michael Baake from the University of Bielefeld. The award is given by the Iowa State University, the United States of America.

3. **Tina Radošević** was the recipient of the award for the best poster presentation with the title "Photocatalytic degradation of synthetic textile microplastic fibers with TiO2 as photocatalysts" at the 28th International Conference on Materials and Technology (28 ICM&T) in Portorož. The prize is awarded by the Institute for Metal Materials and Technologies (IMT) from Ljubljana, Slovenia.

4. **Monika Kušter** was the recipient of the award for the best presentation entitled "Composite material on polymer matrix reinforced with Al-based quasycristal powder" at the 28th International Conference on Materials and Technology (28 ICM&T) in Portorož. The prize is awarded by the Institute for Metal Materials and Technologies (IMT) from Ljubljana, Slovenia.

Organization of conferences, congresses and meetings

1. Project meeting and workshop RECO2MAG: Novel grain boundaries engineered resource efficient Nd-FE-B permanent magnets (PMs), within the EIT RawMaterials, Lipica 17–19 January 2023

2. 1st Annual Conference of the K7 department, Rogla, 28 February to 2 March 2023

3. Project meeting of the group for the development of 4D microscopic techniques: 4D STEM Meeting, Ljubljana, 9 March 2023

4. International workshop and project meeting SUSMAGPRO: Sustainable Recovery, Reprocessing and Reuse of Rare-Earth Magnets in a Circular Economy, Ljubljana, 19–23 April 2023

5. International workshop AdSTEM3: 3rd Advanced School on Scanning Transmission Electron Microscopy, within the ESTEEM3 project, Piran, 14–18 May 2023

6. Presentation meeting by JSI colleagues in the field of catalysis: JSI meeting on catalyst synthesis, characterization and applications, Ljubljana, 25 May 2023

7. Project meeting groups for the development of highly efficient sensors for the detection of persistent and mobile chemicals in the environment: Development of High Performance Sensors for Detection of Persistent and Mobile Chemicals in the Environment (SENSE-PMC), Ljubljana, 30 May 2023

8. Meeting of the M24 PASSENGER project consortium: Pilot Action for Securing Sustainable European Next Generation Efficient RE-free Magnets (co-organization of the event with the K8 department), Ljubljana, 31 May to 1 June 2023

9. Project meeting of the group for the development of 4D microscopic techniques: 4D STEM Meeting, Ljubljana, 7 September 2023

10. MIDEM 2023 Conference: 58th International Conference on Microelectronics, Devices and Materials with a Workshop on Chemical Sensors: materials and applications, Lipica, 27–29 September 2023

11. Meeting of the expert group in the field of cancer research: Mission – Cancer, Ljubljana, 11 October 2023

12. International workshop and annual ATHENA project meeting: an exposition on the foreign information manipulation and interference (co-organization of the event with the K3 department), Ljubljana, 17–18 November 2023

13. International event Innovation Day in Ljubljana with a presentation of the aProMag project: Fast anisotropic prototyping of magnetic materials within EIT manufacturing (co-organization of the event with SRIP ToP), Ljubljana, 6 December 2023

INTERNATIONAL PROJECTS

1. Microwave Ferrites
   Dr. Petra Jenuš Belec
   Antistat GmbH
2. COST CA17140; Nano2Clinic - Cancer Nanomedicine - From the Bench to the Bedside
   Asst. Prof. Nina Kostevšek
   COST Association Aisbl
3. H2020 - ESTEEM3; Enabling Science and Technology through European Electron Microscopy
   Prof. Miran Čeh
   European Commission
4. H2020 - SUSMAGPRO; Sustainable Recovery, Reprocessing and Reuse of Rare-Earth Magnets in a Circular Economy
   Prof. Spomenka Kobe
   European Commission
5. H2020 - ATHENA; Implementing Gender Equality Plans to Unlock Research Potential of RPOs and RFOs in Europe
   Prof. Spomenka Kobe
   European Commission
6. H2020 - ORACLE; Novel Routes and Catalysts for Synthesis of Ammonia as Alternative Renewable Fuel
   Prof. Andraž Kocjan
   European Commission
7. H2020 - PASSENGER; Pilot Action for Securing a Sustainable European Next Generation of Efficient RE-Free Magnets
   Prof. Kristina Žužek
   European Commission
8. H2020 - OCARINA; Novel Recycling and Reprocessing of Permanent Magnets
   Prof. Kristina Žužek
   European Commission
9. EIT RM; INSPIRES - Intelligent and Sustainable Processing of Innovative Rare-Earth Magnets
   Prof. Spomenka Kobe
   Eit Rawmaterials E.v.
10. HE - EUROfusion; WP18: MAT_HE-FU, IREMEV-MAT-1_HE-FU, IREMEV-MAT-2_HE-FU, IREMEV-MAT-3_HE-FU
    Dr. Petra Jenuš Belec
    European Commission
11. HE - EUROfusion; WP21: PRD-1,2_HE-FU
    Dr. Aljaž Iveković
    European Commission
12. EIT RM; RECO2MAG - Grain Boundaries Engineered Resource Efficient Nd-Fe-B Permanent Magnets (PMs)
    Prof. Kristina Žužek
    Eit Rawmaterials E.v.
13. HE - EUROfusion; WP24: TRED_HE-FU, EDU_HE-FU
    Prof. Saša Novak Krmpotič
    European Commission
14. HE - REESilience; Resilient and Sustainable Critical Raw Materials REE Supply Chains for the E-Mobility and Renewable Energy Ecosystems and Strategic Sectors
    Prof. Kristina Žužek
    European Commission
15. HE - GYROMAGS; Green Recycling Route for Sm-Co Permanent Magnet Swarf
    Prof. Kristina Žužek
    European Commission
16. HE - HEO4CAT; Development of New High-Entropy Oxide Catalysts by the Anodic Oxidation of High-Entropy Alloys
    Belisa Alcantara Marinho
    European Commission
17. EIT M; aProMag - Anisotropic fast PROtotyping of MAGnetic materials
    Prof. Spomenka Kobe
    Eit Manufacturing Asbl
18. COST CA21121; MecaNano - European Network for the Mechanics of Matter at the Nano-Scale
    Prof. Sašo Šturm
    COST Association Aisbl
19. Rights and obligations regarding the development, use and commercialization of hydrothermally synthesized TiO2 coatings in metal orthopaedic and dental implants
    Prof. Saša Novak Krmpotič

RESEARCH PROGRAMMES

1. Nanostructured Materials
   Prof. Sašo Šturm
2. Ceramics and complementary materials for advanced engineering and biomedical applications
   Prof. Andraž Kocjan

3. Fusion technologies
   Prof. Saša Novak Krmpotič

R & D GRANTS AND CONTRACTS

1. Advanced 3D cell models: Bridging the gap between in vitro and vivo experimental systems (hep3DGenTox)
   Prof. Saša Novak Krmpotič
2. Post-radiation caries in head and neck cancer patients: Understanding and prevention
   Prof. Andraž Kocjan
3. Degradation of plastics with polyextremotolerant fungi
   Dr. Matejka Podlogar
4. Modulation of fruit polyphenolic profile by sustainable postharvest physical treatments
   Dr. Anže Abram
5. Preclinical and Clinical Investigations of Zirconia Dental Ceramics Fabricated by Additive Manufacturing Technologies (ZIRAMDENT)
   Prof. Andraž Kocjan
6. Development of novel multifunctional metal-oxide-based nanozymes and their toxicological characterisation (NaNoZymSafe)
   Dr. Petra Jenuš Belec
7. Fundamental understanding of the hydrogen formation reaction for a new generation of nickel-based electrocatalysts in alkaline and chloralkali electrolysis
   Prof. Sašo Šturm
8. Designing functionality of lead-free ferroelectrics through domain wall engineering
   Asst. Prof. Matej Andrej Komelj
9. Prediction of the initial stages of electrochemical phase formation by multi-scale modelling and insitu transmission electron microscopy
   Prof. Sašo Šturm
10. Extended defects in natural and synthesized perovskite oxides: nanogeochemcial indicators and functional interfaces
    Prof. Aleksander Rečnik
11. Development of High Performance Sensors for Detection of Persistent and Mobile Chemicals in the Environment (SENSE-PMC)
    Asst. Prof. Kristina Žagar Soderžnik
12. Aragonite: structure and formation
    Prof. Aleksander Rečnik
13. Functionally Graded Materials with Interpenetrating Phases made of Immiscible Alloys
    Dr. Aljaž Iveković
14. Nuclear radiation catalyzed chemistry
    Prof. Sašo Šturm
15. 4D STEM of energy related materials down to quantum level
    Prof. Sašo Šturm
16. Radiation as a Singular Source for Rapid Sintering of 3D Printed Multifunctional Ceramics
    Prof. Andraž Kocjan
17. CerAM-Heat: Additive manufacturing of porous polymer-derived ceramics with magnetic heating capability anbling an electrification of chemical processes
    Dr. Aljaž Iveković
18. Erythrocyte membrane-based nanocarriers for gene silencing cancer therapy
    Asst. Prof. Nina Kostevšek
19. Novel Flow Photoelectrocatalytic Reactors for Degradation of Pharmaceuticals in Waste Water
    Prof. Miran Čeh
20. Portable, highly sensitive and selective nanostructured biosensors for viral rapid detection
    Dr. Špela Trafela
21. Stability and formation of Inversion Boundaries in ZnO: DFT and experimental screening for new IB-forming dopants
    Vesna Ribić
22. DYNAmic phase formations and evolutions of the electroCATalysts for enhanced carbon capture and conversion
    Sorour Semsari Parapari
23. RECEMENT:Re-generating (raw) materials and end-of-life products for re-use in Cement/Concrete
    Prof. Sašo Šturm
    Ministry of Education, Science and Sport
24. AddMag - Additive manafucturing of permanent magnet materials
    Asst. Prof. Matej Andrej Komelj
    Ministry of Higher Education, Science and Innovation
25. Fusion technologies
    Prof. Saša Novak Krmpotič
    Slovenian Research Agency
26. Bio-interactive support materials for coral restoration.
    Dr. Anže Abram
    Slovenian Research and Innovation Agency
27. Services for the Exports
    Dr. Zoran Samardžija
28. External Services
    Prof. Andraž Kocjan

29. AdSTEM3 - European Workshop on 4D STEM Imaging, May 14 - May 18, 2023, Piran, Slovenia
    Prof. Miran Čeh
30. Development funding pillar
    Prof. Sašo Šturm
    Slovenian Research Agency

NEW CONTRACTS

1. Development of complex shape multicomponent permanent magnets with the use of advanced 3D printing technology
   Prof. Spomenka Kobe
   Kolektor Group d. o. o.
2. Novel Flow Photoelectrocatalytic Reactors for Degradation of Pharmaceuticals in WasteWater
   Prof. Miran Čeh
   Arhel Projektiranje in Inženiring d. o. o.
3. Development and optimization of varistor ceramics and volume and multilayer (MLV) varistors

Prof. Slavko Bernik
Bourns d. o. o. Žužemberk

4. Material characterization of biopharmaceutical products and primary packaging
   Prof. Sašo Šturm
   Lek d. d.
5. Monitoring the manufacturing process of varistor ceramics and varistors
   Prof. Slavko Bernik
   Raycap d. o. o.
6. Participation in the measurement process
   Prof. Sašo Šturm
   RLS Merilna tehnika d.o.o.
7. Development and optimization of varistor ceramics and process parameters for the production of volume and multilayer (MLV) varistors
   Prof. Slavko Bernik
   Bourns d. o. o. Žužemberk
8. Monitoring the manufacturing process of varistor ceramics and varistors – 2
   Prof. Slavko Bernik
   Raycap d. o. o.
9. VSM, XRD, TEM and CoNiP measurements
   Prof. Sašo Šturm
   RLS Merilna tehnika d.o.o.

VISITORS FROM ABROAD

1. Anna Katharina Hofer, Lehrstuhl für Struktur und Funktionskeramik, Montanuniversität Leoben, Austria, 19–20 January 2023
2. Martina Kocijan, Sveučilište u Zagrebu, Croatia, 13–14 February 2023
3. Alba Berja Torres, Instituto de cerámica y Vidrio (CSIC/ICV), Madrid, Spain, 1–31 May 2023
4. Prof. Carlo Burkhardt, Hochschule Pforzheim, Germany, 18 April to 20 May 2023
5. Dr Johann Fischbacher, Dr Alexandr Grushko, Prof. Thomas Schrefl, Universität für Weiterbildung Krems, Krems an der Donau, Austria, 24–25 April 2023
6. Yasemin Akyol, Prof. Mehmet Ali Gülgün, Melike Nur Önden, Sabanci University, Faculty of Engineering and Natural Engineering, Tuzla (Istanbul), Turkey, 18–20 May 2023
7. Anna Katharina Hofer, Lehrstuhl für Struktur und Funktionskeramik, Montanuniversität Leoben, Austria, 22–25 May 2023
8. Ana Laura Coria Gutierrez, Institute of Chemistry for Life and Health Sciences (I-CLeHS, SEISAD), Pariz, France, 25–27 May 2023
9. Katarina Tomić, Univerza v Beogradu, Belgrade, Serbia, 5 June to 31 August 2023
10. Prof. Larisa Soldatova, Goldsmiths, University of London, United Kingdom, 8 June 2023
11. Wilfried Bajoun Mbajoun, Dr Pascal Boulet, Dr Vincent Fournee, Dr Julian Ledieu, Jules Valentin, Julien Zollinger, Institut Jean Lamour – Universitet dé Lorraine, Nancy, France, 12–16 June 2023
12. Bertrand Morel, Véronique Peres, Benoit Richebe, Orano, Châtillon, Hauts-de-Seine, France, 19 June 2023
13. Paul Barends, Prachi Vyas, Thermo Fisher Scientific, Eindhoven, Netherlands, 27 June 2023
14. Agata Knabe, Gdańsk University of Technology, Gdańsk, Poland, 10 July to 10 September 2023
15. Russel Hardy, Dr Nynke Krans, Protochips, Morrisville (NC), United States of Amerika, 8–9 August 2023
16. Dr Andrea Bachmaier, Prof. Jürgen Eckert, Erich Schmid Institute of Materials Science of the Austrian Academy of Sciences, Montanuniversität Leoben, Austria, 17–18 September 2023
17. Laura Grau, Hochschule Pforzheim, Pforzheim, Germany, 17 September to 17 October 2023
18. Dr Sanaa Chemchoub, Mohamed El Marini, Monica Parpal Gimenez, Daniel Torres, Prof. Jon Ustarroz, Université Libre de Bruxelles, Brussels, Belgium; Hanieh Jafarian, University of Vienna, Austria, 24 September to 2 October 2023
19. Prof. Cristian Fabrega, University of Barcelona, Electronics and Biomedical Engineering, Barcelona, Spain; Prof. Caroline Duc, Institut Mines-Télécom, Department for Environment and Energy, Douai, France, 26–29 September 2023
20. Vojtěch Mařák, Brno University of Technology, Central European Institute of Technology, Brno, Czech Republic, 2–20 October 2023
21. Prof. Mehmet Ali Gülgün, Sabanci University, Faculty of Engineering and Natural Engineering, Tuzla (Istanbul), Turkey, 2–31 October 2023
22. Mieszko Gosławski-Żeligowski, Lodz University of Tehnology, Lodz, Poland, 2 October–15 December 2023
23. Dr Ahmed Alsadig, Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany, 4 –6 October 2023
24. Ritika Arora, Punjabi University Patiala, Punjab, India, 16 November 2023 to 14 February 2024
25. Wilfried Bajoun Mbajoun, Dr Pascal Boulet, Dr Vincent Fournée, Dr Emilie Gaudry, Dr Julian Ledieu, Vipin Kumar Singh, Weiliang Ma, Institut Jean Lamour – Universitet dé Lorraine, Nancy, France, 30 November to 2 December 2023
26. Dr Kevin Varghese Alex, International & Inter-University Centre for Nanoscience & Nanotechnology, Mahatma Gandhi University, Kottayam, Kerala, India, 3–5 December 2023
27. Daria Jardas Babić, Sveučilište u Rijeci/University of Rijeka, Croatia, 8 December 2023 to 14 June 2024

STAFF

Researchers
1. Dr. Belisa Alcantara Marinho
2. Dr. Muhammad Shahid Arshad
3. Prof. Slavko Bernik
4. Prof. Miran Čeh
5. Prof. Jean Marie Dubois
6. Dr. Aljaž Iveković
7. Dr. Petra Jenuš Belec
8. Prof. Spomenka Kobe
9. Prof. Andraž Kocjan
10. Asst. Prof. Matej Andrej Komelj
11. Asst. Prof. Nina Kostevšek
12. Prof. Saša Novak Krmpotič
13. Dr. Matejka Podlogar
14. Dr. Benjamin Podmiljšak
15. Prof. Aleksander Rečnik
16. Dr. Zoran Samardžija
17. **Prof. Sašo Šturm, Head**
18. Asst. Prof. Kristina Žagar Soderžnik
19. Prof. Kristina Žužek

Postdoctoral associates
20. Dr. Anže Abram

21. Dr. Maja Antanasova*
22. Dr. Fabian Allen Burkhardt
23. Dr. Nataša Drnovšek*
24. *Dr. Živa Marinko, left 01.04.23*
25. Dr. Vesna Ribić
26. Sorour Semsari Parapari, M. Sc.
27. Dr. Tomaž Tomše
28. *Dr. Špela Trafela, left 01.11.23*
29. Dr. Jelena Vujančević
30. Dr. Milan Vukšić

Postgraduates
31. Nikhil Bhootpur, M. Sc.
32. Giulia Della Pelle, M. Sc.
33. Lara Einfalt, B. Sc.
34. Dr. Sina Khoshsima
35. Diana Knyzhnykova, M. Sc.
36. Klara Laura Konda, B. Sc.
37. Abhilash Krishnamurthy, M. Sc.
38. Monika Kušter, B. Sc.
39. Barbara Ljubec Božiček, B. Sc.
40. Dr. Amit Mishra
41. Mihaela Rebernik, B. Sc.

42. Layrton Jose Souza Da Silva, M. Sc.
43. Vinko Sršan, M. Sc.
44. Aleksander Učakar, B. Sc.
45. Anubhav Vishwakarma, M. Sc.

Technical officers

46. Sanja Fidler, B. Sc.
47. Nik Gračanin, B. Sc.
48. Kaja Križman, B. Sc.
49. Ipeknaz Özden Moser, M. Sc.
50. Dr. Boris Saje*
51. Nejc Skoporc, B. Sc.

52. Neža Sodnik, B. Sc.
53. *Kseniia Vyshnevska, M. Sc., left 03.03.23*

Technical and administrative staff

54. Sabina Cintauer, B. Sc.
55. Darko Eterović
56. Tina Radošević, B. Sc.
57. Marija Šebjan Pušenjak, B. Sc.

Note:
* part-time JSI member

DEPARTMENT FOR MATERIALS SYNTHESIS K-8

The research of the Department for Materials Synthesis is mainly related to the synthesis of various advanced materials, especially magnetic materials. Special attention is given to nanostructured materials, such as ferrofluids, functionalized nanoparticles for use in biomedicine, multifunctional nanocomposites, catalysts, and fluorescent nanoparticles.

The synthesis of nanostructured materials at the Department for Materials Synthesis usually involves inorganic nanoparticles, the engineering of nanoparticles' surface properties (either by their coating with inorganic shells and/or by bonding different functionalization molecules onto their surfaces, i.e., functionalization), the preparation of their colloidal suspensions and their assembly into composite materials. The synthesized materials are adapted for specific applications in catalysis, biomedicine or sensorics, if we only mention the ones that were prominent in 2023.

Head:
Prof. Darko Makovec

Synthesis and structural properties of substituted barium-hexaferrite nanoplatelets

In the research group devoted to **nanostructural characterization** the crystalline structures and magnetic properties of barium hexaferrite ($BaFe_{12}O_{19}$) nanoplatelets (NPLs) were studied. Because of their unique magnetic and structural properties, the hexaferrite NPLs found applications in different areas, ranging from the magneto-mechanical destruction of cancer cells to liquid magnets (see below). Synthesis of the NPLs is based on a simple hydrothermal treatment of a suspension of Ba and Fe hydroxides. Magnetic properties of the NPLs can be tailored with the substitution of a part of the Fe^{3+} ions with other ions. In 2023 we studied the influence of substituents Co, Ni, and Mn on the structural and magnetic properties of the hexaferrite NPLs. Even though the three substituents are chemically quite similar, they influenced the structure and the magnetic properties of the hexaferrite NPLs differently. The different influences were related to the different oxidation states of the substituents, which were studied with X-ray photoelectron spectroscopy (XPS) in cooperation with Dr Janvit Tržan from the National Institute of Chemistry.

The Mn substituted the Fe^{3+} ions in the oxidation state 3+. The solid-solubility limit of Mn^{3+} in $BaFe_{12-x}Mn_xO_{12}$ NPLs was relatively high, extending to x ∼ 3. The incorporation of Mn efficiently refined the size of the NPLs, from a width exceeding 200 nm (for the unsubstituted NPLs) to less than 50 nm for x = 3 (the NPLs thickness was always below 5 nm).

On the other hand, the Ni adopted the oxidation state 2+. Ni^{2+} is incorporated into the structure of the NPLs in low concentrations up to x = 0.9 in the $BaFe_{12-x}Ni_xO_{12}$ formula. The addition of Ni in the low concentrations considerably narrowed the size distribution of NPLs. When Ni was added at higher concentrations, composite nanoparticles were formed. The particles are composed of hexaferrite and spinel ferrite ($NiFe_2O_4$) inter-grown inside the single nanoparticles (Figure 1). Such a structure is very interesting as it can provide the exchange coupling of the two magnetic materials within a single nanoparticle. The properties of the hexaferrite are magnetically hard, meaning that it exhibits a high coercivity (H_C), but a modest saturation magnetization (M_S). In contrast, the spinel ferrite is soft magnetic, with modest H_C, but high M_S. Due to the hard-soft exchange coupling the composite nanoparticle can magnetize as a single magnetic phase and can combine the relatively strong M_S provided by the soft phase with a large H_C of the hard phase.

The Co adopted mixed 2+ and 3+ oxidation states during the hydrothermal synthesis of hexaferrite NPLs. It is incorporated into the NPLs hexaferrite structure only at low concentrations, similar to Ni^{2+}. However, when added at higher concentrations, the NPLs with a new structure were formed. The new structure was studied with the combination of direct atomic-resolution scanning-transmission electron microscopy (STEM) imaging and X-ray diffraction (XRD) (in cooperation with Prof Anton Meden from the Faculty of Chemistry and Chemical Technology, University of Ljubljana). The new structure belongs to a large family of hexagonal ferrites, which can be formed by different combinations of three structural blocks: a cubic (Me_6O_8)$^{2+}$ S block, a hexagonal ($BaMe_6O_{11}$)$^{2-}$ R block, and a ($Ba_2Me_8O_{14}$)$^{2-}$ T block (Me stands for Fe

The shape anisotropy of magnetic nanoparticles: an approach to cell-type selective and enhanced internalization.
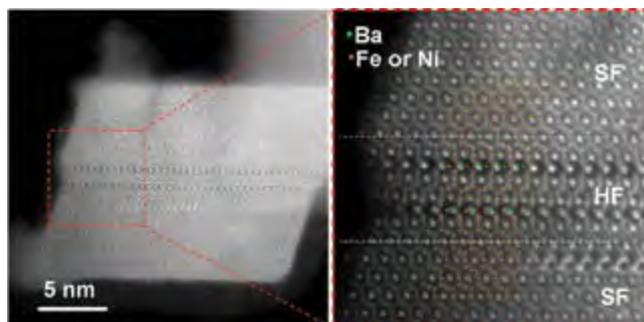

Figure 1: Composite nanoparticle combining hexaferrite (HF) nanoplatelet intergrown in spinel ferrite (SF) matrix.

or other transition metal). The structure of barium hexaferrite is composed of S and R structural blocks; whereas the new structure of heavily Co-substituted hexaferrite NPLs seems to be composed only of the T structural blocks.

The incorporation of any of the three substituents into the structure of hexaferrite NPLs decreased their magnetic properties. The effect was unexpected as the three substituents exhibit a similar electronic structure to the Fe, which is substituted. The research is continuing.

Magnetic bionanomaterials

The Bionanomaterials group focuses on investigations of magnetic iron-oxide nanoparticles and their composites/hybrids with other types of inorganic nanoparticles, polymers and lipids for use in biomedicine. Our research revolves around the understanding and development of new approaches for the magnetic assembly of small magnetic nanocrystals, usually superparamagnetic iron-oxide nanoparticles, into larger magnetically guidable nanostructures preferentially with anisotropic shapes. Recently, the group gives special emphasis to the development of versatile nanoparticle assembly approaches, which allow combining magnetic nanocrystals and gold nanoparticles. Besides the synthesis the bionanomaterials group's research also focuses on applications development where the shape anisotropy of magnetic nanoparticles is exploited in the process of magneto-mechanical actuation. We investigate soft matter such as bacterial biofilms and misfolded protein deposits when exposed to anisotropic magnetic nanoparticles under low frequency and low strength rotating magnetic field. This approach allows braking down the structure of targeted soft matter by remotely triggered magnetic manipulation, which opens many therapeutic options in cancer and neurodegenerative diseases. The concept is not broadly investigated worldwide because researchers face challenges with the assemblies of nanoparticles into anisotropic magnetic nanomaterials suitable for the use in biomedicine. However, the latter is our main research focus and we believe the concept justifies further extensive research input in the coming years.

In 2023 the bionanomaterial part of the departments' research was mainly devoted to four ARIS projects (J2-3043, J3-3079, J7-4420, J2-3040) related to the exploitation of magneto-mechanical actuation of anisotropic magnetic nanoparticles for manipulation of a soft matter, such as eradication of persistent biofilms and disruption of misfolded protein aggregates to smaller fractions. We established collaboration with the group of Prof. Janez Košmrlj from the Faculty of Chemistry and Chemical Technology, University of Ljubljana, where we joined efforts on the development of new affinity ligands for nanoparticle functionalization with the aim to achieve better targeting of amyloids beta. Furthermore, we identified special expertise that was required for the generation of suitable amyloid fibrillar self-assembled structures and for performance of *in-vitro* studies of disrupted protein aggregates on neuronal cells, therefore collaborations with the research groups of Prof. Boris Rogelj (dr. Helena Motaln) from the Department of Biotechnology, JSI and Prof. Stanislav Gobec (dr. Damijan Knez) from the Faculty of Pharmacy, University of Ljubljana have been established.

Synthesis of magnetic catalysts for electrified ammonia production.

Figure 2: Schematic representation (A, B) of internalization process of spherical (A) and anisotropic (B) nanoparticles in co-culture of normal (NPU) and cancer (T24) urothelial cells and corresponding fluorescence microscopy images (C, D). Both types of nanoparticles were internalized preferentially into T24 cells whereas the extent of internalization of nanochains into T24 cells was larger compared to the spherical nanoparticles.

An important part of the research was focused to removal of persistent biofilms, where we established collaboration with experts on microbiology working on preparation of suitable bacterial biofilms (Prof. Jelena Kološnjaj-Tabi, CNRS, University of Toulouse, France, Prof. Jerica Sabotič and Prof. Aleš Berlec from Department of Biotechnology, JSI), with organic chemists from Faculty of Pharmacy UL (Prof. Stane Pajk and Prof. Marko Anderluh) with expertise on organic synthesis of glycan and biocide ligands for targeting specific bacterial biofilm and with an expert on magnetic properties (Prof. Alenka Mertelj, Department of Complex Matter, JSI). Here, on the side of nanomaterials synthesis of new anisotropic magnetic nanoparticles, we also established collaboration with the group from Switzerland (Prof. Irena Milosevic, HEPIA - University of Applied Sciences and Arts Western Switzerland) with the complementary expertise on synthesis of the anisotropic nanomaterials. First research results were protected by completing a patent application (EP23307039 - A magnetic anisotropic material for disruption and/or sensitization of bacterial biofilm) together with the CNRS group from Toulouse, France.

In the national project J2-3040, where we cooperate with the Department of Molecular and Biomedical Sciences (Asst Prof Toni Petan), Biotechnical Faculty, University of Ljubljana (Prof Nataša Poklar Ulrih), and the Institute of Cell Biology, University of Ljubljana (Prof Mateja Erdani Kreft), we develop new nanocarriers mimicking endogenous lipid particles. The nanocarriers were designed to enable the delivery of a large amount of hydrophobic

nanoparticles and lipophilic drugs into cells. The nanocarriers are assembled from hydrophobic nanoparticles and lipophilic molecules in an emulsion system, where the phospholipids and proteins (apolipoprotein or albumin) were used as the surfactants. In 2023 we optimized the assembling method. Our aim was to exploit magnetic hexaferrite nanoplatelets for the destruction of cancer cells with actuation of the nanoplatelets with a low-frequency magnetic field (i.e., magneto-mechanical actuation), different Fe-containing nanoparticles (hexaferrite nanoplatelets and magnetite nanoparticles) in combination with polyunsaturated fatty acids to enable ferroptosis, and fluorescent fluoride nanoparticles. The hexaferrite nanoplatelets are used to trigger the release of the cargo with the magneto-mechanical actuation of the nanoplatelets. First results suggest the nanocarriers mimicking endogenous lipid particles are non-toxic to the cells.

The theory supports experiments: Surface structure and with it, the saturation magnetisation of barium hexaferrite nanoplatelets depend on the pH of an aqueous medium.

In 2023 we continued research on ARIS project J2-3046 in collaboration with researchers from the Faculty of Electrical Engineering, University of Ljubljana (group of Prof. Damijan Miklavčič) where we joined efforts on selective electroporation using gold nanoparticles as targeted nanoelectrodes. We prepared gold nanoparticles with different sizes ranging from 10 to 130 nm and with spherical and rod-like shapes. The nanoparticles were functionalized with HS-PEG-OMe molecules to achieve good colloidal stability in complex fluids used for the electroporation. As a control, spherical silica nanoparticles were synthesized and functionalized with PEG silane molecules.

In 2023 we completed our studies on understanding of the effect of magnetic particles' shape anisotropy on the efficacy of their cellular internalization. We have revealed that an anisotropic shape of magnetic nanochains accelerates the uptake, as well as the extent of the uptake (Figure 2). We have performed studies in cooperation with Faculty of Pharmacy, University of Ljubljana (Prof. Petra Kocbek) and Faculty of Medicine, University of Ljubljana (Prof. Mateja Erdani Kreft.) The results were published in the journal *Nanoscale*.

We also established a collaboration with researchers from the Department of Chemical and Pharmaceutical Sciences, University of Trieste, Italy (Prof Maurizio Prato) on joint project on carbon nanodots selective functionalization which allows new optically communicating elements. The work was published in the journal *Angewandte Chemie International Edition*.

Magnetic catalysis

The Magnetic Catalysis group focuses on research of magnetic nanocomposites for applications in catalysis. Our catalysts are hierarchal nanocomposite materials composed of magnetic nanoparticles embedded within a high-surface-area inorganic matrix decorated with small catalytic nanoparticles. Our research revolves around understanding how chemical parameters of the synthesis such as concentration, pH and temperature control the properties of the catalysts. In collaboration with the Department of Catalysis and Chemical Reaction Engineering, National Institute of Chemistry we develop new approaches for chemical conversions based on magnetic heating of the catalyst. The magnetic heating exploits the heating of magnetic nanoparticles in a high-frequency magnetic field to provide heat for conducting catalytic reactions. Its advantages are in a rapid heating of the catalytic layer and a good temperature control. In addition to electrification, such reactors enable more flexible production of chemicals and fuels in comparison to conventional heating. Flexibility is especially important for the utilization of intermittent electricity obtained from renewable sources. This new heating methodology as well solves some general problems encountered in industrial plants, where start-up times under conventional heating schemes typically require several days to bring the plant under the steady-state regime conditions safely.

At the forefront of our research is the synthesis of the magnetic catalysts. One of the important classes of catalysts is alumina decorated with metallic nanoparticles. In the previous period the synthesis procedure for the nanostructured magnetic alumina was developed in collaboration with Prof Andraž Kocjan form the Department for Nanostructured Materials based on deposition of AlOOH onto the superparamagnetic iron-oxide nanoparticles with the hydrolysis of AlN in the colloidal suspension followed by a thermal treatment. The iron oxide magnetic nanoparticles showed to be unsuitable for applications where highly reducing atmosphere is present, such as, for example, in the process of the synthesis of ammonia. For these purposes we have developed a similar nanocomposite, which contains Co_xNi_{1-x} alloy nanoparticles instead of iron oxide. Focus of the research, which is part of the H2020 project Oracle was on the influence of reduction conditions, such as temperature, temperature ramp and H_2 gas flow, on the size of Co_xNi_{1-x} nanoparticles. Analysis of the reduction revealed a rather complex process that proceeds in two distinct temperature ranges and only finishes at approximately 850 ℃. The reduction for the alloy proceeds at markedly higher temperatures compared to the constituent metals Co and Ni and the reduction temperature is further increased with confinement in the matrix. The study showed that upon exposure of the nanocomposites to ambient air, the Co_xNi_{1-x} alloy nanoparticles partially oxidise. The oxidation was more pronounced at higher Co contents. However, for the nanoparticles containing up to 67 % of Co the formation of an initial surface oxide layer seems to protect the alloy from any further oxidation. The Co_xNi_{1-x}-Al_2O_3 nanocomposites efficiently heated

when they were exposed to high-frequency (118–330 kHz) alternating magnetic fields, already at relatively low amplitudes up to 58 mT. Testing in a fixed-bed reactor relevant for the high-temperature catalytic processes, such as ammonia synthesis/decomposition and steam-methane reforming, showed that high temperatures above 800 °C can be achieved within minutes.

Especially for oxidation reactions, ceria is the preferred material for a catalyst support. For synthesis of magnetic ceria supports to be used in catalysis by magnetic heating, a new method was developed based on coating ceria shell onto magnetic nanoparticles. Iron-oxide nanoparticles and CoNi nanoparticles were used as the magnetic phase. The deposition method was based on the simple controlled precipitation of Ce^{3+} ions in the presence of hexameth-

Figure 3: Ammonia decomposition at non-isothermal dynamical conditions. The highlighted areas mark the time intervals when the heating was turned on (green) and off (red).

ylenetetramine (HMTA). Special attention was given to reveal chemical mechanisms enabling the deposition of homogeneous ceria coatings with a high surface area. We found that the homogeneous ceria can be deposited onto the iron-oxide nanoparticles only when they were previously coated with a thin silica layer, whereas the ceria shell could be deposited directly onto the Co,Ni hydroxides, as the precursors for the CoNi nanoparticles, or to the alumina with embedded CoNi nanoparticles. The deposited shell was composed of small ceria nanocrystallites, 3–5 nm in size. After the deposition of catalytic Ru nanoparticles onto the iron oxide–ceria support, the catalysts were tested in catalytic hydrogenation of hydroxymethyl furfural (HMF) with the conventional and magnetic heating.

Storing and transporting pressurized or liquid hydrogen is expensive and hazardous. As a result, safer methods, such as chemical storage in ammonia, are becoming increasingly important. However, the instantaneous start of a conventionally heated reactor is challenging. In collaboration with the Department of Catalysis and Chemical Reaction Engineering, National Institute of Chemistry and the European consortium of the H2020 Oracle project we developed a responsive and electrified process for ammonia synthesis based on magnetic heating of the CoNi-alumina nanocomposites decorated with catalytic Ru nanoparticles. In addition, the catalyst was very active for the ammonia-decomposition reaction. The study showed that the rapid heating of the magnetic nanoparticles enables rapid changes of the catalyst's temperature and consequently the effluent's composition. The H_2-to-NH_3 ratio in the effluent can be tuned from 0 to 1 on a minute time scale (Figure 3). Examining the NH_3 conversion under isothermal, stationary conditions revealed that the kinetics hampered the conversion and not the heat transfer, as is usually the case with conventionally heated reactors. The results of both studies indicate that the implementation of magnetic heating could lead to the application of ammonia as a hydrogen vector where intermittent renewable electricity is utilized by a single unit.

In the 2023 we continued our research collaboration with the Department of Green Technologies, University of Southern Denmark (Prof Shuang Ma Andersen and Prof Raghunandan Sharma). We contributed to the development of a highly active oxygen evolution reaction catalysts composed of IrO_2 with an Ir-rich surface. The catalytic nanoparticles were deposited on the TiN material. The main finding was improved stability of the catalyst due to TiN corrosion resistance in comparison to traditionally used carbon materials.

Hybrids and liquid ferroics (HI LIFE)

The HI LIFE group focuses on the research of hybrid materials and liquid ferroics. The hybrid materials of our interest are combined from inorganic nanocrystals and organic ligands. Our studies start by understanding the interactions between the inorganic crystalline surfaces and organic matter, chemical stability, and assembly of nanoparticles in various systems, such as liquid ferroics, a liquid alternative to solid-state ferroics. After the development of first ferromagnetic liquid in cooperation with the Department of Complex Matter (Nature, 2013), intensive research continues on magnetoelectric and multiferroic liquids. Our studies include colloidal interactions and ferroic coupling in the dispersions of magnetic nanoplatelets based on barium hexaferrite aiming for possible applications in sensors, microfluidics, smart grids, service robotics, and water purification.

The control of surface properties of nanoparticles through the functionalisation or hybridization with organic ligands enables the preparation of their colloidal suspensions. At the forefront of our research is the preparation of suspensions of permanently magnetic barium hexaferrite nanoplatelets (in cooperation with the Department of Complex Matter). We were interested in different types of systems and their behaviours. Until now, the most stable system is based on 1-butanol suspensions of the barium hexaferrite nanoplatelets functionalized with do-
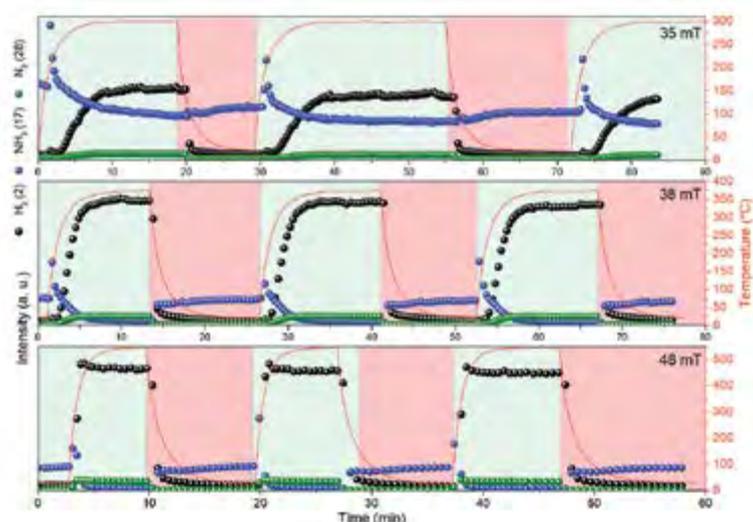
decylbenzenesulfonic acid. We showed, in cooperation with the Institute of Physics, Otto von Guericke University from Magdeburg, that such suspensions respond to an AC magnetic field differently, depending on nanoplatelet concentration.

At sufficiently high concentrations, the suspensions of barium hexaferrite nanoplatelets become ferromagnetic, i.e., they exhibit a spontaneous magnetic ordering and represent liquid magnets (in contrast to well-known paramagnetic ferrofluids). We focus on the understanding of colloidal interactions in the suspensions of hexaferrite nanoplatelets. The most important study from last year is related to the induced flow within a ferromagnetic ferrofluid that can be used in tubeless microfluidics (published in Small 2023).

Our current studies focus on the colloidal stabilization of magnetic nanoplatelets in apolar solvents. The main challenge in comparison to the polar suspensions is the lack of long-range electrostatic repulsion. Until now, the ferromagnetic ferrofluids were obtained only in the systems with sufficiently strong electrostatic repulsive interaction that counterbalanced the long-range attractive magnetic dipolar interaction between the magnetic nanoplatelets. Our study focuses on different macromolecules providing for steric repulsion in efficiently solvating apolar solvents..

The development of a magnetoelectric liquid, as an advancement of ferromagnetic ferrofluids, is a goal of the FET-OPEN project MAGNELIQ, in which we cooperate with the University of Maribor, CNR Trieste, Czech Academy of Sciences and an SME Prensilia from Italy. This year we combined experimental and theoretical studies related to tuning the surface chemistry and structure of the barium hexaferrite nanoplatelets. The surface terminal plane of the nanoplatelets is determined with the post-synthesis conditions, i.e., the final pH of the aqueous suspension. The theoretical calculations predict the highest stability of the *2b*-termination, which was indeed observed at high pH values in a sodium hydroxide aqueous solutions. At low pH values the theory predicts the *12k-* or *12k-O* termination, as was also experimentally observed in aqueous solutions of nitric acid.

Considering possible applications of the above liquid systems that are based on barium hexaferrite nanoplatelets, we are also interested in the way they could interact with the environment after their use. The first study of the interactions of ferrite (pure iron oxide) nanoparticles with catechols did not suggest any significant decomposition of the ferrites. In contrast, the dissolution of the barium hexaferrite nanoplatelets in acid solutions was accelerated in the presence of catechols. Currently, we are studying the related mechanism.

This year we finished with a national project "Surface selective hybridization technology for magnetoelectric hybrids", in cooperation with the Faculty of Chemistry and Chemical Technology, University of Ljubljana. The project was focused on the development of hybridization technology for making magnetoelectric Janus nanoplatelets. Moreover, in cooperation with the Electronic Ceramics Department, we showed evidence of ferroelectricity in a single ferrimagnetic barium hexaferrite nanoplatelet. The coupling of the two ferroic properties is studied experimentally and theoretically.

Some outstanding publications in the past year

1. Poberžnik, Matic, Herrero-Saboya, Gabriela, Makovec, Darko, Lisjak, Darja, Martin-Samos, Layla. Surface phase diagrams of pristine and hydroxylated barium hexaferrite surfaces from first-principles atomistic thermodynamics. *Applied surface science*. 2023, vol. 637, 157890, str. 1-12, ISSN 1873-5584.
2. Gyergyek, Sašo, Tchernychova, Elena, Böőr, Katalin, Nečemer, Marijan, Makovec, Darko. Magnetic carbon nanocomposites via the graphitization of glucose and their induction heating. *Journal of alloys and compounds*. 2023, vol. 953, str. 170139-1-170139-9. ISSN 0925-8388.
3. Potrč, Tanja, Kralj, Slavko, Nemec, Sebastjan, Kocbek, Petra, Erdani-Kreft, Mateja. The shape anisotropy of magnetic nanoparticles: an approach to cell-type selective and enhanced internalization. *Nanoscale*. 2023, vol. 15, iss.19, str. 8611-8618, ISSN 2040-3364.

Awards and Appointments

1. Tina Černič: Krka's award, Novo mesto, 20 October 2023
2. Sebastjan Nemec: Krka's recognition with special recommendation, Novo mesto, 20 October 2023

Organization of Conferences, Congresses and Meetings

1. ORACLE – Project Meeting Ljubljana, 18 to 19 May 2023
2. PASSENGER - Project Meeting, Ljubljana, 31 May to 1 June 2023

INTERNATIONAL PROJECTS

1. H2020 - BeMAGIC; Magnetoelectrics Beyond 2020: A Training Programme on Energy-Efficient Magnetoelectric Nanomaterials for Advanced Information and Healthcare Technologies
Prof. Darja Lisjak
European Commission
2. H2020 - ORACLE; Novel Routes and Catalysts for Synthesis of Ammonia as Alternative Renewable Fuel
Asst. Prof. Sašo Gyergyek
European Commission
3. H2020 - PASSENGER; Pilot Action for Securing a Sustainable European Next Generation of Efficient RE-Free Magnets
Prof. Darko Makovec
European Commission
4. H2020 - MAGNELIQ; A Magneto-Electric Liquid - Better Sensing
Prof. Darja Lisjak
European Commission
5. Investigation of Ferrimagnetic Vortex Iron Oxide (FVIO) Based Nanoparticles for Magnetic Hyperthermia Applications
Prof. Darko Makovec
Slovenian Research Agency
6. In Vitro and In Vivo Magneto-Mechanical Destruction of Tumors by Anisotropic Magnetic Nanoparticles
Asst. Prof. Slavko Kralj
Slovenian Research Agency
7. The Anisotropic Iron Oxide Nanoparticles for Medical Applications: Magneto-Mechanical Effect and Hyperthermia
Asst. Prof. Slavko Kralj
Slovenian Research Agency
8. Maghon - Feasibility Study for Preparation of Magnetically Heatable Honeycombs
Asst. Prof. Sašo Gyergyek
Ceram Austria GmbH
9. Microwave Ferrites
Prof. Darja Lisjak
Antistat GmbH

RESEARCH PROGRAMME

1. Advanced inorganic magnetic and semiconducting materials
Prof. Darko Makovec

R&D GRANTS AND CONTRACTS

1. Bactericidal nanoblades: a proof-of-concept approach for bimodal chemo-mechanicaleradication of persistent biofilms
Asst. Prof. Slavko Kralj
2. Selective electroporation by distributed nanoelectrodes
Asst. Prof. Slavko Kralj
3. The development of a highly sensitive electrochemical method for trace determination of antibiotic compounds based on magnetic polymericnanocomposites in environmental systems
Asst. Prof. Sašo Gyergyek
4. Novel materials based on lignin from biomass with enhanced luminescent activity
Prof. Darja Lisjak
5. Liquid Magnets: fundamental studies of ferromagnetic order in liquids
Prof. Darja Lisjak
6. Surface-selective hybridization technology for magneto-electric hybrids
Prof. Darja Lisjak
7. Magneto Responsive Surfaces for Manipulation of Light and Liquids
Prof. Darko Makovec
8. Magnetically-controllable nanocarriers mimicking endogenous lipid particles for improved drug/nanoparticle delivery
Prof. Darko Makovec
9. Exploitation of the magneto-mechanical effect in the treatment of neurodegenerative diseases
Asst. Prof. Slavko Kralj
10. Selective mechanical removal of bacterial biofilms by conjugated magnetic nanoparticles
Asst. Prof. Slavko Kralj
11. CerAM-Heat: Additive manufacturing of porous polymer-derived ceramics with magnetic heating capability anbling an electrification of chemical processes
Asst. Prof. Sašo Gyergyek

VISITORS FROM ABROAD

1. Dr Alexandru Lixandru, Huawei, Austria, 3 Feb 2023
2. Dr Zhao Dong Chen, Huawei, Austria, 3 Feb 2023
3. Emily Basmaison, Ecole Supérieure d'Ingénieurs Numérique et Matériaux (ESIREM), University of Burgandy, Dijon, France, 17 April to 14 July 2023
4. Pauline Tabel, Ecole Supérieure d'Ingénieurs Numérique et Matériaux (ESIREM), University of Burgandy, Dijon, Francija, 17 April to 14 July 2023
5. DI Dr Roland Nilica, DI Gernot Fauland MSc, DI Georg Kogler, CERAM, Austria, 11 May 2023
6. Dr Yves Huttel, Instituto de Ciencia de Materiales de Madrid (ICMM), CSIC Spain, Spain, 4 July 2023

STAFF

Researchers
1. Asst. Prof. Sašo Gyergyek
2. Asst. Prof. Slavko Kralj
3. Prof. Darja Lisjak
4. **Prof. Darko Makovec, Head**
5. Dr. Igor Zajc

Postdoctoral associates
6. Dr. Stanislav Čampelj
7. Dr. Parvaneh Esmaeilnejad Ahranjani
8. Dr. Sebastjan Nemec
9. *Dr. Jelena Papan Djaniš*, left 01.09.23*
10. Dr. Nina Popov
11. Dr. Janvit Teržan*
12. Dr. Ali Tufani

Postgraduates
13. Maja Caf, B. Sc.
14. Katja Drobež, B. Sc.
15. Nina Križaj Kosi, B. Sc.
16. Žiga Ponikvar, B. Sc.
17. Anja Sedminek, B. Sc.
18. Luka Skubic, B. Sc.
19. Jošt Tručl, B. Sc.

Technical and administrative staff
20. Bernarda Anželak, B. Sc.
21. *Tina Černič, B. Sc., left 01.12.23*
22. Tamara Matevc, B. Sc.

Note:
* part-time JSI member

DEPARTMENT FOR ADVANCED MATERIALS K-9

At the Advanced Materials Department we delve into innovative materials by understanding the interplay between their structural, microstructural, and functional properties. Employing cutting-edge technologies capable of precisely synthesizing materials at the atomic and micro levels, we craft customized, structural 3D materials, thin films, and nanoparticles, ensuring specific crystal structures, chemical compositions, microstructures, and morphologies. Our key goals encompass the advancement of: i) new functional oxides for electronic applications and energy conversion, ii) antibacterial and piezoelectric biocompatible materials, and iii) sustainable heat-insulation materials and superhydrophobic coatings with enhanced properties and sustainability.

Head:
Prof. Matjaž Spreitzer

Novel functional oxides for electronic applications and energy conversion

In the designing of new and efficient photocatalysts, catalysts, and piezocatalysts our team investigated advanced strategies for the low-temperature preparation of (nano)structures with morphologies that otherwise do not form spontaneously. We were focused on the hydrothermal transformations of two-dimensional (2D) Aurivillius $Bi_4Ti_3O_{12}$ phase platelets into 2D $ATiO_3$ (A= Sr, Ba, Ca) perovskites. In guiding the transformation to preserve the 2D morphology, we studied the role of the $Bi_4Ti_3O_{12}$ template quality and lattice mismatches between all $Bi_4Ti_3O_{12}/ATiO_3$ pairs. We found that single crystalline (00l) oriented $Bi_4Ti_3O_{12}$ platelets with a low concentration of defects enabled transformation to the (100) oriented $SrTiO_3$ and (00l) oriented $CaTiO_3$ platelets that preserved the 2D morphology of the template. This was also possible due to a low lattice mismatch (1–2 %) in all relevant orientation relationships between the $Bi_4Ti_3O_{12}$ template and both perovskites. In this case, transformation proceeded through the dissolution of the $Bi_4Ti_3O_{12}$ platelets and epitaxial growth of the perovskite ($CaTiO_3$ or $SrTiO_3$) over both basal surface planes

2D morphology of Bi4Ti3O12 platelets is successfully preserved while transforming them into various ATiO3-type perovskites using low-temperature hydrothermal transformation.

of the template. Through this process, 2D/2D epitaxial $CaTiO_3/Bi_4Ti_3O_{12}$ ($SrTiO_3/Bi_4Ti_3O_{12}$) heterostructural and 2D $CaTiO_3$ ($SrTiO_3$) platelets were formed at the intermediate and final transformation stages, respectively. A higher structural mismatch between $BaTiO_3$ and $Bi_4Ti_3O_{12}$ (~4%) hindered the initial $BaTiO_3$ overgrowth on the $Bi_4Ti_3O_{12}$ basal surfaces and, consequently, the formed $BaTiO_3$ particles (cubes, octahedrons, nanorods) did not resemble the 2D template shape. However, the transformation of $Bi_4Ti_3O_{12}$ into 2D $BaTiO_3$ platelets was possible under similar alkaline hydrothermal conditions with the aid of the surfactant that presumably changed the relative dissolution rates of $[Bi_2Ti_3O_{10}]^{2-}$ pseudo perovskite and $[Bi_2O_2]^{2+}$ layers, fastening the dissolution of the latter and allowing Ba^{2+} ions to enter the structure and replace Bi^{3+} ions in the $[Bi_2Ti_3O_{10}]^{2-}$ structural units. Through this mechanism, $Bi_4Ti_3O_{12}$ gradually transformed into $BaTiO_3$ platelets with the (100) orientation, which was also in this case dictated by the (00l) orientation of the template. We proved that with this surfactant-assisted method, $Bi_4Ti_3O_{12}$ platelets could be transformed into all $ATiO_3$-type perovskites, including $Ba_{1-x}Sr_xTiO_3$ ($0 \le x \le 1$) solid solutions, whereby in all cases the 2D shape of the template was well preserved.

We explored a variety of possibilities for steering the transformation into $ATiO_3$ and heterostructural nanoplatelets with tailored functional properties. Even the simplest method, without surfactants, allowed for proper variation in the synthesis conditions, enabling the preparation of platelets with different functionalities. For example, we prepared $SrTiO_3$ and $SrTiO_3/Bi_4Ti_3O_{12}$ platelets with rough surfaces that showed more than 100 times higher photocatalytic H_2-evolution (from water/methanol solutions) compared to the platelets with the same composition, but smooth surfaces. The improvement in the photocatalytic performance could be attributed to the captured nanosized $Bi°$, acting as a co-catalyst. Trapped and *in-situ* formed $Bi°$ nanostructured non-noble metal co-catalysts are an additional advantage of the 2D perovskite nanostructures prepared with the hydrothermal transformation of Aurivillius $Bi_4Ti_3O_{12}$ platelets.

We developed low-cost cobalt boride nanoparticles integrated on the surface of gC3N4 nanosheets instead of expensive platinum, which promote hydrogen evolution reaction.

We were also active in the development of other photocatalysts based on 2D nanostructures. To achieve higher solar-to-hydrogen conversion efficiencies through photocatalytic water splitting, our group developed 2D graphitic carbon nitride (g-C3N4) nanosheets. Being a narrow bandgap semiconductor (2.7 eV), g-C3N4 is one of the most promising low-cost photocatalysts discovered in the last decade. However, the redox capability of gC3N4 is very poor and it shows meaningful hydrogen evolution rates only when decorated with expensive platinum nanoparticles. To overcome the reliance on platinum, we developed low-cost cobalt boride
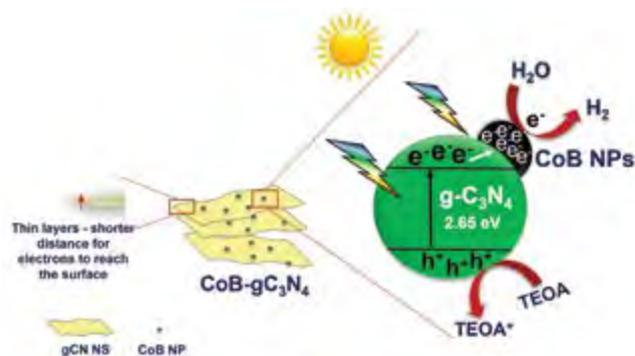
Figure 1: Schematic illustration of the photocatalytic hydrogen-generation mechanism in CoB-gC3N4 composites

Sm-doping greatly enhances the energy storage, piezoelectric, electrocaloric and pyroelectric properties of PMN–PT thin films.

Figure 2: Phases and nanodomain structures of PMN–30PT and Sm-PMN–30PT thin films: B-site atom displacements from the center of four neighboring A-site atoms of a perovskite unit cell (see schematics on the top-left side) for (A) PMN–30PT and (B) Sm-PMN–30PT films, respectively. The length of arrows indicates the magnitude of the relative displacement of B-site atoms from the ideal position. B-site atom displacement magnitude maps (with contour lines) for (C) PMN–30PT and (D) Sm-PMN–30PT thin films, respectively. Phase-field modeling of the nanodomain structures of (E) PMN–30PT and (F) Sm-PMN–30PT films, respectively

Depositing a reduced graphene oxide interlayer retained epitaxial growth of Si on STO and increased the stability against corrosion.

nanoparticles (size < 5 nm) that were directly integrated onto the surface of gC3N4 nanosheets. A CoB-gC3N4 composite could absorb a wide portion of the solar spectrum (~450–700 nm), producing a large number of electron-hole pairs. The nanosheet morphology of the exfoliated gC_3N_4 provided a shorter distance for the photo-generated charges to reach the surface, where electrons are instantly trapped by CoB nanoparticles to prevent their recombination. The electron-enriched CoB nanoparticles provide active redox centres in the form of surface boron and cobalt sites with favourable H-adsorption energy to promote a hydrogen evolution reaction (HER) (Fig. 1). This was manifested by an over 60-time higher hydrogen generation rate in the CoB-gC_3N_4 composite compared to bare g-C_3N_4 nanosheets.

The growing demand for miniaturized and nanoscale electrical devices requires multifunctional materials capable of storing energy, rapidly releasing the stored energy, and harvesting the heat generated during energy production. Recently, Sm-doped $Pb(Mg_{1/3}Nb_{2/3})O_3–PbTiO_3$ (Sm-PMN–PT) bulk materials have revealed outstanding ferroelectric and piezoelectric properties due to enhanced local structural heterogeneity. By employing epitaxial thin films using pulsed laser deposition (PLD), we demonstrated that the Sm-doping enhances the energy storage, piezoelectric, electrocaloric and pyroelectric properties of PMN–PT thin films. Fatigue-free and thermally-stable energy storage properties, a colossal electrocaloric effect (59.4K) and pyroelectric energy density (40 J/cm³), along with a remarkable pyroelectric energy efficiency of 85.5% relative to Carnot, were obtained. By using scanning transmission electron microscopy and phase-field modeling, we found that these giant properties arise from the increased local structural heterogeneity and strong local electric fields along spontaneous polarization directions facilitating nucleation of slush-like polar structure with extremely small domain sizes (2–5 nm). Our findings suggest that Sm-PMN–PT films have significant potential for capacitive energy storage and electrothermal energy conversion, allowing a strategy applicable to other relaxor ferroelectrics for developing robust, multifunctional materials.

Development of a robust photocathode using low-cost and high-performing materials, e.g., p-Si, to produce clean fuel hydrogen has remained challenging as a semiconductor substrate is easily susceptible to (photo)corrosion under photoelectrochemical (PEC) operational conditions. A protective layer over the substrate, simultaneously providing corrosion resistance and maintaining an efficient charge transfer across the device is therefore needed. We utilized pulsed laser deposition (PLD) to prepare a high-quality $SrTiO_3$ (STO) layer to passivate the p-Si substrate using a buffer layer of reduced graphene oxide (rGO). Specifically, a very thin (3.9 nm ~10 unit cells) STO layer epitaxially overgrown on rGO-buffered Si showed the highest onset potential (0.326 V vs RHE) in comparison to the counterparts with thicker and/or nonepitaxial STO. The photovoltage, flat-band potential, and electrochemical impedance spectroscopy measurements revealed that an epitaxial photocathode was more beneficial for charge separation, charge transfer, and targeted redox reaction than a nonepitaxial one. **STO/rGO/Si with a smooth and highly epitaxial STO layer outperforming the directly contacted STO/Si** with a textured and polycrystalline STO layer showed the importance of having a well-defined passivation layer. In addition, the numerous pinholes formed in the directly contacted STO/Si led to a rapid degradation of the photocathode during the PEC measurements. Stability tests demonstrated the soundness of the epitaxial STO layer in passivating Si against corrosion. Additionally, similar experiments were performed on germanium, a possible replacement for Si, where we showed that the epitaxial growth of STO with PLD is more straightforward on germanium than on Si.

Pulsed laser deposition was also used to grow HfO_2 thin films on graphene/SiO_2/Si. As graphene is easily damaged under standard oxide-film deposition conditions, the process needs to be adjusted to minimize the oxidation and the collision-induced damage. A systematic study was conducted in order to identify the crucial deposition parameters for diminishing the defect concentration in a graphene interlayer. In our case, defects were mainly a consequence of the high kinetic energy of the plasma-plume particles. Using a relatively high Ar process pressure, a sufficiently low defect concentration was ensured, without compromising the quality of the HfO_2 thin film. This enabled us to successfully prepare memristive devices with the filamentary type of switching, utilizing the graphene layer as the bottom electrode. The findings of this study can be easily transferred to other systems for the development of oxide electronic devices. The results are published as a scientific article in the Advanced Functional Materials (https://doi.org/10.1002/adfm.202309558).

Our reaserch also extended to the field of solid-state batteries. Using the PLD tehnology, $LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$ (NMC) thin films (cathodes) were prepared on $SrRuO_3$/0.5 wt.% Nb-doped $SrTiO_3$ (Nb:STO) substrates with (001), (110) and (111) out-of-plane orientations. Twinned domains were observed at the microstructural level, related to different orientations of lithium slabs in NMC thin films (Fig. 3). We observed the influence of the crystal orientation on NMC electrochemical properties by charging and discharging a battery at different rates.

Due to the frequent occurrence of secondary phases in the preparation of epitaxial thin layers of $Li_4Ti_5O_{12}$ (LTO) anode material on Nb:STO substrates, LTO samples were also prepared on Nb:STO substrates, covered with a thin epitaxially deposited $La_{0.05}Ba_{0.97}SnO_3$ (LBSO) interlayer. The purpose of the interlayer was to create more favorable conditions for the growth of single-phase LTO since LBSO matches the LTO lattice parameter better than Nb:STO. A comparison of the structural and electrochemical properties of the LTO samples with and without an LBSO interlayer was made, with the formation of secondary phases being most significantly reduced for the LTO samples with an LBSO interlayer and (110) out-of-plane orientation, while the LTO samples grown on deposited interlayers retained their specific capacities during galvanostatic charging and discharging.

We continued with a detailed study of Ruddlesden-Popper (RP)-type planar defects inside $Li_{3x}La_{2/3-x}\square_{1/3-2x}TiO_3$ (LLTO) grains, a ceramic material with promising applications as a solid electrolyte. In LLTO with a starting La:Ti ratio of 0.6 and excess of Li, microstructure development starts with the formation of a layered RP-type $Li_2La_2Ti_3O_{10}$ phase and continues with the crystallization of LLTO perovskite. The preferential formation of the $Li_2La_2Ti_3O_{10}$ phase at lower temperatures, in comparison to LLTO perovskite, was confirmed with DFT calculations. LLTO grains with RP-type defects exhibit exaggerated growth (Fig. 4). At around 1250°C, the RP-type sequences become thermally unstable and they gradually recrystallize to LLTO perovskite via ion exchange as determined with the quantitative HAADF-STEM analysis. At higher sintering temperatures, the microstructure development is controlled with Ostwald ripening. The self-seeded microstructure development is an innovative approach for the preparation of a coarse-grained LLTO solid electrolyte with a low fraction of resistive grain boundaries.

Epitaxial thin-film microbatteries were prepared by depositing LTO | LLTO | NMC thin film stacks on Nb:STO substrates with the (001), (110) and (111) out-of-plane orientations. X-ray diffraction confirmed the presence of individual phases and their epitaxial growth. Preliminary measurements of electrochemical properties of the prepared microbatteries were performed in custom-made battery cell set-ups.

In the scope of the basic research project "Nanoscale investigations of diffusion controlled topotaxial phase transformations in rutile-corundum host systems" funded by ARIS (J1-9177) we investigated the possibility of preparing pseudobrookite-based ceramics (Fe_2TiO_5-$FeTi_2O_5$) using natural

Using a relatively high Ar process pressure during PLD, a sufficiently low defect concentration was ensured on the graphene interlayer.
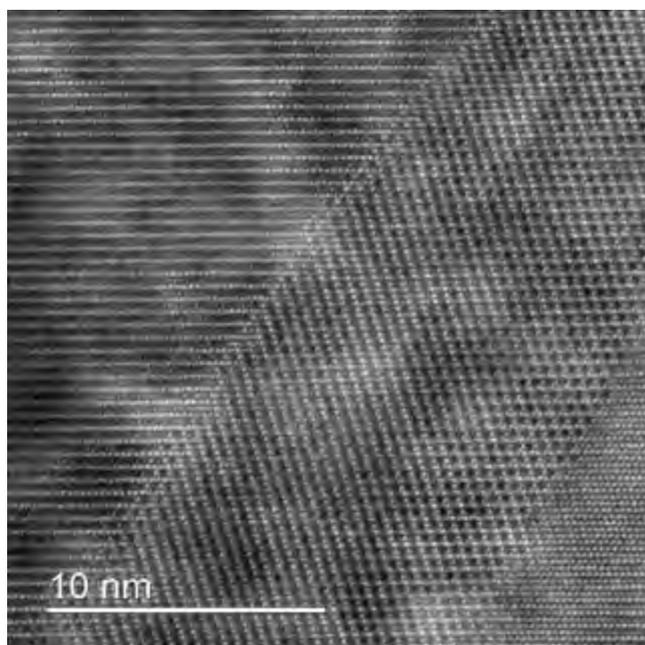
Figure 3: Twin boundary in an NMC thin film

We managed to prepare fully epitaxially grown thin-film microbatteries prepared with PLD, depositing LTO|LLTO|NMC thin-film stacks on Nb:STO substrates.
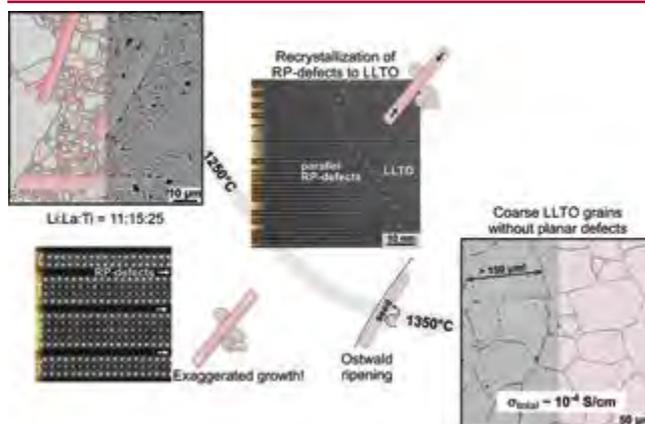

Figure 4: Microstructure development of LLTO ceramics containing Ruddlesden-Popper (RP)-type planar defects at lower sintering temperatures. The final LLTO microstructure consists of large grains without defects and exhibits improved ionic conductivity.

Fe-Ti–rich heavy mineral sands (HMSs) for thermoelectric applications. Fe-Ti-rich HMSs are abundant, low-cost, and environmentally friendly raw materials, mainly used for the extraction of TiO_2. Starting powders composed of ilmenite ($FeTiO_3$) and pseudorutile ($Fe_2Ti_3O_9$) were pre-oxidized for the modification of the $Fe^{2+}:Fe^{3+}$ ratio and exsolution of rutile, and densified with conventional sintering and spark plasma sintering in an argon atmosphere. While high-purity starting chemicals are typically used in the conventional synthesis of advanced ceramics to avoid the effect of impurities, our findings reveal that the prepared samples exhibit comparable properties as high-purity chemicals. We show that the thermoelectric properties of sintered compacts depend on the Fe:Ti ratio, the consequent fraction and distribution of rutile in the microstructures and, most importantly, on the $Fe^{2+}:Fe^{3+}$ ratio. The results confirm that natural Fe-Ti-rich heavy sands with a ~95% purity are promising raw materials for the preparation of thermoelectric ceramics. The results were published as a scientific article in the Journal of the European Ceramic Society (doi: https://doi.org/10.1016/j.jeurceramsoc.2023.07.071).

By using natural, low-cost Fe-Ti rich heavy mineral sand, we achieved thermoelectric properties comparable to those obtained with high-purity starting chemicals.

Our research also involved exploring the room temperature fabrication (RTF) method, which uses a partially water-soluble inorganic compound that can be cured at room temperature under pressure (Fig. 5). This method presents an alternative to the high-temperature sintering of ceramics, which can be time- and energy-consuming. We studied the upside-down composite systems using different binders, such as Li_2MoO_4, Na_2SiO_3, Na_2MoO_4, Na_2WO_4, and $MgSO_4$. For the first time, we conducted mechanical testing of such binder-ST composites using the ball-on-three-ball biaxial bending method. We compared the mechanical strength of the composites with that of binder monoliths and ST ceramics. The choice of binder was found to be crucial, as it significantly affects the dielectric and mechanical properties. We discovered that the mechanical strength of Na_2SiO_3-$SrTiO_3$ composites is seven times higher than that of Li_2MoO_4/$SrTiO_3$ composites. In addition, OOF2 simulations were performed to study the effects of cracks and a coating of $SrTiO_3$ ceramic filler particles on the polarization of the electric field and relative permittivity. Experimental results of the composites show a relative permittivity between 67 and 129 and dielectric losses between 0.0029 and 0.0142 in the radio and microwave frequency range. Using the RTF method, we prepared composites exhibiting relative permittivity between 20 and 50% of conventionally sintered $SrTiO_3$ ceramics. Such materials are promising for the fabrication of passive electronic components.

The choice of the binder for composite preparation, using room temperature fabrication, was found to be crucial as it significantly affects the dielectric and mechanical properties.

Figure 5: Schematics of the RTF process for ceramic binder-SrTiO₃ composites

In the investigation of phase relations in ternary oxide systems, where new compounds and solid solutions form and exhibit interesting electric properties, we determined the synthesis conditions for the preparation of a single-phase ceramic based on $La_{4.5}Ta_{22}O_{62}$ in the La_2O_3-TiO_2-Ta_2O_5 system. This compound is mentioned in the scientific literature, having molar ratios of La_2O_3:Ta_2O_5 as 1:5, 1:6 and even 1:7.

In the study of cold sintering (CSP) of selected clay minerals such as kaolinite, illite, and sepiolite at temperatures below 300°C, we successfully prepared monolithic specimens without any cracks or delamination, which was proved with X-ray micro-tomography. The samples exhibited a much larger bending strength in comparison to the samples sintered at 1300°C.

Antibacterial and piezoelectric biocompatible materials

In the area of biomaterials our work is focused on designing new approaches in healing and tissue regeneration by developing organic piezoelectric biomaterials and novel antimicrobial technologies. Within the project that ended last year, "Mechano-chromic, voltage-sensitive electrostimulators: innovative piezoelectric biomaterials for electro-stimulated cellular growth", which is a bilateral collaboration with a Swiss partner from the Institute of Robotics and Intelligent Systems (ETH), we designed new piezoelectric biomaterials based on poly(l-lactide) (PLLA) with a small amount (1 wt.%) of crystalline filler particles. This increased their piezoelectricity and the filler-modified PLLA films provided a 20-fold larger voltage output than the non-modified PLLA during ultrasound-assisted activation (Fig. 6a). On a bare piezoelectric PLLA sample, both in stretched film and nanotextured form, we observed the anticipated immune response (Fig. 6b); we also observed around 20% differentiation of blood monocytes into macrophage, which act as the first line of defence against bacteria, viruses or other foreign materials.

The development of PLLA-based piezoelectric biomaterials mixed with functional nano/micro particles enhanced voltage output and has shown promising avenues for infection control and tissue engineering applications.

We continued the research on gallium-based antibacterial materials. Using FTIR and DSC analyses, we observed the interactions within the composite of gallium nanoparticles with polylactide and checked their cytocompatibility with keratinocyte cells. They grew normally in the presence of composite films and successfully attached to them.

We also checked the stability of a colloidal solution of gallium nanoparticles and their dissolution in various aqueous media, and began to study, in more detail, their mechanism of acting against bacterium *P. aeruginosa*.

We also started research on developing biocompatible electrospun fibers for tissue engineering (Fig. 6c). Together with colleagues from the Department of Surface Engineering (F4), we studied the influence of surface changes caused by plasma on the characteristics of these materials. Within the project "On-demand contact-based antimicrobial surfaces: human and environmentally safe infection control strategy", we are developing highly antimicrobial materials based on piezoelectric composite films and antimicrobial nanoparticles. We are combining the piezoelectricity of PLLA composite films and the contact-based antimicrobial mechanism of functionalized gold nanoparticles in order to create the synergy of these two effects, and increase the antimicrobial properties of these materials.

Figure 6: (A) Ultrasound-mediated mechanical stimulation of a PLLA piezoelectric film activates the generation of charges on the surface, affecting the polarization of human keratinocyte cells, imitating the naturally formed endogenous-like potential; (B) monocyte-derived macrophage attached onto a PLLA nanotextured or stretched surface; (C) good biocompatibilty was observed between keratinocyte cells and electrospun PLLA fibers.

Materials for heat-insulation applications and superhydrophobic surface coating

Insulation materials play a key role in modern construction practices, especially in the context of energy efficiency and sustainability. These materials are integral components in buildings, serving to regulate indoor temperatures, minimize energy consumption for heating and cooling, and reduce greenhouse gas emissions. Amid global concerns about climate change and the imperative to transition towards more sustainable practices, the significance of construction insulation materials cannot be overstated. The same applies to research in the field in question, where in the light of changes in connection with critical raw materials, alternative and recycled materials will play an increasingly important role.

The use of hydrated waste glass has a favorable effect on the thermal conductivity properties of the final material.

Following the aforementioned guidelines, we continued our research of foamed glass, where we focused on the sustainable aspect of the synthesis of this product with a high added value. The direct use of waste glass in the synthesis process, which minimizes the impact on the environment, can affect the quality of the product mainly due to unwanted crystallization. We showed that the use of water glass can reduce the proportion of crystallization in the foaming of glass from waste bottles, which has a favorable effect on the final properties of the material. In the continuation of the research, we showed that the properties of waste glass can be adjusted with the hydration process to such an extent that it replaces the role of water glass. By using water glass or hydrated waste glass, the foaming process can be carried out in an air atmosphere, further contributing to the sustainability of the research process.

As part of the ReMaBrick project, we are investigating the potential reuse of waste glass-containing products in the preparation of fired bricks. Fiber-reinforced polymers are important materials used in the rapidly growing wind energy industry. With the ever-increasing amount of wind power plants, we can also expect the need to recycle the materials they contain in the future. The inclusion of waste glass and fiber-reinforced composites has a beneficial effect on the carbon footprint of the final product as it replaces part of the raw material, and due to the glassy phase in the composite, the optimal temperature of brick firing also decreases. We tested various combinations of waste materials and two types of clay, with samples containing high proportions of wastes (up to 30 wt.%) showing promising properties.

Figure 7: Structure of the foamed glass depending on the furnace atmosphere (above Ar, below air) and the amount of added water glass (left: 12 wt.%, right: 24 wt.%)

The primary goal of the AMULET project is to create new value chains by supporting the widespread adoption of advanced lightweight materials. Focused on the inter-regional and cross-sectoral knowledge exchange, we are engaged in four key sectors: automotive industry, aerospace & aeronautics, energy, and building. Together, we are getting closer to achieving our goal of fostering innovation and advancing technologies in these vital industries. In the AMULET project, our department plays a pivotal role in providing support towards discovering and delivering technological solutions that empower small and medium enterprises (SMEs). Our focus has been on leveraging our expertise in diverse characterization and testing techniques, contributing to the development and market introduction of innovative products.

A combination of hydrophobic SiO_2 nanopowders in a polymer binder system results in a superhydrophobic coating with a contact angle of >160° and only a 4% loss in transmittance.

Figure 8: Superhydrophobic coating: (A) Transmittance of plain glass vs. superhydrophobic coating; (B) SEM image of superhydrophobic-coating micro and (C) nanostructure; and (D) contact angle of a water drop

Solar cells are often installed outdoors, but over time, dirt accumulates on their surfaces, which reduces their ability to absorb sunlight and lowers their efficiency in power generation. Currently, expensive manual or machine cleaning is used to clean them. Using spray deposition, we are developing superhydrophobic (SHP) coatings with micro/nano dual structures. These coatings are more economical and promising because of their self-cleaning ability. We have fabricated a superhydrophobic coating with a high contact angle of 166° and only a 4% loss in transmittance using a combination of hydrophobic SiO_2 nano-powders and a polymer binder system.

Some outstanding publications in the past year

1. Jovanović, Zoran M., Trstenjak, Urška, Ho, Hsin-Chia, Butsyk, Oleana, Chen, Binbin, Tchernychova, Elena, Borodavka, Fedir, Koster, Gertjan, Hlinka, Jiři, Spreitzer, Matjaž. Tiling the silicon for added functionality: PLD growth of highly-crystalline STO and PZT on graphene oxide-buffered silicon surface. *ACS Applied Materials & Interfaces*. 2023, vol. 15, issue 4, pp. 6058–6068. ISSN 1944-8244. DOI: 10.1021/acsami.2c17351.

2. Ho, Hsin-Chia, Smiljanić, Milutin, Jovanović, Zoran M., Čekada, Miha, Kovač, Janez, Koster, Gertjan, Hlinka, Jiři, Hodnik, Nejc, Spreitzer, Matjaž. Robust SrTiO3 passivation of silicon photocathode by reduced graphene oxide for solar water splitting. *ACS Applied Materials & Interfaces*. [Online ed.]. 2023, vol. 15, iss. 37, pp. 44482–44492, illustr. ISSN 19448252. DOI: 10.1021/acsami.3c07747.

3. Trstenjak, Urška, Daneu, Nina, Belhadi, Jamal, Samardžija, Zoran, Matavž, Aleksander, Bobnar, Vid, Koster, Gertjan, Spreitzer, Matjaž. Non-stoichiometry and its implications for the properties of PMN–PT thin films. *Journal of Materials Chemistry. C, Materials for Optical and Electronic Devices*. [Print ed.]. 2023, vol. 11, iss. 3, pp. 1144–1154. DOI: 10.1039/D2TC04070K.

4. Vukomanović, Marija, Gazvoda, Lea, Kurtjak, Mario, Maček, Marjeta, Spreitzer, Matjaž, Pané, Salvador, et al. Filler-enhanced piezoelectricity of poly-L-lactide and its use as a functional ultrasound-activated biomaterial. *Small*. 2023, vol. 19, iss. 35, [article no.] 2301981, pp. 1–16, illustr. ISSN 1613-6829. DOI: 10.1002/smll.202301981.

5. Daneu, Nina, Radošević, Tina, Bernik, Slavko, Hanžel, Darko, Mazaj, Matjaž, Maček, Marjeta, Verhovšek, Dejan, Kocjan, Andraž, Vrabec, Mirijam, Spreitzer, Matjaž, Guilmeau, Emmanuel. Thermoelectric properties of pseudobrookite-based ceramics prepared from natural Fe-Ti-rich heavy mineral sand concentrate. *Journal of the European Ceramic Society*. [Print ed.]. 2023, 29 pp. ISSN 0955-2219. DOI: 10.1016/j.jeurceramsoc.2023.07.071.

6. Borštnar, Petruša, Žuntar, Jan, Spreitzer, Matjaž, Dražić, Goran, Daneu, Nina. Exaggerated grain growth and the development of coarse-grained microstructures in lithium lanthanum titanate perovskite ceramics. *Journal of the European Ceramic Society*. [Print ed.]. 2023, vol. 43, iss. 3, pp. 1017–1027, illustr. ISSN 0955-2219. DOI: 10.1016/j.jeurceramsoc.2022.11.004.

Awards and Appointments

1. Dr Suraj Gupta: Best Poster Award, Singapore, Singapore, granted by Elsevier at the Materials Today Conference 2023, for a poster entitled SrTiO3-based two-dimensional nanoplatelets for low-cost solar-hydrogen generation

2. Blaž Jaklič: Best student-poster presentation, Paris, France, granted by Organizing committee of the International Workshop on the Characterization & Quantification of Lithium

Organization of conferences, congresses and meetings

1. Electronic Materials & Applications Meeting 2023 (EMA 2023), American Ceramic Society, Orlando, USA, 17 - 20 January 2023; conference chair and organization of a symposium

2. 15th International Postgraduate School Students' Conference (IPSSC23), Kamnik, 31 May - 2 June 2023; co-organization

3. Materials Science & Technology Conference 2023, American Ceramic Society, Columbus, USA, 1- 4 October 2023; organization of a symposium

INTERNATIONAL PROJECTS

1. Noveon - JSI; Investigation of NdDyCoCuFe Rare Earth Alloys and Related Compounds
   Prof. Matjaž Spreitzer
   Noveon Magnetics Inc.
2. Development and Characterisation of Mineral Wool Fibres and Binder Systems
   Prof. Matjaž Spreitzer
   Knauf Insulation S.p.r.l.
3. COST CA20116; OPERA - European Network for Innovative and Advanced Epitaxy
   Prof. Matjaž Spreitzer
   COST Association Aisbl
4. H2020 - AMULET; Advanced Materials and Manufacturing Technologies united for LightwEight
   Dr. Jakob König
   European Commission
5. EDF; AMALIA - Additive Manufacturing of Metallic Auxetic Structures and Materials for Lightweight Armour
   Prof. Matjaž Spreitzer
   European Defence Agency (EDA)
6. HE - ANEMEL; ANion Exchange Membrane Electrolysis from Low-grade water sources
   Suraj Gupta
   European Commission
7. HE - INDUSAC; Quick Challenge-driven, Human-centered Co-Creation mechanism for INDUStry-Academia Collaborations
   Prof. Matjaž Spreitzer
   European Commission
8. ReMaBrick – Recycled Materials Integrated in Bricks, Supporting the Circular Economy in the Construction Industry
   Dr. Jakob König
   Innovation Fund Denmark
9. NATO - FRAPCOM; Flexible Nano-Ferroelectrics for Rapid Cooling of Combat Electronic
   Prof. Matjaž Spreitzer
   NATO - North Atlantic Treaty Organisation
10. COST CA22123; EU-MACE - European Materials Acceleration Center for Energy
    Suraj Gupta
    COST Association Aisbl
11. Multilayer hybrid scaffolds with antimicrobial, anti-inflammatory, proangiogenic and piezoelectric properties as personalized wound dressings
    Asst. Prof. Marija Vukomanović
    Slovenian Research Agency

RESEARCH PROGRAMMES

1. Contemporary Inorganic Materials and Nanotechnologies
   Prof. Matjaž Spreitzer

R & D GRANTS AND CONTRACTS

1. Model system based interface design for enhancement of the electrochemical performance of Ni-rich NMC for Li-ion batteries
   Prof. Matjaž Spreitzer
2. Subglacial carbonate deposits - a new source for studying the presence of glaciers in a glaciokarstic environment
   Prof. Srečo Davor Škapin
3. Strain and domain structure engineering in epitaxial relaxor ferroelectric thin films
   Prof. Matjaž Spreitzer
4. Mechano-chromic, voltage-sensitive electrostimulators: innovative piezoelectric biomaterials for electro-stimulated cellular growth
   Asst. Prof. Marija Vukomanović
5. Engineering of relaxor ferroelectric thin films for piezoelectric and energy storage applications
   Prof. Matjaž Spreitzer
6. Photoelektrochemical Hydrogen Evolution from Graphene Oxide Enabled Epitaxial Silicon-Oxide Heterostructures
   Prof. Matjaž Spreitzer
7. Semiconductor - dielectric heterostructures for photoelectrochemical hydrogen evolution, SeDiHe
   Prof. Matjaž Spreitzer
8. Extended defects in natural and synthesized perovskite oxides: nanogeochemcial indicators and functional interfaces
   Prof. Nina Daneu
9. Applicability of the cold sintering process to clay minerals
   Prof. Srečo Davor Škapin
10. Multiscale modeling of photocatalytic CO2 reduction with computer intensive simulations
    Dr. Marjeta Maček Kržmanc
11. Innovative procedures for advanced surface properties of medical stainless steel
    Asst. Prof. Marija Vukomanović
12. Novel Surface Modification of Dental Prosthetic Replacements by Gaseous Plasma
    Asst. Prof. Marija Vukomanović
13. On-demand Contact Based Antimicrobial Surfaces: Human and Environmental Safe Infection Control Strategy
    Asst. Prof. Marija Vukomanović
14. Experimental realization of 2D boridene electrocatalysts for anion-exchange membrane water electrolyzers
    Suraj Gupta
15. Remote epitaxy of Ag(Nb,Ta)O3 thin films through graphene - A synergistic approach for improving energy storage performance
    Dr. Urška Trstenjak
16. ANTISOLVO - Antisolvent precipitation to extract the value from end-of-life Nd-Fe-B magnets
    Prof. Srečo Davor Škapin
    Ministry of Education, Science and Sport
17. XRD Analysis
    Prof. Matjaž Spreitzer

VISITORS FROM ABROAD

1. Darija Petković, Vinča Nuclear Research Institute, Belgrade, Serbia, 12 February – 8 April 2023
2. Dr Thomas Lippert, Dr Daniele Pergolesi and Dr Nikita Shepelin, Paul Scherrer Institut, Villigen, Switzerland, 22 – 24 February 2023
3. Dr Jiří Hlinka, Dr Olena Butsyk, Dr Fedir Borodavka, Dr Alexis Theodorou, Dr Eva Sediva and Nastja Pylypets, Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic, 9 – 10 May 2023
4. Dr Federico Baiutti, Catalonia Institute for Energy Research, Barcelona, Spain, 7 – 11 August 2023
5. Dr Jamal Belhadi, Laboratoire de Physique de la Matière Condensée, Université de Picardie Jules Verne, France, 4 – 16 October 2023
6. Dr Matija Čulo, Dr Marko Kuveždić and Dr Damir Dominko, Institute of Physics, Zagreb, Croatia, 30 November 2023
7. Dr Zoran Jovanović, Dr Sonja Jovanović, Dr Željko Mravik, Marko Jelić and Darija Petković, Vinča Institute of Nuclear Science, Belgrade, Serbia, 3 – 6 December 2023

STAFF

Researchers
1. Prof. Nina Daneu
2. Dr. Suraj Gupta
3. Dr. Heli Maarit Jantunen
4. Dr. Jakob König
5. Dr. Gertjan Koster
6. Dr. Špela Kunej
7. Dr. Marjeta Maček Kržmanc
8. **Prof. Matjaž Spreitzer**, Head
9. Prof. Srečo Davor Škapin
10. Dr. Marija Vukomanović

Postdoctoral associates
11. Dr. Zouhair Hanani
12. *Dr. Hsin-Chia Ho, left 16.11.23*

13. Dr. Uroš Hribar
14. Dr. Mario Kurtjak*
15. *Dr. Sonja Smiljanić, left 01.07.23*
16. Dr. Urška Trstenjak

Postgraduates
17. Petruša Borštnar, B. Sc.
18. Lucija Bučar, B. Sc.
19. *Alja Čontala, B. Sc., left 09.01.23*
20. Lea Gazvoda, B. Sc.
21. Blaž Jaklič, B. Sc.
22. Nina Kuzmić, B. Sc.
23. Jošt Oblak, B. Sc.
24. Martina Žabčić, M. Sc.
25. Jan Žuntar, B. Sc.

Technical officers
26. Vesna Butinar, B. Sc.
27. David Fabijan, B. Sc.
28. Daška Mohar, B. Sc.
29. Damjan Vengust, B. Sc.
Technical and administrative staff

30. Tina Radošević, B. Sc.
31. Silvo Zupančič

Note:
* part-time JSI member

DEPARTMENT OF BIOCHEMISTRY, MOLECULAR AND STRUCTURAL BIOLOGY

B-1

The research efforts of the Department of Biochemistry, Molecular and Structural Biology (B1) primarily concentrate on investigating the physiological functions of proteases and their native protein inhibitors during both normal and disease states. These studies encompass the action mechanisms of proteases, and the structural and functional attributes of proteases, their inhibitors, and other enzymes. The molecular mechanisms governing protease action and regulation are not fully understood, indicating much ongoing work is necessary, particularly in identifying additional physiological substrates and the signalling pathways they influence.

Head:
Prof. Boris Turk

Research on proteases has expanded over the last decade, primarily because of rapid advances in technologies like quantitative proteomics, in-vivo imaging, and the extensive application of in-vivo models. These developments have facilitated the discovery of physiological substrates and catalysed a shift in understanding proteases from merely protein-degrading enzymes to critical signalling molecules. Their enzymatic activities are meticulously controlled, mainly through zymogen activation and regulation by endogenous protein inhibitors. Any disruption in these regulatory mechanisms can lead to various pathologies, including infectious, autoimmune, cardiovascular, neurological, and neurodegenerative diseases, as well as cancer. Consequently, proteases are now recognized as crucial targets for therapeutic interventions.

The researchers in our department investigated the specificity of cysteine cathepsins, which lack strict P1 pocket-like caspases and trypsin-like proteases. Using proteomic analysis, they identified 30,000 cleavage sites for human cathepsins K, V, B, L, S, and F, analysed through the SAPS-ESI platform, which clusters data and trains machine-learning models. They experimentally confirmed cleavage-site predictions on the SARS-CoV-2 S protein, suggesting cathepsins behave similarly to furin. Crystal structure analysis of cathepsin V with peptides revealed rigid and flexible regions aligning with SAPS-ESI data. These findings support the design of selective drug conjugates and drug-discovery efforts (Tušar et al., 2023).

In a major international collaboration, researchers in our department confirmed that Calpeptin is a highly effective inhibitor of cysteine cathepsins, supported by X-ray crystallography results. Cell infection assays have demonstrated its effectiveness against SARS-CoV-2, and treatment using Calpeptin in infected Golden Syrian hamsters greatly reduced viral loads in the trachea. Although there are risks of side effects, targeting host proteins like cathepsins offers an advantage due to their genetic stability compared to the rapidly mutating viral proteins. This suggests that inhibiting cathepsins with Calpeptin could be a viable strategy for treating SARS-CoV-2 and possibly other viral infections (Reinke et al., 2023).

In another collaboration, we participated in research focusing on the enzyme photolyase, which uses light to catalyse DNA repair, through a time-resolved crystallography experiment. The findings revealed that photolyase captures the active cofactor, flavin adenine dinucleotide (FAD), in an excited state with a notably bent geometry. This state facilitates electron transfer to the damaged DNA, initiating a repair. It was discovered that the repair process, breaking two covalent bonds, proceeds via a single-bond intermediate. As the substrate converts into the product, it crowds the active site and disrupts hydrogen bonds within the enzyme. This leads to a sequential release of the repair product, starting with the 3′ thymine, followed by the 5′ base (Christou et al., 2023).

Continuing the research on the role of stefin B, an inhibitor of cysteine proteases, in diseases, Kopitar et al. discovered that mice with an extra copy of the stefin B gene showed reduced inflammation and enzyme activity linked to less cellular stress in the macrophages. This additional expression also seemed to enhance cellular cleaning processes and reduce mitochondrial stress. Their findings enhance our understanding of stefin B's role in cell regulation, which could be pivotal in developing new treatments (Trstenjak-Prebanda et al., 2023).

Following our previous work on designing targeting systems, the research in our department focused on aspartic protease cathepsin D. It is notably overexpressed in numerous cancers and plays a critical role in the development, progression, and metastasis of tumours. Although typically an intracellular protein, cathepsin D is secreted into the extracellular matrix under pathological conditions, which highlights its potential as a target for drug delivery systems. In this context, our department developed and evaluated a novel delivery system aimed at tumour targeting, utilizing immunoliposomes functionalized with pepstatin A–a natural peptide inhibitor of cathepsin D. To facilitate integration into the liposomal lipid bilayer, a lipid tail was attached to pepstatin A. The efficacy of this

targeting system was validated using recombinant cathepsin D and tumour cell lines, demonstrating the viability of this approach and its prospective utility for in-vivo theranostic applications (Kozak et al., 2023).

In a different study, Mikhaylov et al. developed a bioluminescent probe called BiNR to non-invasively track Nicotinamide riboside (NR) uptake, a form of vitamin B3 with potential in treating metabolic and age-related disorders. They also refined an assay for NR uptake that does not require gene transfection, making it applicable to human clinical samples, such as T cells. Using this probe in a triple-negative breast-cancer (TNBC) model, they discovered that NR increases cancer prevalence and brain metastases, underscoring the need for cautious use of NR in cancer patients (Maric et al., 2023).

Žerovnik in collaboration with other researchers continued her investigation of protease inhibitor stefin B and its formation of amyloid fibrils. They discovered that these fibrils display birefringence without needing staining—a property typically seen only after applying specific dyes. They also observed that these fibrils naturally arrange in patterns similar to other anisotropic materials, like protein crystals and liquid crystals. Additionally, they detected an unusual fluorescence emission at 425–430 nm in some fibril arrangements, suggesting a potential for the label-free detection of amyloids through optical microscopy. These findings could lead to new, non-invasive methods for identifying amyloid fibrils across different conditions (Novak et al., 2023). In another study, Žerovnik and collaborators used stefin B as a model protein for studying protein folding and analysed it using infrared spectroscopy to monitor its aggregation and amyloid formation. The study focused on the Amide I band's low frequency part, showing that structural changes in stefin B are influenced by temperature rather than pH. The results indicated that stefin B is less stable in acidic environments and more stable in neutral or basic ones. The analysis, which included multivariate curve resolution (MCR), highlighted early structural changes and different protein conformation states. This led to the proposal of a new model for stefin B aggregation based on these findings (Zganec et al., 2023).

Some outstanding publications in the past year

1. Patrick Y. A. Reinke, Jure Loboda, Katarina Karničar, Aleksandra Usenik, Nataša Lindič, Andreja Sekirnik, Dušan Turk, et al., „Calpeptin is a potent cathepsin inhibitor and drug candidate for SARS-CoV-2 infections", Communications biology, 2023, vol. 6, str. 1058-1-1058-13, ISSN 2399-3642, DOI: 10.1038/s42003-023-05317-9. [COBISS.SI-ID 169049859]

2. Livija Tušar, Jure Loboda, Robert Vidmar, Matej Vizovišek, Marko Mihelič, Marko Fonović, Jaka Horvat, Gregor Kosec, Boris Turk, Dušan Turk, et al., „Proteomic data and structure analysis combined reveal interplay of structural rigidity and flexibility on selectivity of cysteine cathepsins", Communications biology, 2023, vol. 6, str. 450-1-450-15, ISSN 2399-3642, DOI: 10.1038/s42003-023-04772-8. [COBISS. SI-ID 150294275]

3. Nina-Eleni Christou, Virginia Apostolopoulou, Diogo V. M. Melo, Matthias Ruppert, Alisia Fadini, Alessandra Henkel, Janina Sprenger, Ajda Kunavar, Saša Bajt, Dušan Turk, et al., „Time-resolved crystallography captures light-driven DNA repair", Science, 30 Nov. 2023, vol. 382, iss. 6674, str. 1015-1020, ilustr., ISSN 1095-9203, https:// www.science.org/doi/10.1126/science.adj4270, DOI: 10.1126/science.adj4270. [COBISS.SI-ID 176873475] financer: ARIS, Programska skupina, P2-0162

4. Mojca Trstenjak-Prebanda, Monika Biasizzo, Klemen Dolinar, Sergej Pirkmajer, Boris Turk, Véronique Brault, Yann Hérault, Nataša Kopitar-Jerala, „Stefin B inhibits NLRP3 inflammasome activation via AMPK/mTOR signalling", Cells, 2023, vol. 12, no. 23, str. 2731-1-2731-16, ISSN 2073-4409, DOI: 10.3390/ cells12232731. [COBISS.SI-ID 176921091]

5. Andreja Kozak, Georgy Mikhaylov, Pavlo Khodakivskyi, Elena Goun, Boris Turk, Olga Vasiljeva, „A new cathepsin D targeting drug delivery system based on Immunoliposomes functionalized with lipidated pepstatin A", Pharmaceutics, [Online ed.], 2023, vol. 15, no. 10, str. 2464-1-2464-11, ISSN 1999-4923, DOI: 10.3390/ pharmaceutics15102464. [COBISS.SI-ID 172388099]

Organization of conferences, congresses and meetings

1. 40th Winter School on Proteinases and their Inhibitors, 1-5 March 2023, co-organizer.

INTERNATIONAL PROJECTS

1. COST CA20117; Mye-InfoBank - Converting Molecular Profiles of Myeloid Cells into Biomarkers for Inflammation and Cancer
Prof. Nataša Kopitar – Jerala
Cost Association Aisbl

2. Development of in Vitro Bioassay to assess the Effect of Cathepsin Inhibitors on SARS-CoV-2
Prof. Dušan Turk
Slovenian Research Agency

RESEARCH PROGRAMMES

1. Structural biology
   Prof. Dušan Turk
2. Proteolysis and its regulation in health and disease
   Prof. Boris Turk

R & D GRANTS AND CONTRACTS

1. Cathepsins B and X in breast cancer stem cells – molecular targets and relevance for antitumor therapy
   Prof. Marko Fonović

2. Aptamers and hydrodynamic cavitation, an accessible tool for the analysis of organic residuals in archaeological pottery
   Prof. Marko Fonović
3. Human cathepsin F: An unusual cysteine protease involved in neurodegeneration
   Prof. Veronika Stoka
4. Dissecting cancer activome to develop new generation of antibody-drug conjugates
   Prof. Boris Turk
5. Systemic determination of legumain physiological roles
   Prof. Marko Fonović
6. Erythrocyte membrane-based nanocarriers for gene silencing cancer therapy
   Prof. Boris Turk

STAFF

Researchers
1. Dr. Iztok Dolenc
2. Prof. Marko Fonović
3. Prof. Nataša Kopitar - Jerala
4. Prof. Jure Pražnikar*
5. Prof. Veronika Stoka
6. Dr. Andrej Šali
7. **Prof. Boris Turk, Head**
8. Prof. Dušan Turk
9. Asst. Prof. Livija Tušar
10. Prof. Olga Vasiljeva
11. Prof. Eva Žerovnik

Postdoctoral associates
12. *Dr. Monika Biasizzo, left 12.11.23*
13. Dr. Katarina Karničar
14. Dr. Andreja Kozak
15. Dr. Nataša Lindič
16. *Dr. Jure Loboda, left 01.10.23*
17. Dr. Georgy Mikhaylov
18. Andreja Novak, M. Sc.
19. Dr. Metka Stantič
20. Dr. Aleksandra Usenik
21. Asst. Prof. Robert Vidmar

Postgraduates
22. Bor Bokalj, B. Sc.
23. Klemen Dretnik, B. Sc.
24. Ana Ercegovič Rot, B. Sc.

25. *Marija Grozdanić, B. Sc., left 01.07.23*
26. Matija Hrovatin, B. Sc.
27. Sara Ivanovski, B. Sc.
28. Matej Kolarič, B. Sc.
29. Ana Kump, B. Sc.
30. Ernestina Lavrih, B. Sc.
31. Petra Matjan Štefin, B. Sc.
32. Matej Novak, B. Sc.
33. Tilen Sever, B. Sc.
34. Tea Sinožić, M. Sc.
35. Mojca Trstenjak Prebanda, B. Sc.
36. Eva Vidak, B. Sc.
37. Miki Zarić, B. Sc.

Technical officers
38. Marinka Horvat, B. Sc.
39. Helena Kastelic, B. Sc.
40. Maja Orehek, B. Sc.
41. Andreja Sekirnik, B. Sc.
42. Ivica Štefe, B. Sc.

Technical and administrative staff
43. Dejan Pelko
44. Polonca Pirš
45. Vahida Suljić

Note:
* part-time JSI member

DEPARTMENT OF MOLECULAR AND BIOMEDICAL SCIENCES B-2

The research programme of the Department of Molecular and Biomedical Sciences is focused mainly on basic research in protein biochemistry, molecular and cellular biology, and genetics. The primary goal of our investigations is the acquisition of a new understanding of mammalian pathophysiology, with the aim of improving human and animal health.

Head:
Prof. Igor Križaj

Toxinology

One of our traditional research topics in the field of toxinology is the study of molecular mechanisms of the toxic action of secreted phospholipases A_2 ($sPLA_2$s) from animal venoms. In particular, we are focused on those endowed with presynaptic neurotoxicity (β-neurotoxins). The knowledge that we are gaining by studying toxic $sPLA_2$s is helping us to discover the pathophysiological roles of orthologous mammalian $sPLA_2$s, and to develop novel and more effective therapeutic treatments of envenomation.

The molecular mechanism of action of ammodytoxin A (AtxA), a potent β-neurotoxic $sPLA_2$ from the venom of the nose-horned viper (*Vipera a. ammodytes*; *Vaa*), has already been well described. However, one of the questions that still needs some clarification, is the role of the phospholipase activity in β-neurotoxicity. To this end, we prepared an enzymatically inactive mutant of AtxA, AtxA(D49S). In collaboration with the research group led by Professor R. Frangež from the Veterinary Faculty, University of Ljubljana (VF/UL), we concluded in 2023 a comparative electrophysiological characterization of AtxA and its enzymatically inactive mutant. We demonstrated that the effects of AtxA independent of enzymatic activity cannot be studied with conventional electrophysiological measurements on the isolated neuromuscular preparation. Our results also suggested that the inhibition of cytochrome c oxidase activity by AtxA is not involved in the rapid neuromuscular blockade by this β-neurotoxin, but that its pathological consequences are rather long term (M.C. Žužek et al., *Toxicon*, submitted).

Animal venoms are a rich source of new substances and molecular tools to improve human and animal health.

AtxA has been used as a tool to study the mechanism of regeneration for the nerve terminal after trauma. In a consortium, led by Professor C. Monteccucco from the Department of Biomedical Sciences, University of Padua, and the Institute of Neuroscience, National Research Council, Padua, Italy, we published a research paper on the action of an agonist of a G-protein-coupled chemokine receptor CXCR4. We demonstrated that a small molecule agonist of CXCR4, dubbed NUCC-390 induces a rapid regeneration of the motor axon terminal with functional recovery of the neuromuscular junction. Our results qualify NUCC-390 as a promising novel therapeutic agent capable of improving recovery from the paralysis caused by the snakebite of neurotoxic vipers (M. Stazi et al., *Journal of Neurochemistry* (2023), doi: 10.1111/jnc.15803).

It has been demonstrated that certain $sPLA_2$s specifically bind to nicotinic acetylcholine receptors (nAChRs). The binding of ACh or other agonists, such as nicotine and its derivatives, to nAChRs has been linked to uncontrolled cell division, the prevention of apoptosis and the induction of angiogenesis, ultimately supporting tumour growth and metastasis. However, antagonists of nAChRs showed opposite effects on the cells, indicating their potential value in cancer therapy. Among the naturally occurring nAChR antagonists, found in various venoms, snake venom $sPLA_2$s were also shown to suppress ACh-elicited ion currents. For this reason, we investigated the anti-cancer effect of an array of human $sPLA_2$s and their single-point enzymatically inactive mutants to assess their lung-cancer therapeutic potential. In collaboration with pharmacologists from the University of Leuven, Belgium, we have been determining the effect of these proteins on α7- and muscle-type nAChRs. The most interesting result was obtained with GV(H48Q), which was absolutely selective for α7-nAChR. We then used GV(H48Q) to assess its effects on viability, cytotoxicity, proliferation and apoptosis of various lung-cancer cell lines as well as one non-cancerous lung-cell line. We demonstrated that GV and GV(H48Q) are able to prevent the ACh-induced cell proliferation and viability. In parallel, we were also involved in a similar study with another group of α7-nAChR antagonists, 3-alkylpyridinium salts (APS). A paper describing the effects of APS7 and APS8, either free or packed in gelatine nanoparticles, on human lung cancer cells is under revision (A. Joukhan et al., *Marine Drugs*, submitted). A second paper on this subject has been submitted for publica-

Figure 1: The cover page of the FEBS Journal issue advertising our paper on the evolution of novel biological functions in serine pseudoproteases. The cover page is from FEBS J. 290(9) (2023).

tion (V. Kononenko, *Journal of Controlled Release*, submitted). We also prepared a review paper on the role of nAChR in cancer – it has been accepted for publication (T. Bele et al., *BBA – Molecular Basis of Disease*, in press).

In 2023 we continued the study of snake-venom proteins that affect the process of blood coagulation – haemostasis. In the scope of the research project J1-2475, funded by the Slovenian Research and Innovation Agency (ARIS), we have been investigating a unique anticoagulant homologue of a serine protease from the venom of the nose-horned viper (*Vipera a. ammodytes*, *Vaa*), VaaSPH-1, in order to develop completely new and safe drugs with anticoagulant activity. We searched for the best possible conditions for the expression of VaaSPH-1 as well as its binding protein, blood-coagulation factor VIIIa (FVIIIa), in mammalian HEK293-F cells. In parallel we have been designing low-molecular-mass FIX antagonists. We have a promising peptide candidate to test its action *in vitro*. On this topic, we published an invited review article on serine pseudoproteases (N. Zupanič et al., *FEBS Journal* 290 (2023), 2263–2278), in which we highlighted and discussed a previously neglected possibility of the non-enzymatic functions of these SP molecules. Our paper was featured on the cover page (Figure 1).

Following the publication of a detailed description of the serine protease VaaSP-VX, which promotes blood clotting by activating FV and FX, we isolated a structurally very similar molecule VaaSP-6 from the *Vaa* venom. Since the entire cDNA sequence of VaaSP-6 is known, we will produce this protein recombinantly to characterize it. Hopefully, the recombinant VaaSP-6 will exhibit the same unique procoagulant activity as VaaSP-VX, so that it could replace the unreliable dilute Russell's viper venom (dRVV) assay currently used in clinics for the determination of lupus anticoagulants (LA test).

Figure 2: Dr. I. Križaj receiving the Zois award. At the ceremony in Cankarjev dom, on the 28th November 2023, I. Križaj received the Zois Award, the highest national science award. Left from Dr. Križaj is Dr. Nataša Vaupotič, the president of the Zois Awards Committee. On the right-hand side is the Minister of Higher Education, Science and Innovation, Dr. Igor Papič. The justification of Dr. Križaj's decoration is available at https://www.gov.si/novice/2023-11-28-podeljene-najvisje-drzavne-nagrade-v-znanstvenoraziskovalni-in-razvojni-dejavnosti/.

In the last year we also concluded our ARIS experimental research project J3-2534. In this project, together with colleagues from the Centre for Clinical Toxicology and Pharmacology of the University Medical Centre Ljubljana (UMCL), we investigated an interesting clinical effect observed in patients envenomed by the nose-horned viper, namely a profound, transient and reversible thrombocytopenia of functional platelets. Platelets play a central role in thromboembolic diseases such as myocardial infarction and ischemic stroke. Existing antiplatelet drugs have a common side effect – a reduced number of platelets whose activity is inhibited. This condition carries a high risk of bleeding (haemorrhage), especially in interventional cardiology and angiology that use an antithrombotic approach. Our results could pave the way for the development of a new group of antiplatelet agents that would reduce the risk of dangerous bleeding in interventional cardiology and angiology, and increase the efficacy of vasodilatation and clot removal. We have demonstrated that reversible thrombocytopenia in patients envenomed by the *Vaa* is induced by proteins similar to type-C lectins (snaclecs). We have isolated several snaclecs from the *Vaa* venom and showed that snaclec 3/2 in particular induces severe thrombocytopenia through its interaction with the GPIb platelet receptor. In collaboration with our partners from the VF/UL, we have performed an *in vivo* study in a mouse model of arterial thrombosis to validate the potential of snaclec 3/2 to prevent clot formation and arterial occlusion after experimentally induced vascular injury, and to determine its potential for medical applications. The first set of results has already been published (M. Dobaja Borak et al., *Thrombosis Research* 229 (2023), 152–154). However, the preparation of two further research papers on this topic (M. Dobaja Borak et al., *Thrombosis Research*, submitted; M.C. Žužek et al., in preparation) and a review paper (K. Požek et al., in preparation) has already been initiated.

Within the research network – comprising experts from UMCL, University Hospital and University of Split, University of Zagreb (UZ) and from our group – we analysed samples of patients who were envenomed by *Vaa* and treated with different antidotes. A publication is underway (T. Kurtović et al., in preparation).

Our scientific achievements in the field of toxinology were very well recognised also in 2023. I. Križaj has been invited as a lecturer at the Société Française pour l'Etude des Toxines (SFET) annual meeting in Paris from the 30th November to the 1st December 2023. He was also invited to act as a Guest Editor in two well-established journals, *Toxins* (I. Križaj, *Toxins* 15 (2023), 212) and the *International Journal of Molecular Sciences* (P. Veranič and I. Križaj, *International Journal of Molecular Sciences* 24 (2023), 13667). However, the most prestigious recognition for the outstanding research work of I. Križaj and his team was the Zois Award, the highest science award in Slovenia (Figure 2).

Lipid metabolism and signalling

Lipids are essential for life. They constitute the membranes of all cells and organelles, and serve as the most efficient form of energy storage. However, owing to their structural and functional diversity and the complexity of their assemblies, the roles of lipids and lipid metabolism in health and disease remain poorly defined. Lipid droplets are recently recognized organelles that could help us understand the mechanisms underlying lipid function at the cellular level and in various pathophysiological conditions associated with dysregulated lipid metabolism. These dynamic fat-storage organelles are involved in essential cellular processes, ranging from energy production and membrane homeostasis to infection and inflammation. Our work in this field has been focused on answering the following questions: (1) Are lipid droplets involved in the generation of lipid signalling molecules involved in intercellular communication? (2) What is the role of the lipid droplets in cellular lipid trafficking and the regulation of membrane integrity and function? and (3) How does autophagy cooperate with lipid-droplet breakdown mechanisms during nutrient stress?

In our recent report (E. Jarc Jovičić et al., *Molecular Metabolism* 76 (2023), 101791), we described a novel mechanism of fatty-acid trafficking between membrane phospholipids and triglycerides stored in lipid droplets, which is critical for the generation of potent lipid mediators that promote tumour growth and inflammation. We demonstrated that certain types of fatty acids are enriched in lipid droplets of cancer cells and discovered the molecular mechanism of their release from lipid droplets (Figure 3). This research uncovers a previously unrecognized central role for lipid droplets in fatty-acid metabolism and signalling, and significantly expands the current membrane-centric paradigm of lipid-mediator production.

In an invited review (M. Danielli et al., *Frontiers in Cell and Developmental Biology* 11 (2023), 1104725) published in a special issue entitled "The evolving role of lipid droplets: Advancements and future directions", we highlighted the concept of lipid droplets having multifaceted, context-dependent and often contradictory roles, ranging from the production of lipid-signalling molecules to the control of membrane lipid peroxidation and cell death, including ferroptosis. We explored how these evolving concepts in lipid-droplet biology can improve our understanding of cell adaptability and resilience to stress and how they can be harnessed in the fight against cancer.

Our report on autophagy and lipid droplets highlights the complex interplay between autophagy/lipophagy and lipid droplets in the regulation of cellular homeostasis and adaptation to stress (M. Jusović et al., *Cancers* 15 (2023), 4857). Our findings suggest a cooperation between autophagy and lipid-droplet metabolism in protecting cancer cells against starvation (Figure 4). Using a strategy of combined targeting of autophagy and lipid-droplet biogenesis, we impaired two essential processes for cancer-cell resistance, thereby revealing a potential novel approach for cancer treatment. Our currently unpublished work on the mechanisms that control lipid-droplet breakdown and direct lipids to other organelles is in preparation for publication (Š. Koren et al., in preparation). Our ongoing work on the capacity of lipid droplets to control cellular lipid fluxes and manage ferroptotic cell death is in preparation for publication (A. Kump et al., in preparation; L. Perne et al., in preparation). These results were recently presented at two renowned conferences (EMBO Lipid Droplets Workshop; EMBO Ferroptosis Workshop) and were accepted exceptionally well by our peers. For our studies on ferroptosis and lipid droplets we were awarded an EMBO Advanced Collaboration Grant, which financed the expansion of our work into lipidomics and epilipidomics. Our studies on lipid droplets were also presented through invited talks at several other conferences and institutions, including the 63rd ICBL Meeting in Spain and the Institute of Physiology at the Czech Academy of Sciences.

In a collaboration with several European groups working on lipids, we published a review discussing the current state and challenges of organelle lipidomics (M.J. Sarmento et al., *Cellular and Molecular Life Sciences* 80 (2023), 237).
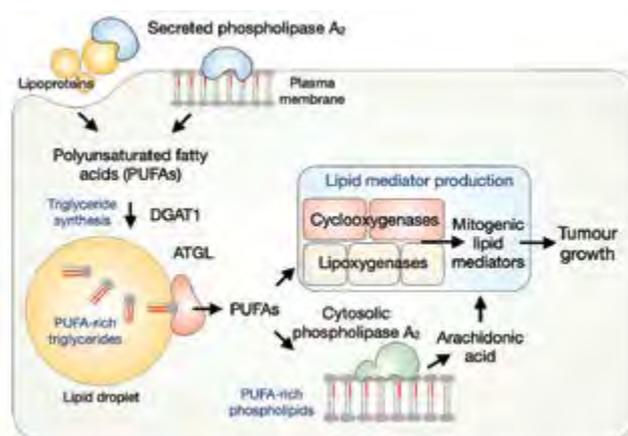
Figure 3: Mechanism of lipid-droplet-controlled generation of lipid signals that promote tumour growth. Our study shows that lipid droplets control the supply of ω-3 and ω-6 polyunsaturated fatty acids (PUFAs) for the production of lipid mediators, which in turn drive cancer-cell proliferation. The esterification of PUFAs into triacylglycerols (TAGs) and their release from lipid droplets are necessary for PUFA entry into lipid mediator production pathways (E. Jarc Jovičić et al., Mol. Metab. 76 (2023), 101791).

Lipid droplets orchestrate key metabolic and signalling processes that control the balance between cellular life and death.
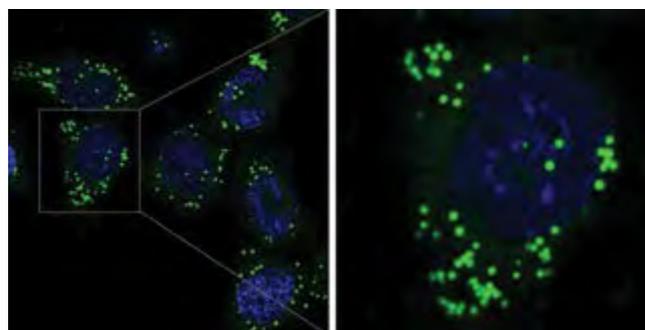
Figure 4: Lipid droplets and autophagy work together to protect cells from severe nutrient deficiency. In our work (M. Jusović et al., Cancers 15 (2023), 4857), we demonstrate that lipid droplets accumulate in starving cancer cells in an autophagy-dependent manner and that combined targeting of autophagy initiation and lipid-droplet biogenesis leads to cancer-cell death (BODIPY-stained lipid droplets are green, cell nuclei are blue).
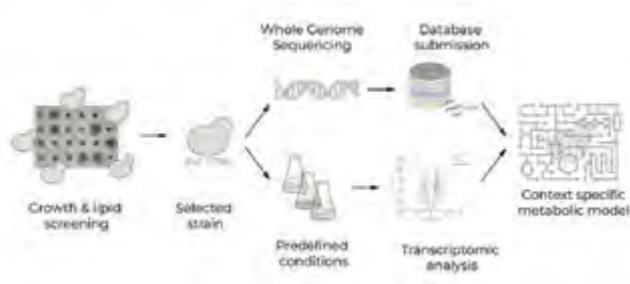
Figure 5: Scheme of strain selection, genomic and transcriptomic analysis to identify metabolic routes involved in microbial oil production from short-chain fatty acids.

Yeast genetics, functional genomics and synthetic biology for basic research and biotechnology.

High-throughput genetics and functional genomics in yeast *Saccharomyces cerevisiae*

The budding yeast *Saccharomyces cerevisiae* is a well-established model organism for basic research and a cell factory in biotechnology. In biotechnological applications it is also important for synthetic biology given its highly efficient homology recombination-based assembly of DNA fragments, called *in yeasto* assembly.

Within the ARIS project L4-3181, *Hierarchical DNA assembly for advanced applications in biopharmaceuticals production and cell therapy*, we have been developing a toolbox for hierarchical DNA assembly by combining *in vitro* and *in yeasto* assembly approaches. We successfully developed an experimental pipeline for the assembly of genomes of recombinant bacteriophages with a modified host range. This pipeline will be of great importance for the industrial partner and co-financer of the project. The results were presented in an invited lecture at a scientific conference and a research paper (G. *Žun* et al., *Yeast* 40 (2023), 32–41).

With our partners in the ERACoBioTech project OLEOFERM (https://oleoferm.eu/), we found a new biotechnologically useful strain of the oleaginous yeast species *Yarrowia lipolytica* with a promising potential for lipid production from short-chain fatty acids (SCFAs) using yeast cell factories. We have performed genomics and transcriptomics analyses with the aim to identify the metabolic routes involved in this biotransformation (Figure 5). The results have been compiled and will be published in 2024.

Within the ARIS project J4-4560, *Engineering of polygenic traits in S. cerevisiae*, we have started developing custom-made methods for haploid selection and a novel assay for protein-secretion screening. Preliminary results were presented at local student conferences.

Evolutionary genomics

Peptidases of the papain family play a key role in protein degradation, regulated proteolysis, and the host–pathogen arms race. Although the papain family has been the subject of many studies, knowledge about its diversity,

Evolutionary, genomic and structure-function analysis of proteases and their homologues. Genome and transcriptome analysis of cave adaptations, chemosensory system and repetitive DNA.

origin, and evolution in Eukaryota, Bacteria and Archaea is limited. In the past year, we addressed this gap by tracing the birth and expansion of the papain family with a phylogenomic analysis using publicly available information from numerous prokaryotic and eukaryotic proteomes, transcriptomes and genomes (D. Kordiš and V. Turk, *International Journal of Molecular Sciences* 24 (2023), 11761). We found that the papain family

was present in the last universal common ancestor and expanded greatly during eukaryogenesis through massive gene innovation and diversification, which resulted in eight ancestral C1A lineages in the ancestor of eukaryotes. These eight ancestral eukaryotic C1A peptidase lineages are cathepsins B, C, X, L, H and F, 26/29 kDa peptidase and type-1 long C1 peptidase, which are present in all eukaryotic supergroups (Figure 6). The papain family expanded further during eukaryotic evolution, especially through extensive gene duplications in the ancestral cathepsin L and B lineages. Together, we demonstrated that diversification of the papain family predates the origin of eukaryotes and that a burst of innovation during eukaryogenesis led to a eukaryotic ancestor with a complex set of ancestral C1A lineages. The findings of this comprehensive study provide guidelines for future structural and functional studies of the papain family.

Pore-forming toxins form pores in cell membranes and represent one of the most fundamental defence systems of organisms. Proteins of the aerolysin superfamily contain a pore-forming aerolysin domain and a receptor-binding domain (RBD). In contrast to the highly conserved pore-forming domains, RBDs are very variable, and their structural variations lead to differences in target recognition and, consequently, of the way of action. In numerous genomes and transcriptomes of basal metazoans (sponges, ctenophores and cnidarians) we discovered unexpectedly large diversity and many novel domain architectures of the aerolysin superfamily. We analysed the origin, diversity and domain architecture of the aerolysin superfamily in basal metazoans as well as in diverse invertebrates (crustaceans and molluscs) and deuterostomes. Our analysis demonstrates that the aerolysin superfamily is incredibly diverse in metazoans where it plays important roles from host defence to the innate immunity (D. Kordiš, in preparation).

In 2022 the first draft assembly of the huge cave salamander (*Proteus anguinus*) genome was made at the Beijing Genomics Institute. With 34 gigabase (Gb), it is among the largest genomes ever sequenced, more than 10 times larger than the human genome. In the scope of the ARIS project J1-2469, led by our colleagues at the Biotechnical Faculty UL (BF/UL), we continued with the analysis of genomic and transcriptomic data of the cave salamander. Besides the analysis of transposable elements (TEs) we investigated diverse cave adaptations, such as

the chemosensory system (olfactory receptors, vomeronasal receptors and taste receptors), its G-protein-coupled receptors repertoire as well as the genome defence systems against TEs (APOBEC, SCAN-ZNF and KRAB ZNF genes) of this cave animal.

Figure 6: Early diversification of the papain family in the eukaryotic ancestor. The rooted maximum likelihood (ML) tree shows the evolutionary relationships between the seven ancestral eukaryotic orthologous gene families, cathepsins B, C, X, L, H and F, and the 26/29 kDa peptidase. The ML tree represents bootstrap consensus following 1000 replicates. Sequences were obtained from the GenBank database. Species names and protein accession numbers are displayed.

Other subjects

In 2023 we also participated in different projects outside the thematic scope of our department that were funded by ARIS or others. Only the projects for which papers have been published or are in preparation are listed below.

In the scope of the ARIS project J1-2482 (leading institution: BF/UL), we have been determining the impact of environmentally relevant nano- and microplastics on terrestrial vertebrates by mass spectroscopy. We also performed the proteomic analysis of the haemolymph of the terrestrial crustacean *Porcellio scaber* and revealed components of its innate immunity under baseline conditions (A. Jemec Kokalj et al., *Biochimie* 213 (2023), 12–21).

As partners on the ARIS project J2-3040 on magnetically controllable nanocarriers that mimic endogenous lipid particles to improve drug/nanoparticle delivery, we participated in analysing the effects of barium-hexaferrite nanoplatelets in low-frequency magnetic field on cancer cells (T. Goršak et al., *Journal of Colloid and Interface Science*, in press).

We also collaborated informally with several groups at home and abroad. Colleagues from the Ruđer Bošković Institute and UZ were assisted in researching the mechanism of formation and morphogenesis of biomineral nanostructures of the *Archa noae* shell. We performed a structural identification of protein components of the shell that are potentially involved in the biomineralization process (I. Sondi et al., in preparation).

In a study led by colleagues from the Faculty of Electrical Engineering UL, we analysed the protein corona composition of different types of nanoparticles using a proteomic approach to specify the serum protein binding (L. Peternel et al., in preparation).

We came to the aid to our colleagues from the Medical Faculty UL performing the confocal microscopic analysis for the functional validation of an α-FREM2 nanobody as a molecular tool for targeting specifically glioblastoma stem cells (N. Šamec et al., *FEBS Journal*, submitted).

We joined our colleagues from the Department of Gaseous Electronics (F6) at the Jožef Stefan Institute (JSI) to study the reduction of antigenicity of common ragweed pollen and its primary allergen Amb a 1 with cold atmospheric pressure air plasma (N. Hojnik et al., *Journal of Hazardous Materials*, submitted).

In a collaboration led by our colleagues from the Department for Nanostructured Materials (K7), JSI, we investigated the potential of vesicles from red-blood-cell membranes as a safe and efficient delivery system for therapeutic nucleic acids (G. Della Pelle et al., in preparation).

Some outstanding publications in the past year

1. Dobaja-Borak, M., Grenc, D., Reberšek, K., Podgornik, H., Leonardi, A., Kurtović, T., Halassy, B., Križaj, I. and Brvar, M.: Reversible and transient thrombocytopenia of functional platelets induced by nose-horned viper venom. Thrombosis Research, 229 (2023), 152–154

2. Jarc Jovičić, E., Pucer Janež, A., Eichmann, T.O., Koren, Š., Brglez, V., Jordan, P.M., Gerstmeier, J., Lainšček, D., Golob-Urbanc, A., Jerala, R., Lambeau, G., Werz, O., Zimmermann, R. and Petan, T.: Lipid droplets control mitogenic lipid mediator production in human cancer cells. Molecular Metabolism, 76 (2023), 101791

3. Žun, G., Doberšek, K. and Petrovič, U.: Construction and evaluation of gRNA arrays for multiplex CRISPR-Cas9. Yeast, 40 (2023), 32–41

4. Kordiš, D. and Turk, V.: Origin and early diversification of the papain family of cysteine peptidases. International Journal of Molecular Sciences, 24 (2023), 11761

Awards and Appointments

1. Prof. Igor Križaj: Zois Award for outstanding achievements in toxinology. State award in the field of science, research and development, Committee of the Republic of Slovenia for the presentation of prizes and awards for outstanding achievements in science, research and development.

Organization of conferences, congresses and meetings

1. Prof. Igor Križaj, member of the International Scientific Committee – organizer of the section Molecular Interactions and networking,

2. 15th Meeting of the Slovenian Biochemical Society Portorož, 20–23 September 2023

INTERNATIONAL PROJECTS

1. COST CA19144; EUVEN - European Venom Network
   Prof. Igor Križaj
   COST Association Aisbl
2. COST CA19105; LipidNET - Pan-European Network in Lipidomics and Epilipidomics
   Prof. Toni Petan
   Cost Association Aisbl

RESEARCH PROGRAMME

1. Toxins and biomembranes
   Prof. Igor Križaj

R&D GRANTS AND CONTRACTS

1. Genomic and transcriptomic insights into the exceptional biology of proteus (Proteus anguinus)
   Prof. Dušan Kordiš
2. Impact of environmentally relevant nano- and micro-plastics on soil invertebrates
   Prof. Igor Križaj
3. Inflammatory process in interstitial cystitis and evaluation of the influence of cannabinoid receptor agonists in urinary bladder - from cells to patients
   Prof. Igor Križaj
4. „Reversibility of transient thrombocytopenia induced by a snake venom component offers asafe antithrombotic prevention in interventional angiology and cardiology"
   Prof. Igor Križaj
5. Parasitic-like modulation of Bacillus thuringiensis development and larvicidal activity by a bacteriophage
   Prof. Igor Križaj
6. Adaptation of wine yeasts to climate change
   Prof. Uroš Petrovič
7. Development of an innovative drug to treat venous thromboembolism based on a unique viper venom anticoagulant
   Prof. Igor Križaj
8. Magnetically-controllable nanocarriers mimicking endogenous lipid particles for improved drug/nanoparticle delivery
   Prof. Igor Križaj

9. Engineering polygenic traits in S. cerevisiae
   Prof. Uroš Petrovič
10. Hierarchical DNA assembly for advanced applications in biopharmaceuticals production and cell therapy
    Prof. Uroš Petrovič
11. Lipid droplets as sources of inflammatory lipid mediators in cancer
    Dr. Eva Jarc Jovičić
12. The interplay between lipolysis and lipophagy in the modulation of ferroptosis in cancer
    Mauro Danielli
13. OLEOFERM - Sustainable oleochemicals biopreoduction from carboxylates via oleaginous fermentation

Prof. Uroš Petrovič
Ministry of Education, Science and Sport
14. Analysis for the Export
    Prof. Igor Križaj

NEW CONTRACT

1. Hierarchical DNA assembly for advanced applications in biopharmaceuticals production and cell therapy
   Prof. Uroš Petrovič
   Jafral d. o. o.

VISITOR FROM ABROAD

1. Prof. Manjunatha Kini, Department of Biological Science, National University of Singapore, Republic of Singapore, 17–24 September 2023

STAFF

Researchers
1. Prof. Dušan Kordiš
2. **Prof. Igor Križaj, Head**
3. Asst. Prof. Adrijana Leonardi
4. Prof. Toni Petan
5. Prof. Uroš Petrovič*
6. Prof. Jože Pungerčar
7. Dr. Jernej Šribar
Postdoctoral associates
8. *Dr. Mauro Danielli, left 01.10.23*
9. Dr. Eva Jarc Jovičić
10. Dr. Nina Mikec
Postgraduates
11. *Tadeja Bele, M. Sc., left 01.10.23*
12. *Dr. Adrijan Ivanušec, left 01.09.23*

13. Špela Koren, B. Sc.
14. Leja Perne, B. Sc.
15. Kity Požek, B. Sc.
16. Neža Škofljanc, B. Sc.
17. Mia Žganjar, B. Sc.
18. Gašper Žun, B. Sc.
Technical officer
19. *Katja Doberšek, B. Sc., left 01.10.23*
Technical and administrative staff
20. Igor Koprivec
21. Vahida Suljić
22. Maja Šimaga, M. Sc.

Note:

* part-time JSI member

DEPARTMENT OF BIOTECHNOLOGY
B-3

At the Department of Biotechnology we study biological molecules from animal, plant, fungal, and microbial sources using advanced biotechnological methods. Our goal is to apply these molecules for diagnostic and therapeutic purposes in both human and veterinary medicine, as well as for plant protection, the production of safe and high-quality food, and environmental protection. By doing so, we aim to contribute to the improvement of human health and the well-being of the environment. Our research primarily focuses on cancer progression, immune responses, neurodegenerative processes, fungal biology, and the development of innovative biotechnological approaches and products.

Head:
Prof. Boris Rogelj

Regulation of antitumor immune response

In 2023 we continued our studies of the role of cysteine peptidases and their inhibitors in the regulation of antitumor immune response. We focused our work on the endogenous inhibitor cystatin F. It is an important modulator of the cell cytotoxicity of natural killer cells and cytotoxic T cells. We showed that the glycosylation profile of cystatin F determines its transport to intracellular compartments, as well as its secretion and cellular uptake. The ratio between high-mannose glycosylation and complex glycosylation has an impact on the cytotoxicity of NK cells. In super-charged NK cells, which have been shown to be very effective in antitumor therapy, the complex type of glycosylation was predominant in cystatin F. This profile impairs the transport to endosomal/lysosomal compartments, decreasing in this way the role of cystatin F in the activation of granzymes, which is critical for NK cell cytotoxicity. On the other hand, in NK-92 cells a high mannose type of glycosylation is predominant in cystatin F, explaining the lower cytotoxic potential of these cells. The regulation of cystatin F glycosylation represents a new tool to improve the efficacy of cancer immunotherapy. The results have been published in *Cellular and molecular life sciences*. 2024, vol. 81, [COBISS.SI-ID 177482499].

Glycosylation profile determines the role of cystatin F in cytotoxicity of NK cells.

In collaboration with colleagues from UCLA, Los Angeles, we investigated cystatin F in super-charged NK cells in a humanized mouse BLT model. We used various proteomic methods to test its expression, localization and function in immune and tumor cells. The results of the study have been submitted for publication. We further showed that sequential therapy with supercharged NK cells with either the chemotherapy drug cisplatin or anti-PD-1 antibody decreases the tumor size and enhances the NK function in Hu-BLT mice. The results have been published in *Frontiers in immunology*, vol. 14, 2023 [COBISS.SI-ID 150785283].

COVID-19

We continued the research on the role of cysteine peptidases in the replication and infection of the SARS-CoV-2 virus. For peptidase inhibitors from our inhibitor library we found the most promising antiviral effect for cathepsin B inhibitors. For the uptake to host cells the virus explores two main mechanisms, membrane fusion and endocytosis. They differ regarding peptidases involved in the cleavage of S protein, in endocytosis the crucial peptidases are cathepsins B and L. It is now known that different variants of the SARS-CoV-2 virus prefer one or another mechanism, Omicron, for example utilizes an endocytic path-
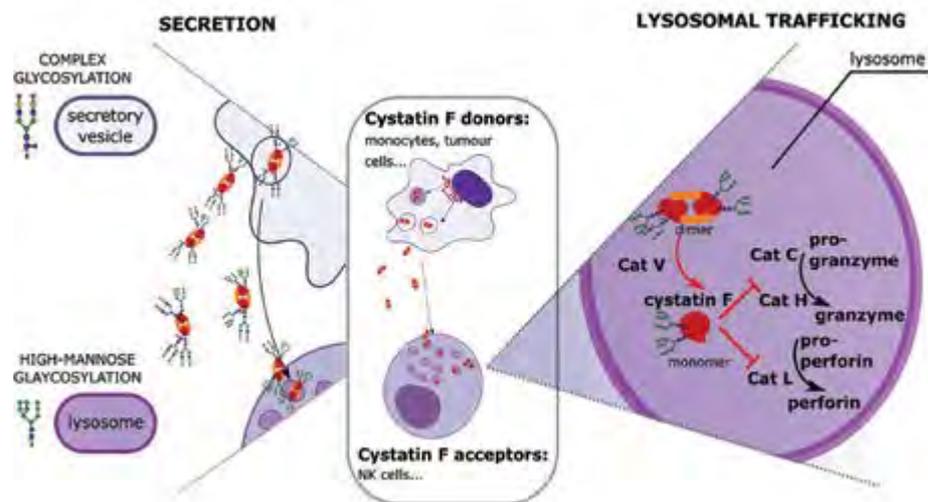
Figure 1: Role of glycosylation profile in sorting of cystatin F in NK cells
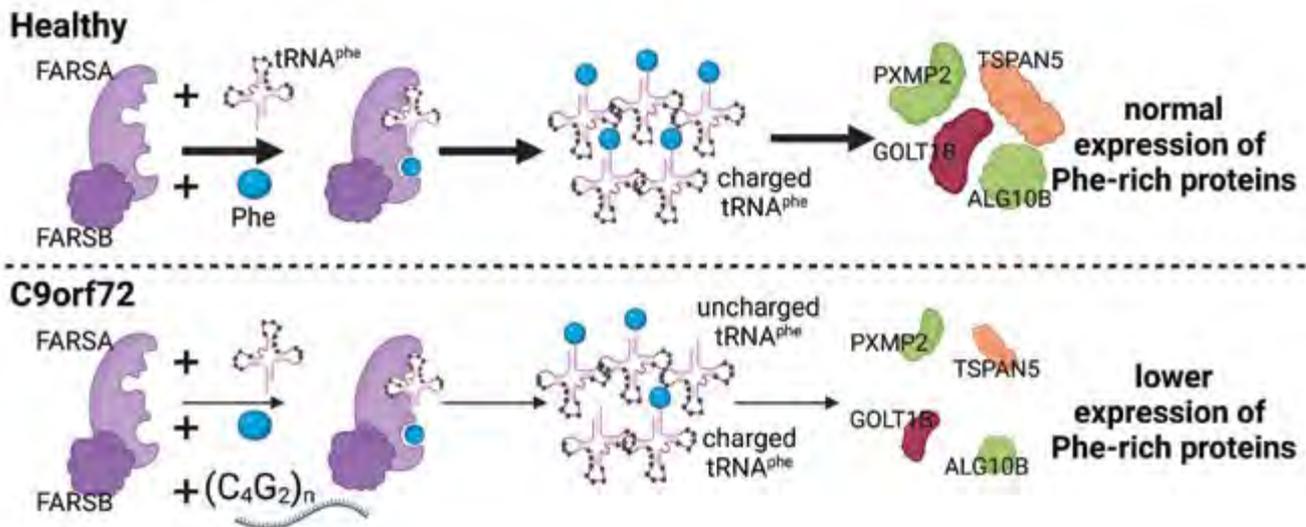
Figure 2: Antisense RNA repeats (C4G2)ₙ that result from the C9orf72 mutation affect the function of the phenylalanine-tRNA synthetase and lead to reduced expression of phenylalanine-rich proteins in patients.

way for cell entry. The results have been published in *Antiviral Research*, vol. 216, 2023 [COBISS.SI-ID 156890115]. In collaboration with colleagues from ICGEB in Trieste, ETH and the University of Zurich we investigated the role of cysteine peptidases also in patients with post-Covid complications, reflected in human-brain vasculature.

Molecular neurodegeneration

With the aging population and lack of useful therapy, neurodegenerative diseases are increasing and becoming one of the leading causes of death worldwide. In this field our main focus is on selected genes and their protein products (TDP-43, FUS, C9orf72, SFPQ, MATR3, etc.) associated with amyotrophic lateral sclerosis (ALS), fronto-temporal dementia (FTD) and Alzheimer's disease (AD). The majority of them are in some way associated with RNA biogenesis, processing, transport and turnover. We study their nuclear transport, cellular stress response and macromolecular interactions leading to mislocalization and aggregation.

Mutation in the C9orf72 gene interferes with the use of phenylalanine in protein synthesis.

In the past year, we have continued to study the STAU2 protein, a previously identified FUS interactor. Since STAU2 binds dsRNA, we were able to confirm an increased accumulation of dsRNA in the cytoplasm of cells with the concomitant accumulation of mSc-FUS and mSc-FUSdNLS, which also sequesters STAU2, using HEK293 FlpIn lines expressing mSc, mSc-FUS and mSc-FUSdNLS. Whether this mechanism is potentiated under stress conditions, where it could slow down the proper translation of proteins in neurons and contribute to their degeneration, remains a subject for further research. After studying the effect of FUSp-Y526 on the formation of cytoplasmic aggregates in different cell models in 2022, we continued to investigate the occurrence of FUSp-Y526 in brain neurons in frontotemporal dementia (FTD). We confirmed an increased level of phosphorylated FUSp-Y526 in pyramidal neurons in human postmortem frontal cortex tissues, compared to controls. The pattern of appearance of the phosphorylated form of FUSp-Y526 in neurons coincided with the increased expression of the active form of the Src family tyrosine kinase c-Abl. The fine-grained nature of intracellular FUSp-Y526-positive aggregates confirmed the role of FUS phosphorylation in the initial stages of its pathological aggregation. The latter is strongly increased
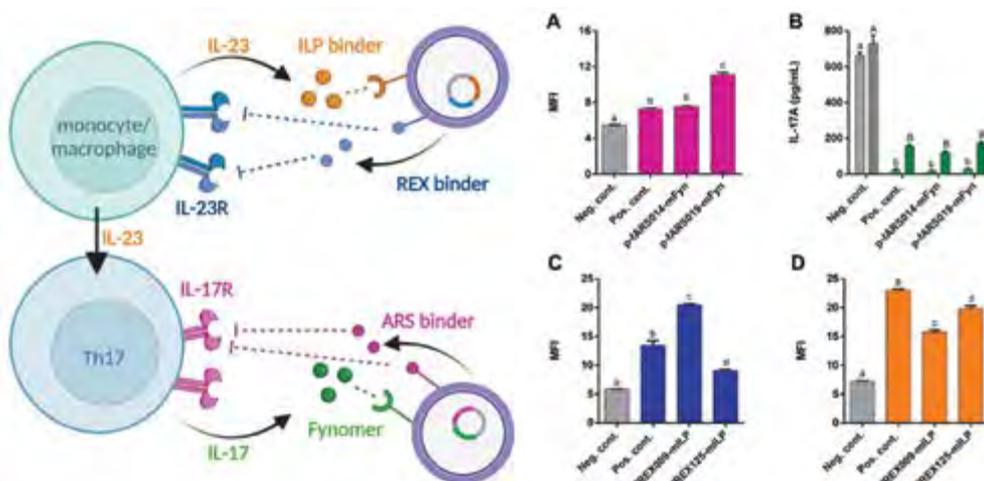
Figure 3: Schematic representation (left; Biorender.com) of the envisaged activity of bifunctional L. lactis simultaneously targeting IL-23 and IL-23R, or IL-17 and IL-17R, and demonstration of binding of IL-17A, IL-23 and their receptors (right) by bifunctional L. lactis cells displaying ARS binders (A), fynomer binder (B), REX binders (C) and ILP binder (D).

under conditions of oxidative stress and c-Abl kinase activation, as demonstrated by a prepared FlpIn SH-SY5Y cell line stably expressing fluorescently labelled G3BP1 protein, a basic building block of stress granules, protein aggregates formed in early response to stress. The study was published in the journal Brain in 2023 and received the Outstanding Achievement Award at the ARIS Excellence in Science Awards.

To determine the changes in the interactome of TDP-43 during stress granule formation and dissolution, we proteomically evaluated four stable cell lines expressing different forms of TDP-43 in fusion with ascorbate peroxidase (APEX2). In addition, in mouse brains with TDP-43 or mutant TDP-43dNLS, we observed the localization of TDP-43 interactors SFPQ, NONO, KPNA4, and FUS. We have also been expressing TDP-43 in bacterial cells. We used the purified protein for in-vitro aggregation assays. Our focus was on the effect of tRNA on TDP-43 aggregation. We found that tRNA inhibits TDP-43 aggregation and keeps the protein soluble for several days.

We introduced a novel synergistic strategy for the treatment of intestinal inflammations by simultaneously targeting multiple players of the IL-23/Th17 proinflammatory axis with probiotic bacteria as in-situ delivery vehicles.

With colleagues from the Laboratory for Molecular Immunology, Department of Biotechnology, University of Rijeka, we studied the crosstalk between the TDP-43 and OPTN. The results of our collaboration were published in the journal *Scientific Reports*. As part of this collaboration, we also published two review articles in the *Biomedicines* journal last year.

We completed a study on the impact of RNA repeats C4G2, resulting from a mutation in the C9orf72 gene, on the function of the phenylalanyl-tRNA synthetase (FARS) protein. We demonstrated that an impaired FARS function leads to reduced protein expression in disease-relevant models such as differentiated motor neuron-like cells NSC-34 and in brain tissues obtained from patients with the C9orf72 mutation. Our findings were published in the journal Nature Communications in September 2023. We also continued research on the influence of nuclear transport molecules from the karyopherin family (KPNA proteins) on the transport of TDP-43 and ORF1 proteins into the nucleus. In doing so, we examined the effects of various KPNA proteins on nuclear transport in experiments where we isolated both proteins and most representatives of the KPNA family. Additionally, using established stable cell lines to observe the TDP-43 protein, we investigated the impact of KPNA4 on its transport.

Figure 4: Selective labelling of microbial biofilm members from the aquatic environment. The so-called eubacteria are labelled green, cyanobacteria red and all biofilm members blue, as the dye non-selectively binds to the DNA of all organisms.

Probiotics

IL-23/Th17 proinflammatory axis drives inflammation in Crohn's disease and ulcerative colitis and represents a therapeutic target of monoclonal antibodies. The cytokine IL-23 activates the IL-23 receptor (IL-23R) and stimulates the differentiation of naïve T helper (Th) cells into a Th17 cell population. This in turn secretes inflammatory cytokines, such as IL-17. Non-immunoglobulin binding proteins based on the *Streptococcus* albumin-binding domain (ABD) provide a small protein alternative to monoclonal antibodies. We engineered safe lactic acid bacterium *L. lactis* to display or secrete ABD-variants against the IL-17 receptor (IL-17R). Its expression and functionality were confirmed with flow cytometry using specific antibody and recombinant IL-17R, respectively. In addition, we engineered *L. lactis* into multifunctional bacteria that simultaneously expressed two binders from our recently developed pNBBX plasmid. Binders of IL-17R were combined with a binder of IL-17, and binders of IL-23R were combined with binders of IL-23. Their functionality was confirmed by flow cytometry using the recombinant receptors IL-17R and IL-23R or the p19 subunit of IL-23 as targets. IL-17-binding recombinant bacteria (2×10^9) removed 97% of IL-17 from solution. Moreover, multifunctional bacteria targeting IL-17/IL-17R prevented IL-17A-mediated activation of downstream signalling pathways in HEK-Blue IL-17 cell model. Additionally, to focus on the practical application of the developed bacteria, we compared the growth of engineered bacteria with the growth of control bacteria, and observed only a slight decrease in growth rate. We also monitored the stability of the plasmid in the absence of antibiotic selection pressure and observed that the plasmids are stably maintained over the course of 4 days, confirming the applicability of the system.
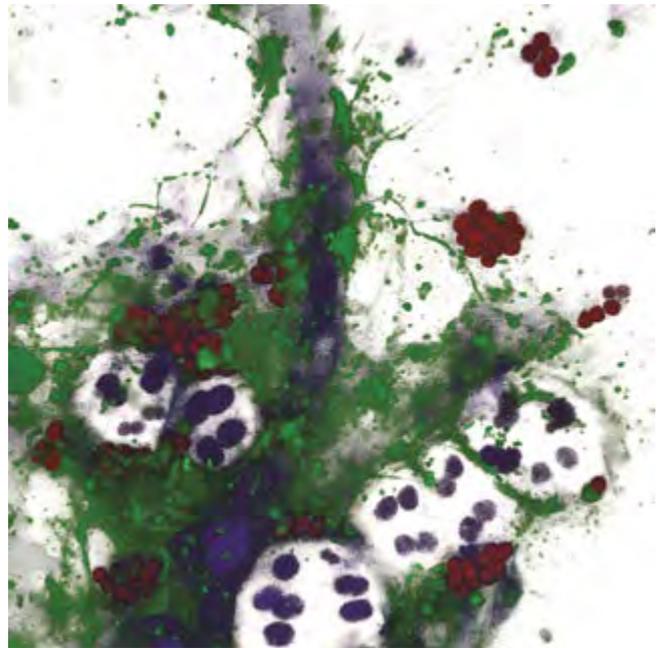
The development of new methods is crucial for the further development of the research field of microbial glycobiology.

Microbial glycobiology

In the field of microbial glycobiology, we continued our research into the molecular mechanisms of bacterial biofilm development. We focused on the development of methods and prepared a detailed protocol description for the Simba method, which was developed in collaboration with the Faculty of Biotechnology at the University of Ljubljana and allows us to distinguish between the antimicrobial and anti-biofilm activity of the tested compounds in a model of the pathogenic bacterium *Salmonella*. In addition, we organised a mini-symposium on the use of nuclear magnetic resonance (NMR) in microbial glycobiology, which showed that the development of new and the optimization of existing methods is important for the further development of research in microbial glycobiology. The development of methods for the investigation of bacterial biofilms is also the focus of interdisciplinary projects carried out in collaboration with the Department for Materials Synthesis (K8) and the Department of Knowledge Technologies (E8) and the Department of Condensed Matter Physics. Another aspect of bacterial biofilm research is addressed in a review article on the current state of knowledge of the individual structures that make up the cell surface of *Campylobacter jejuni* and that are associated with biofilm development or attachment to different surfaces. A comprehensive understanding of the properties of the surface structures involved in the process of biofilm formation is of great importance as understanding the role of surface structures will contribute to the development of new strategies to control the microorganisms that pose the greatest threat to human and animal health.

In the field of glycobiology and the applications of bioactive proteins, we continued our research on the molecular mechanisms of the action of fungal lectins and analysed the toxicity of fungal peptidase inhibitors and lectins on invasive pests as part of the FunContrAPest project (Novel fungal proteins as biopesticides for the control of invasive non-native agricultural pests), which is co-funded by the Slovenian and Hungarian research agencies. In collaboration with the project partners, we focused on the mechanisms of action of selected lectins on the larvae of the Colorado potato beetle and the Western corn rootworm.

Some outstanding publications in the past year

1. Malnar, Mirjana, Čerček, Urša, Yin, Xiaoke, Tin Ho, Manh, Repič-Lampret, Barbka, Neumann, Manuela, Hermann, Andreas, Rouleau, Guy, Suter, Beat, Mayr, Manuel, Rogelj, Boris. Phenylalanine-tRNA aminoacylation is compromised by ALS/FTD-associated C9orf72 C4G2 repeat RNA. *Nature communications*. 2023, vol. 14, article no. 5764, str. 1-15, ilustr. ISSN 2041-1723. https://www.nature.com/articles/s41467-023-41511-3#Abs1, DOI: 10.1038/s41467-023-41511-3. [COBISS.SI-ID 166968323], **IF 14,7**

2. Knez, Damijan, Diez-Iriepa, Daniel, Chioua, Mourad, Gottinger, Andrea, Meden, Anže, Pišlar, Anja, Kos, Janko, Žakelj, Simon, Stojan, Jure, Gobec, Stanislav, Marco-Contelles, José, et al. 8-Hydroxyquinolylnitrones as multifunctional ligands for the therapy of neurodegenerative diseases. *Acta pharmaceutica sinica B*. 2023, 13,. 2152-2175 [COBISS.SI-ID 139883267], **IF 14,5**

3. Motaln, Helena, Čerček, Urša, Yamoah, Alfred, Tripathi, Priyanka, Aronica, Eleonora, Goswami, Anand, Rogelj, Boris. Abl kinase-mediated FUS Tyr526 phosphorylation alters nucleocytoplasmic FUS localization in FTLD-FUS. *Brain : journal of neurology*. Oct. 2023, vol. 146, iss. 10, str. 4088-4104, ilustr. ISSN 0006-8950. https://academic.oup.com/brain/article/146/10/4088/7127731, Repozitorij Univerze v Ljubljani – RUL, DOI: 10.1093/brain/awad130. [COBISS.SI-ID 151014403], **IF 10,6**

4. Bonotto, R. Milan, Mitrović, Ana, Sosič, Izidor, Martinez-Orellana, Pamela, Dattola, Federica, Gobec, Stanislav, Kos, Janko, Marcello, Alessandro. Cathepsin inhibitors nitroxoline and its derivatives inhibit SARS-CoV-2 infection. *Antiviral research*, 2023, vol. 216, [COBISS.SI-ID 156890115]. **IF 7,6**

5. Sabotič, Jerica, Janež, Nikolaja, Volk, Manca, Klančnik, Anja. Molecular structures mediating adhesion of Campylobacter jejuni to abiotic and biotic surfaces. *Veterinary Microbiology*. [Print ed.]. Dec. 2023, vol. 287, [article no.] 109918, str. 1-14. ISSN 0378-1135. https://www.sciencedirect.com/science/article/pii/S0378113523002729, Repozitorij Univerze v Ljubljani – RUL, DOI: 10.1016/j.vetmic.2023.109918. [COBISS.SI-ID 174177027] **IF 3,3**.

Awards and Appointments

1. Helena Motaln, Urša Čerček, Boris Rogelj, Excellent in science 2023, ARIS, for publication Motaln et al. Brain, 2023.Oct 3;146(10):4088-4104. doi: 10.1093/brain/awad130

2. Jerica Sabotič: EBTNA Award for Poster Presentation, Ljubljana, European Biotechnology Congress 2023, poster presentation entitled *Diabrotica v. virgifera* resists the effect of entomotoxic fungal protease inhibitors in food

3. Stojanov Spase Krka special recognition award for doctoral dissertation "Engineering of fluorescent vaginal Lactobacillus species for their monitoring in nanofibers and cell models", Novo mesto, Krka d.d.

Organization of conferences, congresses and meetings

1. Berlec Aleš, Cell4Chem 3rd Mid-Term Meeting, Institute Jožef Stefan, Ljubljana, 10–11 October 2023
2. Čerček Urša, Motaln Helena, Nimac Jerneja, Rogelj Boris, SiNAPSA Neuroscience Conference '23, Ljubljana, 28–30 September 2023
3. Sabotič Jerica, NMR in microbial glycobiology: mini symposium, Institute Jožef Stefan, Ljubljana, 24 January 2023

INTERNATIONAL PROJECTS

1. ALS CURE Project; Impact of TDP-43 and FUS Phosphorylation Status in Disease
   Prof. Boris Rogelj
   Als Cure Project, Inc.
2. COST CA18238; Ocean4Biotech - European Transdisciplinary Networking Platform for Marine Biotechnology
   Dr. Jerica Sabotič
   COST Association Aisbl
3. COST CA19123; PHOENIX - Protection, Resilience, Rehabilitation of Damaged Environment
   Prof. Aleš Berlec
   COST Association Aisbl
4. Increasing NK Cell Cytotoxicity Through Modulation of Cystatin F
   Dr. Milica Perišić Nanut
   Slovenian Research Agency
5. Characterization of Novel Fungal Lectin
   Dr. Jerica Sabotič
   Slovenian Research Agency
6. COST CA21135; IMMUNO-Model: Modelling Immunotherapy Response and Toxicity in Cancer
   Dr. Milica Perišić Nanut
   COST Association Aisbl
7. Virtual Mobility for Project COST CA18238; Optimising the Analysis of Selectively Labelled Biofilm Communities to explore the Composition of Natural Biofilms
   Dr. Jerica Sabotič
   COST Association Aisbl
8. Evaluation of the effects of cystatin F inhibition in experimental autoimmune encephalomyelitis: Potential therapeutic approach for multiple sclerosis (TARGET-CYSF-MS)
   Dr. Milica Perišić Nanut
   Slovenian Research Agency

RESEARCH PROGRAMMES

1. Pharmaceutical Biotechnology: Knowledge for Health
   Prof. Janko Kos
2. Marine and microbial biotechnology
   Dr. Jerica Sabotič

R & D GRANTS AND CONTRACTS

1. Bactericidal nanoblades: a proof-of-concept approach for bimodal chemo-mechanicaleradication of persistent biofilms
   Dr. Jerica Sabotič
2. Cathepsins B and X in breast cancer stem cells – molecular targets and relevance for antitumor therapy
   Asst. Prof. Ana Mitrović
3. Intra-biofilm dynamics of Campylobacter with other bacteria: effects on biofilm formation and composition with a view to the design of innovative control strategies
   Dr. Jerica Sabotič
4. Recombinant probiotics as bio-alternative antimicrobial approach against Clostridioides difficile
   Prof. Aleš Berlec

5. Molecular mechanisms of specificity in regulation of secretion and action of muscle-derived cytokines
   Prof. Boris Rogelj
6. Nanofibers for codelivery of selected microbiota cocktails and antimicrobials for local treatment of vaginal infections
   Prof. Aleš Berlec
7. Microplastics as a vector of microbial contamination, infection and resistance: the case of Campylobacter bacteria in poultry meat production
   Dr. Jerica Sabotič
8. A new class of alanine-rich motifs that mediate liquid-liquid phase separation in RNA-binding proteins
   Prof. Boris Rogelj
9. Electroporation as a potentiator of antimicrobial efficacy
   Dr. Jerica Sabotič
10. Bacterial Biofilm Formation Inhibitors: A Novel Approach to Combat Antimicrobial Resistance
    Dr. Jerica Sabotič
11. Nuclear transport defects in frontotemporal dementia
    Prof. Boris Rogelj
12. Cystatin f as a mediator of immunosuppression in glioblastoma microenvironment
    Dr. Milica Perišić Nanut
13. FunContrAPest: Novel Fungal Proteins as Biopesticides for Control of Challenging Invasive Alien Agricultural Pests
    Dr. Jerica Sabotič
14. Small protein blockers of IL-23/IL-17 axis as intestinal inflammation inhibitors secreted by probiotic bacteria
    Prof. Aleš Berlec
15. Targeting protein phase separation and aggregation in neurodegenerative TDP-43 proteinopathies
    Prof. Boris Rogelj
16. Translational irregularities underlying C9orf72-associated amyotrophic lateral sclerosis and frontotemporal dementia
    Prof. Boris Rogelj
17. On-demand Contact Based Antimicrobial Surfaces: Human and Environmental Safe Infection Control Strategy
    Dr. Milica Perišić Nanut
18. Exploring the biofilm phenotype and surfactome of Listeria monocytogenes to predict its persistence and pathogenicity potential using machine learning
    Dr. Jerica Sabotič
19. Selective mechanical removal of bacterial biofilms by conjugated magnetic nanoparticles
    Prof. Aleš Berlec
20. Antibacterial alloys: development by additive 3D manufacturing, characterization and clinical applications
    Asst. Prof. Helena Motaln
21. Plasma VUV and UV radiation – a method for successful deactivation of Aflatoxins
    Asst. Prof. Helena Motaln
22. Engineering lactic acid bacteria for tumour targeted delivery of anticancer agents
    Dr. Abida Zahirović
23. NK cell therapy for glioblastoma: Modulating cystatin F to improve efficacy
    Dr. Emanuela Senjor
24. Cell4Chem: Engineering microbial communities for the conversion of lignocellulose into medium-chain carboxylates
    Prof. Aleš Berlec
    Ministry of Higher Education, Science and Innovation
25. Marine and microbial biotechnology
    Dr. Jerica Sabotič
    Slovenian Research Agency

VISITORS FROM ABROAD

1. Dr. Stefano Cacciatore, ICGEB - International Centre for Genetic Engineering and Biotechnology, Cape Town, South Africa, 22 March 2023
2. Giulia Candini, PhD student, University of Bologna, Bologna, Italy, 1 January to 31 March 2023
3. Dr. Lionel Muller Igaz, School of Medicine, University of Buenos Aires, Buenos Aires, Argentina, 4–5 September 2023.
4. Dr. Stefan Toepfer in Dr. Szabolcs Toth, Univerza MATE, Godollo, Hungary, 10 October 2023

STAFF

1. ResearchersProf. Aleš Berlec
2. Prof. Janko Kos*
3. Asst. Prof. Helena Motaln
4. Dr. Milica Perišić Nanut
5. **Prof. Boris Rogelj, Head**
6. Dr. Jerica Sabotič
7. Prof. Borut Štrukelj*

Postdoctoral associates

8. Dr. Nikolaja Janež
9. Asst. Prof. Ana Mitrović
10. Dr. Tina Vida Plavec
11. Dr. Emanuela Senjor
12. Dr. Spase Stojanov
13. Dr. Nives Škorja Milić
14. Dr. Abida Zahirović

Postgraduates

15. Karolina Belingar, B. Sc.

16. Urša Čerček, B. Sc.
17. Anja Dremelj, B. Sc.
18. Jerneja Nimac, B. Sc.
19. Petra Štravs, B. Sc.
20. Nika Zaveršek, B. Sc.

Technical officers

21. Manca Černila, B. Sc.
22. Tjaša Peternel, B. Sc.
23. Dr. Jure Pohleven
24. Klementina Polanec, B. Sc.

Technical and administrative staff

25. Vahida Suljić
26. Maja Šimaga, M. Sc.
27. Tadeja Tumpej, B. Sc.

Note:

* part-time JSI member

DEPARTMENT OF ENVIRONMENTAL SCIENCES O-2

The Department of Environmental Sciences investigates the interplay of physical, chemical, and biological processes shaping our environment, as well as the impact of human activities on the environment. Our research is interdisciplinary and multidisciplinary, conducted in several areas such as environmental analytical chemistry, substance and element cycling in the environment, microbial systems ecology, environment, health and food, environmental technologies, and environmental monitoring. We also work on the development of technical solutions for environmental problems and environmental management. The department also includes ISO-FOOD – ERA Chair for Food Quality, Safety and Traceability Using Isotopic Techniques, the Mass Spectrometry Infrastructure Center (CMS), the Infrastructure Center for Ionizing Radiation Measurements (ICMIS), and ELME – Ecological Chemical Laboratory with a Mobile Unit.

Head:
Prof. Milena Horvat

Analytical chemistry of the environment and biological systems

Inorganic analysis and speciation

The role of trace chemical elements and their impact on the environment and living organisms depend not only on their total concentrations but also on the chemical forms in which they are present. Therefore, we focus on developing new analytical procedures for determining elements and their chemical species in environmental and biological samples. In the speciation of trace elements, we have initiated a systematic study on the impact of the operation of galvanizing in Unior on the health of workers, residents of Zreče, and the environment in the wider area of Zreče. We are developing and optimizing new analytical methods for the speciation of chromium in biological and environmental samples.

Within the MSCA STROMASS scholarship, we have developed a rapid method for determining Sr-90 in water and milk samples using ICP-MS, enabling a faster analysis of a larger number of samples, especially in emergency situations. The method has been tested in an inter-laboratory comparison by the IAEA with excellent results.

For an accurate determination of the isotopic composition of Cd in seawater, we began to develop a new analytical method. We also developed a method for determining the isotopic ratio of 87Sr/86Sr in cement and a method for analyzing the stable isotopes of mercury in water samples.

Within the national project WellBEEing, we are developing analytical procedures for the identification and quantification of inorganic nanoparticles and microplastics in bee samples and pollen, and we are optimizing the sample preparation using microwave digestion for the determination of the multi-element composition in insect samples with an ICP-MS analysis.

In the GMOS-Train and SI-Hg projects, we focused on the measurements of atmospheric Hg species. We assessed the existing parameters for the speciation of atmospheric Hg, including sampling, preconcentration, and calibration. The suitability of sampling and preconcentration procedures (sorbent traps, sorbent membranes, impinger solutions, and denuders) was tested for their suitability for a traceable speciation of atmospheric Hg.

Organic analysis

We synthesized molecularly imprinted polymers (MIPs) designed for the extraction of the bupivacaine drug from blood samples. While this material showed promising results at higher concentrations, MIPs for determining lower concentrations of bupivacaine proved unsuitable due to the persistent release of deeply bound bupivacaine at trace concentrations. We addressed this issue by modifying the MIP synthesis, replacing the bupivacaine template with analogs similar in chemical structure and binding properties.

Additionally, we developed a reference method for the local anesthetic bupivacaine and sedative dexmedetomidine in blood plasma, utilizing nonspecific interactions for solid-phase adsorption. We then applied this method to pharmacokinetic studies on anesthetized dogs following single intravenous or perineural administration of drugs. Such studies are important for improving pain management in dogs after tooth extraction.

We optimized, simplified, and revalidated the analytical method for determining bleomycin in blood and tumor samples. In this context, we incorporated advanced extraction materials and transferred the method to a pressure-assisted extraction system on 96-well microtiter plates. During the method revalidation, we investigated

the analyte stability in various matrices and established the appropriate method quality control. The method was further adapted for determining bleomycin at trace concentrations in in-vitro systems.

In collaboration with the Department of Condensed Matter Physics (F5), we explored the use of volatile organic compounds in lung cancer diagnostics, associated analytical techniques, and challenges related to the processing and standardization of exhaled breath samples. We transferred and optimized the established methodology for extracting volatile organic compounds for analysis from exhaled breath. To obtain profiles of VOCs from various materials used for capturing exhaled breath, we employ headspace solid-phase microextraction (HS-SPME) coupled with gas chromatography and mass spectrometry (GC-MS).

We developed a new method for analyzing stable carbon isotopes in illicit drugs, enabling the tracing of their origin. The study suggests that the stable carbon isotope analysis can be useful for tracking the sources of illicit drugs, such as morphine, isolated from wastewater.

Metrology

Metrology in the traditional analysis of stable isotopes of light elements encompasses various activities:

- Participation in inter-laboratory comparisons at the highest metrological level. In 2023 the final report on CCQM-204: Comparison on CO_2 isotope ratios in pure CO_2 was produced, providing recommendations to promote more consistent measurement practices and achieve greater consistency in future inter-laboratory tests.
- Within the STELLAR project, we conducted analyses on prepared synthetic isotope mixtures and determined the isotopic content ratios $n(^{13}C)/n(^{12}C)$ on samples with known or certified $d^{13}C$ values to enable the tracking of stable isotope measurements expressed as delta values to SI units.
- We investigated the isotopic stability of 43 selected volatile organic compounds, covering various functional groups. We focused on the compounds commonly found in aromatic profiles of fruits, truffles, and fish. Our main goal was to identify volatile organic compounds with great potential for use as laboratory reference materials.
- In collaboration with the University of Indiana, the U.S. Geological Survey (USGS), Caltech, Fondazione Edmund Mach (FEM), the Helmholtz Centre for Environmental Research (UFZ), and Atmospheric Sciences, we began developing ten pure liquid volatile organic compounds (VOCs) to serve as reference materials for stable isotopes of light elements.

The department is also actively involved in European metrology networks such as METROFOOD-RI, where the JSI is the coordinator of the Slovenian node (METROFOOD-SI), and the European Metrology Research Programme (EURAMET) metrology network for food safety and sustainability (EMN-FOOD) and pollution monitoring (POLMO – European Metrology Network for Pollution Monitoring).

Within the GMOS-Train and SI-Hg projects, we continued work in the metrology of atmospheric Hg species measurements. Together with colleagues from the University of Utah, we evaluated gas-permeable tubing for gaseous oxidized mercury (HgII) and gaseous elemental mercury (Hg0). We compared the efficiency of these gas-permeable tubes with the performance of our newly developed calibration system based on non-thermal plasma oxidation of elemental mercury to oxidized Hg species in the presence of specific reaction gases (oxygen, chlorine, bromine). This calibration approach was confirmed using NIST SRM 3133, making it the first SI-traceable calibration procedure for HgII species at environmental concentrations. Within the SI-Hg project, we compared multiple calibration methods for gaseous oxidized and gaseous elemental mercury in the atmosphere, including our calibration method for gaseous oxidized mercury based on cold plasma oxidation. We also tested and compared in-situ measurements of atmospheric mercury fractions using four commonly used commercial instruments for Hg speciation.

Within the EPM project MetroPOEM, we focused on the metrology of Cd isotope ratio measurements in seawater. We tested the capabilities of different ICP-MS systems (ICP-QMS, ICP-MS/MS, and MC-ICP-MS) for accurate and precise measurements of isotope ratios and evaluated their contributions to measurement uncertainty.

As part of our role as the national reference laboratory for determining trace elements in organic and inorganic materials, we participated in inter-laboratory proficiency testing schemes SIM.QM-S12 and APMP.QM-P41 Trace Elements in Natural Water, APMP.QM-S19 and P40 Toxic Elements in Seafood, CCQM-K158 Elements and Inorganic Arsenic in Rice Flour, and CCQM-K160 Pt Group Elements in Automotive Catalyst.

Nanomaterials in biosensors

In collaboration with the National Chemistry Institute, Ljubljana, and the Hebrew University of Jerusalem, we investigated the deposition, testing, and antioxidant properties of ultra-thin (1-3 nm) mono-, di-, and tri-layer hybrid organic-inorganic polyhedral oligomeric silsesquioxanes (POSS) on Inconel 617. We anticipate that such coatings will have significant potential as base coats for spectrally selective absorber coatings for the concentrated

solar power (CSP) hybrid absorber technology. The production, synthesis, characterization, enlargement, and properties of 2D nanomaterials were also studied within various international and national projects. Findings were published in the *Nano Select* journal.

We also collaborated with the Department of Electronic Ceramics (K5) to develop thin- and thick-film nanomaterials using screen printing methods on two different substrates (Al_2O_3 and LTCC) and used them as biosensor platforms based on transducers for the detection of various target analytes. In our work on electrochemical biosensors for SARS-CoV-2 and cancer research, we collaborated with the National Institute of Biology. Within this framework, we prepared peptides and bioconjugates for targeting cancer cells and developed strategies for immobilizing biomolecules on nanomaterials.

Within the GMOS-Train project, we began developing a biosensor for Hg detection based on specific bacterial proteins, which will be tested in various aquatic media.

In collaboration with the Faculty of Health Sciences at the University of Ljubljana, we were involved in research on the antibacterial and antiviral properties of textile surfaces coated with nanomaterials. In this context, we evaluated the antibacterial properties of various textile materials intended for prosthetic inserts, coated with CuO nanoparticles. The x-dry material showed the most promising results due to a slow release of Cu, prolonged antibacterial action, and its compatibility with human cells. Additionally, we participated in a study aiming to develop a new multilayer coating with poly(allylamine hydrochloride) (PAH) and immobilized ZnO nanoparticles to create effective antibacterial and biocompatible fabrics from cotton, polyester, and nylon. Results demonstrated successful formation of the PAH/ZnO coating with complete immobilization of ZnO nanoparticles on the coated textile, preventing the release of nanoparticles from the textile surface. Due to better adhesion of ZnO nanoparticles, cotton exhibited slightly greater antibacterial effectiveness than nylon and polyester.

Biogeochemistry and climate change

We assessed the potential of stable isotopes of magnesium (Mg) and strontium (Sr) as novel hydrogeochemical tracers in the Ljubljanica karst aquifer. We analyzed their presence in water, rocks, and soils and conducted laboratory experiments on soil and rock leaching. The research showed that soils, especially during rainy periods, have a significant impact on the Mg^{2+} balance in the aquifer and can substantially affect the Mg/Ca ratio, which could significantly influence the interpretation of groundwater based on traditional geochemical tracers.

In collaboration with colleagues from the University of Zaragoza (Spain), we studied the impact of global warming on CO_2 sink processes in river systems on the Iberian Peninsula. We also collaborated with the Mendel University in Brno (Czech Republic) and the University of Arizona (Tucson, USA) to investigate carbon fluxes and aquifer weathering in the Czech silicate catchment area.

Within the UPTAKE project, we examined the uptake and distribution of metal-doped polystyrene nanoplastics and their impact on the uptake and distribution of elements in hydroponically grown tomato plants. The results showed that tomato roots contained the highest concentrations of selected elements and nanoplastics, while the lowest concentrations were recorded in the fruits.

We also participated in the research within the Danube Hazard m3c project, where we studied the influence of water hardness on the concentrations of potentially toxic elements in river waters with high hardness. In the project New Climate Change Indicators in Stalagmites in Slovenia, we continued paleoclimatic studies in the Small Cave in Dovček in southeastern Slovenia. Based on the $\delta 18O$ isotopic records in stalagmites, we determined temperature fluctuations in the cave during different periods.

Through collaboration with the Velenje Coal Mine, we investigated the mechanisms of gas release and the origin of gas trapped in lignite layers at active mining faces in the Velenje Basin.

In the field of archaeology, using stable isotopes of C and N, we examined the causes of changes in the Holocene environment and human adaptation to these changes. Our research revealed rapid environmental changes in the SE Alps and their impact on the lake formation and dietary patterns of cave bears. This new method of stable carbon and nitrogen isotope analysis provides insights into the past and understanding of cave bear paleobiology.

Additionally, we participated in the artistic project One Tree ID in collaboration with KONTEJNER company from Zagreb, Croatia, where we identified volatile organic compounds in Ginkgo biloba trees for perfume creation.

Water cycle

Based on the data on the isotopic composition of precipitation ($\delta 18O$ and $\delta 2H$) in the Mediterranean, we developed a model that can reproduce isotopic composition of precipitation in the areas where data are scarce or unavailable. Local meteoric water lines (LMWLs) were calculated using linear regression for the stations with at least 4-year datasets between 2000 and 2015, and then interpolated across the region using statistical methods and machine learning. Differences in interpolated LMWLs highlight the importance of using spatially continuous

estimates of lines compared to the aggregating data from distant stations. If data are unavailable, we recommend using the values presented in the interpolated map.

On the Idrijca River, we continued sampling and measuring various forms and fractions of mercury (Hg) and various water parameters. We conducted a full-day sampling on the Idrijca River to assess daily cycles of Hg speciation and their impact on the bacterial community structure. Pilot sampling was also conducted in the Bay of Trieste, which will be the subject of further research. Water discharges from the Idrijca River still introduce significant amounts of Hg into the Bay of Trieste, with the species ratios of Hg depending on location, environmental conditions, and biogeochemical processes in rivers and the bay.

In collaboration with the Ivan Rakovec Institute of Paleontology, ZRC SAZU, we determined the isotopic composition of Sr in sediments in the area where remains of cave bears were found. These data will help us understand the changes in the Sr isotopic composition in the teeth of cave bears.

In the late summer of 2023, severe floods in the Meža Valley caused a displacement of contaminated sediments and soils. We checked the concentrations of potentially toxic elements (Pb, Zn, Cd, As, etc.) in ten sediment samples and found that the levels of Pb and Zn exceed the threshold values for soils. Using the isotopic composition of Pb and Sr, we confirmed that Pb was present in the sediments of natural origin. The floods transported contaminated sediment all the way to Dravograd and further on along the Drava River.

Air research

In the ARIS project CAEmissionMonitor, we utilize time series of radon concentrations in outdoor air to assess the height of the atmospheric mixed layer, enabling the determination of primary emission rates and secondary production of carbonaceous aerosol particles. Radon measurements are conducted hourly at the ARSO Ljubljana Bežigrad meteorological station, with the project being part of the larger international project called Sarajevo Aerosol Experiment: Composition, Sources and Health Effects of Atmospheric Aerosol (SAAERO, EU H2020).

Figure 1: Slope (A) and intercept (B) of the interpolated map of the Mediterranean local meteoric water lines (LWMLs) produced by the RF machine learning algorithm. The colored circles with a white and black outline indicate the LMWLs of the precipitation monitoring stations belonging to different quality categories according to the number of data recorded at each station during 2000–2015 (Hatvani et al., 2023).

In the Slovenian-Japanese project Role of Environmental Parameters on Microbial Community Structure in Buildings in Slovenia and Japan, we investigate the influence of building characteristics and ventilation methods on the exchange of indoor air with the outdoor environment. Participants conduct research in selected educational institutions in Slovenia and Japan, using radon and carbon dioxide as indicators of ventilation efficiency.

We concluded the SRNSFG project Radon Mapping and Radon Risk Assessment in Georgia, where we investigated the radon levels in air in buildings, water, and soil in selected areas in Georgia.

As part of the GMOS-Train project, we carried out various activities in the field of air research. We organized a workshop in Reno, Nevada, USA, addressing the current challenges and new approaches in air monitoring and analysis, with a focus on mercury. Additionally, we conducted a research involving air quality assessment, mercury emissions monitoring, and identification of mercury air pollution sources.

Furthermore, we participated in a study on concentrations and isotopic composition of CO_2 in the air in Croatia, where we determined the influence of marine and biogenic CO_2 as well as the contribution of CO_2 from fossil fuels in the atmosphere.

Colloid biology

Within the SURFBIO project (Twinning Funding Scheme), we conducted several training activities with a consortium of research partners, including the IJS, focusing on expertise in material surfaces, bacterial communities, and colloidal biology. We initiated the establishment of a research and innovation hub aimed at fostering new scientific collaborations and industrial partnerships.

Under the GREENER project, we utilized artificially constructed multicellular structures to biotransform complex polymer compounds, such as lignin, into value-added compounds. This innovation has been described in a newly submitted patent application.

Figure 2: SURFBIO INNOVATION HUB: As part of SurfBio, an EC funded twinning project, the JSI established a new innovation hub, a collaborative network of several European research institutions, performing fundamental and applicative research in colloid biology, to provide solutions for bioremediation, agronomy, biotech and medicine.

Within the BIOSYSMO project, we unite forces with our partners to model various metabolic pathways and reconstruct them with our method of assembling bacterial consortia to form artificial consortia capable of performing modeled biotransformation processes.

Our approach to building artificial bacterial consortia has been implemented in several other ongoing projects funded by the Public Agency for Research Activities of the Republic of Slovenia. Witin the international project BE MERMAiD, we demonstrated that artificially constructed cellular aggregates form significant niches for mercury methylation.

In the international project CROSSING, we analyzed interactions between bacteria and nanoparticles as well as bacteria and metal surfaces with different physical properties.

To promote the scientific field of colloid biology, we successfully launched our website and began disseminating scientific content on social media platforms.

In collaboration with the National Institute of Biology, we investigated the microbial community in the biofilm on the walls of the reactor vessel at the TRIGA reactor of the Jožef Stefan Institute, which could serve as a model environment for analyzing the response of microbial communities to exceptional events related to radioactive contamination.

Environment, food and health

Human biomonitoring

Within the MerFish project, a 3-month exchange of doctoral student Neža Palir took place at the University of Sao Paulo (USP), Ribeirao Preto in Brazil. The first month was dedicated to sampling in the Amazon, where 1216 volunteers were surveyed, followed by two months of work in the university laboratory. Among the results was the publication "Risk characterization of human exposure to polycyclic aromatic hydrocarbons in vulnerable groups".

Continuing the project, we investigated interactions between genes and the environment. Using statistical models, we explored connections between maternal genotypes, fetal sex, number of pregnancies, and lead concentrations in maternal and umbilical cord blood. We found a correlation between maternal APOE ε2 allele and higher levels of Pb in maternal and umbilical cord blood, and between APOE ε4 allele and lower levels of Pb, especially in mothers with female fetuses.

In relation to genetic interactions, we studied ten gene polymorphisms for the enzyme delta-aminolevulinic acid dehydratase (ALAD) and their association with lead concentrations in the blood and urine of adult males. We observed some associations between individual polymorphisms and Pb concentrations in blood and urine.

Within the national HBM program (HBM2018-24), we continued with the recruitment and sampling of children and adolescents to assess exposure to environmental chemicals. We successfully completed sampling of children and adolescents in Zasavje and started recruiting new participants in the areas of Idrija, Posočje, and Koper.

We also completed recruitment of pregnant women and collection of biological samples during pregnancy and after childbirth for women and their newborns from the Celje area. We determined trace elements in maternal blood, plasma, urine, and hair samples.

In collaboration with the University Medical Centre Ljubljana (UKCL) within the ARRS project "Impact of endocrine disruptors on childbirth, infertility, and ovarian cancer in Slovenia", we completed the analysis of chemicals in collected biological materials from pregnant women.

As part of the PARC project (Partnership for Assessment of Risk from Chemicals), we participated in the preparation of materials for harmonizing studies at the European level and standardized the questionnaire of the Slovenian national HBM program. Internally, we continued data processing of the HBM4EU project and we are establishing sustainable data infrastructure in collaboration with the Department of Knowledge Technologies (E8).

The department is also actively involved in the EIRENE PPP, aiming to prepare a consolidated European research infrastructure enabling the development of advanced technologies and complementary services for characterizing complex environmental exposures and their impact on the European population.

In the study following the release of chromium trioxide from the Unior Zreče plant, we investigated its effects on human health. We found minimal exposure of workers and residents, reducing the risk to human health, animals, and the environment.

Figure 3: As part of the obligations arising from the Minamata Convention, we summarized data on the developed understanding of risks to human health due to mercury and published them in an article available at https://doi.org/10.1007/s13280-023-01831-6. From this, it follows that the department will continue to actively participate in the research, especially where the risk is greatest, as also shown in the above graph.

Participatory research and citizen science

The URBANOME project focuses on integrating health and quality of life into urban policies and citizen activities. Through the Urban Living
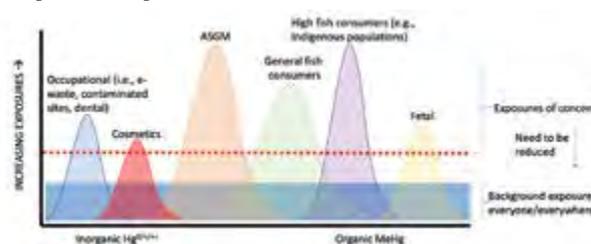
Lab, we examined exposure to urban stressors during cycling and developed measures together with numerous stakeholders to reduce this exposure.

Within the INQUIRE project, air quality sampling is conducted in enclosed spaces in 30 households in Celje. The aim is to identify various chemical and biological factors and strategies to promote healthy homes.

The RadoNorm-SLO project focuses on measuring radon concentrations in Bela krajina, where this risk is increased. Volunteers conducted measurements and monitored air quality in their homes, helping us understand the impact of geophysical parameters on the radon concentration.

Wastewater epidemiology

Wastewater-Based Epidemiology (WBE) enables the acquisition of objective data on the use of psychoactive drugs in the population. We participated in the annual monitoring of illicit drug use in seven Slovenian cities within the SCORE network. The highest biomarker concentrations were observed in Ljubljana, Velenje, and Koper. We also analyzed trends in antidepressant use and found that their use increased, without clear spatial patterns associated with the COVID-19 pandemic.

Through the development of analytical methods, we obtained retrospective trends in antidepressant use in Slovenia. Our method, based on solid-phase extraction, allows simultaneous determination of multiple compounds with low quantification limits. Additionally, we examined the presence of new psychoactive substances in wastewater from educational institutions, finding that the most common synthetic stimulants, 3-MMC, ephedrine, and ethcathinone, are particularly prevalent in the capital city of Slovenia.

Figure 4: Process of examining wastewater from educational institutions in Slovenia for the presence of new psychoactive substances

In collaboration with researchers from Italy and Australia, we conducted three international studies on new psychoactive substances in wastewater. We confirmed the presence of numerous new psychoactive substances, highlighting the importance of the WBE approach in monitoring changing drug use profiles.

Other studies

We conducted an assessment of the ecotoxicity of ten residues of permitted and illicit drugs using the ECOSAR software and an algae growth inhibition test. Despite the predicted effects on aquatic plants, we did not observe significant growth inhibition when exposed to algae.

Within the SECURE project, we developed strategies for separating radionuclides for the production of radiopharmaceuticals. Initial results are promising as we achieved excellent separation yields.

In collaboration with the Institute of Oncology Ljubljana, we are developing new analytical methods for studying metal imbalance in trace levels as a biomarker for biliary tract cancer.

Through a clinical study, we aim to determine serum levels of Cu, Zn, and Fe and their mutual relationship. We are also collaborating with researchers from France and Canada on a study of safe long-term electrical stimulation of neurons.

The use of the conductive polymer PEDOT:PSS has proven to be a promising approach for extending the lifespan of electrodes. In a previous study, we developed and optimized a methodology for determining the profiles of volatile organic compounds in sebum as a non-invasive biomarker for Parkinson's disease. The goal is to use these profiles to improve Parkinson's disease diagnostics.

Activities of ERA Chair ISO-FOOD

The research on stable isotopes of light elements has significantly contributed to food authenticity, quality, and sustainability. A key focus has been in the development of a robust traceability system, including method optimization, the establishment of a stable isotope database for authentic food samples IsoFoodTrack (www.isofoodtrack.ijs.si), and statistical model development to verify correct labelling either country or type of production. This system has been applied and tested on selected commodities in real-life applications within different EU projects, including fish (FishEUTrust), spices such as paprika, cinnamon, and saffron (PROMEDLIFE), and pork meat. Additionally, the collected data are integrated into the e-components in FoodTraNet, METROFOOD-RI, and FNS-Cloud projects, enhancing food transparency and traceability at the European level. Furthermore, research on the quality of dry-cured ham, conducted in collaboration with the KRAS d.o.o. company, explores the impact of different storage conditions to ensure product quality and optimize preservation methods.Given the increasing use of purified wastewater in agriculture, we have examined the risks of introducing harmful chemicals into crops. The results showed a low risk

to human health but will aid in reevaluating the risks. We are also assessing the quality of tomatoes using various methods, with the results currently being processed.

Adapting agricultural practices to climate change is crucial for preserving natural resources and limiting crop losses. In a study examining nitrogen uptake in drought conditions in two varieties of chili peppers, we found that restricting irrigation and fertilization did not negatively impact the yields and fruit quality, enabling significant savings in water and fertilizers.

The THEROS project focuses on modernizing the verification of organic and geographical indication of food products and preventing counterfeiting. It utilizes technologies such as Earth observation, photonics, the Internet of Things, DNA authenticity, blockchain, and artificial intelligence to ensure traceability and quality control. It proposes a comprehensive blockchain-based traceability system and dynamic digital product passport for enhanced data security and transparency. The project will be tested through pilot demonstrations in multiple countries, involving all relevant stakeholders and addressing various food products.

With the population growth and climate change, the use of purified wastewater for irrigation is becoming a more realistic alternative. It is important to understand the risks associated with the introduction of harmful chemicals into crops. In this study, we examined the intake of contaminants of emerging concern (CECs) in tomato fruits grown in soil and hydroponics. The results indicate the presence of BPS, 2,4-BPF, and naproxen in tomatoes, and the impact of CECs and growing conditions on the elemental content. The estimated dietary exposure to CECs is low and does not pose a risk to human health compared to toxicological reference values. The results will help in future risk assessments with further development of the knowledge on the toxic properties of CECs. We also assessed the quality of tomatoes based on various parameters, but the results are still being processed.

Figure 5: Assimilation of contaminants into tomatoes grown in lysimeters (soil) and hydroponics (soilless)

Environmental technologies

In collaboration with the Department of Nanostructured Materials, we investigated electrochemical pathways for recycling rare-earth-based permanent magnets (Sm-Co). We developed an environmentally friendly approach for recycling Nd-Fe-B magnets, involving selective chemical leaching using diluted citric and nitric acid. We found that 1 M citric acid was highly selective in leaching the Nd-rich phase, while exposure to nitric acid caused structural damage.

We concluded a study on the interactions of cement-organic compounds-radionuclides for a safe disposal of low- and intermediate-level radioactive waste within the EURAD H2020 project. We examined the PEG sorption on cement and the impact of superplasticizer PCE degradation on the mobility of radionuclides in a cementitious environment. We developed, optimized, and validated analytical methods for determining drug residues in wastewater and surface waters. We found that activated sludge and membrane bioreactors are effective in removing drug residues, while the MBBR reactor is less efficient.

We identified environmental risks due to drug residues in surface waters. We investigated the occurrence and origin of drug residues in the Ljubljana aquifer and found that they were more prevalent downstream from urban areas. We also studied advanced treatment of wastewater with cold atmospheric plasma (CAP) and continued research on the biological degradation of tritium and wastewater treatment with cold plasma.

We collaborated in the development of a system for cleaning organic pollutants in paper production and prepared new research projects for the biotransformation of olive mill waste and the production of new types of fertilizers. In collaboration with the Institute for Construction, we examined the environmental properties of geotechnical composites for the revitalization of mining areas, finding that some composites are suitable for construction as an alternative to untreated materials.

Environmental management, environmental impact assessment and risk assessment

Within the SmartMOVE project, we analyzed environmental impacts due to the introduction of dynamic transport as a sustainable alternative to car mobility. We studied employee transport from home to work and back, conducted by GoOpti company vans, on routes including Kamnik – Mengeš – Domžale – BTC Ljubljana area – UKC Ljubljana, and Kranj – Šiška (Verovškova Street) – BTC Ljubljana area – UKC Ljubljana. We used GoOpti business data and user survey results to analyze differences in the travel time, and assess the reduction in CO_2, NOx, and particulate emissions. As part of the same project, we developed a method for awarding a mobility certificate to companies actively advocating for sustainable mobility.

We prepared criteria and a decision model for obtaining the certificate and adjusted the questionnaire multiple times to ensure that the certificate not only verifies but also encourages mobility improvements in companies.

In the STAGES project, we analyzed the potential for renovating a theater building towards sustainable development. The work included an evaluation and situational analysis plan and showed potential for infrastructure, organizational, and mobility improvements.

For UNIOR d.d., we conducted an investigation into an incident of liquid discharge from a chrome plating bath. We systematically searched for the causes of the event, analyzed management communication with stakeholders, and made recommendations for improving the management system.

In the PARC project, we continued to assess the existing legislative frameworks and processes for reducing workplace exposure, focusing on literature review and conducting a survey on the implementation of legislation in practice. Our goal was to identify knowledge gaps and propose legislative improvements.

Environmental monitoring

In collaboration with the Croatian Environmental Agency, we continued the measurements of organotin compounds and total mercury in marine and river waters. For Novartis, we performed numerous expert analyses of microelement contents in active pharmaceutical ingredients.

We continued regular measurements of precipitation isotope composition in Slovenia within the Slovenian Network of Isotopes in Precipitation (SLONIP) and updated the database with the latest values (https://slonip.ijs.si/).

The monitoring of natural radionuclides in the influence area of the former uranium mine on Žirovski vrh was conducted. We also participated in the external monitoring of the Krško Nuclear Power Plant (NEK) by determining strontium and tritium in environmental samples and tritium and radioactive carbon in NEK gas emissions.

The methods used for determining strontium, tritium, and radioactive carbon for monitoring purposes are accredited by the Slovenian Accreditation Body (SA LP-090). Mercury monitoring in precipitation for the Environment Agency of the Republic of Slovenia was continuously conducted in 2023 at the Iskrba meteorological measuring station, considered a pristine area.

In 2023 we conducted the monitoring of organotin compounds (OTCs) in the Slovenian part of the Adriatic Sea for the Environmental Agency of the Republic of Slovenia. The results showed good environmental conditions regarding OTCs.

Figure 6: SCIENCE FOR ALL: During the Researchers Night event the Group for Colloid Biology prepared several demonstrations of laboratory experiments to disseminate to the general public how scientific research is conducted in a laboratory. There is no lack of curiosity among young future scientists.

Education

The department is closely associated with the postgraduate studies at the Jožef Stefan International Postgraduate School, where most of the qualified staff are habilitated, and where master's and doctoral students are educated.

As part of the A-CINCH project, we created a virtual laboratory for radiochemistry, used for practical training and summer school for high school students.

Within the ITN MSCA project GMOS-train, we provided training in metrology, significantly improving the competencies of young researchers in the project and at the department.

As part of the TunTwin project, we organized a workshop on the analysis of stable isotopes in environmental and food samples, acquainting participants with the measurement methods and validation.

We also conducted the citizen science club with the Vodice Elementary School, preparing students for the role of citizen scientists and teaching them how to read cartographic data.

Infrastructure Center for Mass Spectrometry (CMS)

We actively engage in various projects, research, and measurements using fourteen different mass spectrometers. Our activities include the analysis of chemistry, biochemistry, pharmaceutical and synthetic chemistry, medical sciences, food control, and environmental protection. We particularly emphasize the studies and analytical procedures within research programs addressing pollutants in the environment, food control, and the impact of various substances on human health. Among our tasks are the speciation of chemical elements, determination of nanoparticle size distribution, spatial distribution of trace elements, toxicity of elements in food products, geochemical cycles, identification of biological molecules and therapeutic agents, quality and origin of food based on isotopic measurements, and tracking the transport and origin of pollutants in the environment.

Additionally, we conduct environmental monitoring measurements, contributing to the protection of human health and the environment, including air, surface water, and drinking water sampling. Last year, at the Department of Environmental Sciences, we performed compound characterization, identification of compounds in complex samples, development and validation of analytical methods, and participated in clinical research in collaboration

with industry partners, research partners, and other departments at the Jožef Stefan Institute.

We also initiated the implementation of the methods for a non-targeted analysis in biological matrices on the newly installed high-resolution tandem mass spectrometer Orbitrap ExplorisTM 240. Our achievements include the development of methods for determining exposure biomarkers in urine and phthalate metabolites in maternal milk. Additionally, we conducted analyses of the microbiological degradation of lignin and diesel oil, assessing the success of degradation involving different strains, identifying biodegradation products.

Infrastructure Center for Ionizing Radiation Measurements (ICMIS)

Together with the Department of Low and Medium Energy Physics, we manage the Infrastructure Center for Ionizing Radiation Measurements, which combines the infrastructure capabilities of both departments in the field of ionizing radiation measurements. It includes an extensive range of research equipment, special facilities, and accredited procedures for the radiological characterization of samples from the environment, industrial processes, production of construction materials, chemicals and pharmaceuticals, as well as materials from landfills and mining tailings. The infrastructure comprises spectrometric systems for detecting gamma, beta, and alpha rays, as well as complex systems for sampling and preparing

Figure 7: Installation of DELTA Q IRMS represents a significant advance in isotope analysis, integrating exceptional sensitivity, linearity, and stability. Connected with a wide range of Thermo Scientific™ peripherals, it aimed at supporting varying investigations including metrology, food science, environmental studies, and archaeology. Beyond the existing instrumental capabilities in Slovenia, DELTA Q is set to benefit a wide spectrum of research and industrial partners.

samples. The ICMIS, operates as the key national infrastructure for detecting ionizing radiation in the environment and the national standard for ionizing radiation in the international metrological system, supporting numerous public research organizations, universities, and state authorities in the Republic of Slovenia. The highest measurement capabilities of the ICMIS are entered into the Key Comparison Database (KCDB) of the International Bureau of Weights and Measures (BIPM).

Ecological Laboratory with a Mobile Unit (ELME)

Within the Department of Environmental Sciences, the Ecological Laboratory with a Mobile Unit (ELME) operates, providing support within the Civil Protection and Rescue Units in cases of environmental pollution and ecological emergencies involving hazardous substances. In 2023 ELME intervened seventeen times in the field due to pollution of surface waters and soils, industrial facility explosions, burning of waste, and other fires, as well as extensive flooding that affected Slovenia in August 2023. In addition to emergency interventions, members of the mobile chemical laboratory ELME verified their competence in two regular ELME exercises, in an international exercise for operations in emergencies involving hazardous substances at sea, and improved their knowledge and analytical procedures with the mobile chemical laboratory.

Figure 8: During the August floods in the Meža Valley, ELME conducted the measurements of toxic metals in sediment and debris samples.

Some outstanding achievements in the past year

1. Opening of the SURFBIO Innovation Center for Colloidal Biology and Surface Biology, operating within the department.
2. We organized the international conference "2nd ISO-FOOD Symposium: From food sources to health" in collaboration with the International Postgraduate School of the Jožef Stefan Institute.
3. In January 2023, the JSI/O-2 section submitted four new applications for the registration of calibration and measurement capabilities (CMCs) for review by EURAMET in category 5: Water, subcategory 5.1. Freshwater. These CMCs for Cd, Ni, Pb, and Se relate to river water and drinking water matrices and were supported by a successful participation in the EURAMET.QM-S11 study on Elements in River Water. After a thorough review, the CMCs were published in the BIPM KCDB in September 2023. This step increased the total number of CMCs for the section, which is a significant achievement.
4. Our study on exposure biomarkers in Slovenian children received the Excellent in Science 2023 award. Published in Environmental Pollution and presented at the National ARIS Day 2023, the study demonstrates an innovative high-performance workflow for non-targeted analysis, revealing children's exposure to various chemicals.

5. As part of the EU MSCA ITN GMOS-Train project, an important study was published in the journal Nature Geosciences. It suggests that most of the mercury from hydrothermal vents is diluted in seawater, indicating a small global hydrothermal flux compared to anthropogenic emissions.

6. Dr R. Chouhan, M. Štrok and colleagues published an article on anodic materials for microbial fuel cells in the journal Renewable and Sustainable Energy Reviews, addressing challenges and future directions in the MFC research.

7. Dr Ana Kovačič and Lidija Strojnik were honored with the summa cum laude distinction at the International Postgraduate School of the Jožef Stefan Institute for their outstanding academic achievements.

Some outstanding publications in the past year

1. Chouhan, Raghuraj S., Gačnik, Jan, Živković, Igor, Vijayakumaran Nair, Sreekanth, Van De Velde, Nigel Willy, Vesel, Alenka, Šket, Primož, Gandhi, Sonu, Jerman, Ivan, Horvat, Milena. Green synthesis of a magnetite/graphitic carbon nitride 2D nanocomposite for efficient Hg^{2+} remediation. Environmental Science: Nano. 2023, 10/10, 2658–2671, DOI: 10.1039/D3EN00367A.

2. Zamljen, Tilen, Lojen, Sonja, Zupanc, Vesna, Slatnar, Ana. Determination of the yield, enzymatic and metabolic response of two Capsicum spp. cultivars to deficit irrigation and fertilization using the N stable isotopes. Chemical and Biological Technologies in Agriculture. 2023, 10, art. no. 129, 11 pp. DOI: 10.1186/s40538-023-00501-9.

3. Runkel, Agneta Annika, Stajnko, Anja, Snoj Tratnik, Janja, Mazej, Darja, Horvat, Milena, Přibylová, Petra, Kosjek, Tina. Exposure of children and adolescents from Northeastern Slovenia to per- and polyfluoroalkyl substances. Chemosphere. 2023, vol. 321, 138096, pp. 1–11, DOI: 10.1016/j.chemosphere.2023.138096.

4. Palir, Neža, Stajnko, Anja, Snoj Tratnik, Janja, Mazej, Darja, Sešek-Briški, Alenka, France Štiglic, Alenka, Horvat, Milena, Falnoga, Ingrid, et al. ALAD and APOE polymorphisms are associated with lead and mercury levels in Italian pregnant women and their newborns with adequate nutritional status of zinc and selenium. Environmental Research. [Online ed.]. 2023, vol. 220, [article no.] 115226, pp. 1–16, DOI: 10.1016/j.envres.2023.115226.

5. Novak, Rok, Robinson, Johanna A., Kanduč, Tjaša, Sarigiannis, Dimosthenis, Kocman, David. Simulating the impact of particulate matter exposure on health-related behaviour: A comparative study of stochastic modelling and personal monitoring data. Health & Place. 2023, vol. 83, [article no.] 103111, pp. 1–14, DOI: 10.1016/j.healthplace.2023.103111.

6. Kikaj, Dafina, Chambers, Scott D., Crawford, Jagoda, Kobal, Matjaž, Gregorič, Asta, Vaupotič, Janja. Investigating the vertical and spatial extent of radon-based classification of the atmospheric mixing state and impacts on seasonal urban air quality. Science of the Total Environment. 2023, vol. 872, [article no.] 162126, pp. 1–13, DOI: 10.1016/j.scitotenv.2023.162126.

7. Verovšek, Taja, Šuštarič, Ariana, Laimou-Geraniou, Maria, Krizman Matasić, Ivona, Prosen, Helena, Eleršek, Tina, Kramarič Zidar, Vlasta, Mislej, Vesna, Mišmaš, Boštjan, Stražar, Marjetka, Levstek, Meta, Cimrmančič, Bernardka, Lukšič, Simon, Uranjek, Nataša, Kozlovič-Bobič, Tjaša, Kosjek, Tina, Kocman, David, Heath, David John, Heath, Ester. Removal of residues of psychoactive substances during wastewater treatment, their occurrence in receiving river waters and environmental risk assessment. Science of the Total Environment. [Online ed.]. 2023, vol. 866, [article no.] 161257, pp. 1–9, DOI: 10.1016/j.scitotenv.2022.161257.

8. Kovačič, Ana, Gulin, Martin Rafael, Nannou, Christina, Koronaiou, Lelouda-Athanasia, Kosjek, Tina, Heath, David John, Maier, Mark S., Lambropoulou, Dimitra A., Heath, Ester. Aerobic degradation of tetramethyl bisphenol F (TMBPF) with activated sludge: kinetics and biotransformation products. Environmental Research. [Online ed.]. 2023, vol. 227, [article no.] 115790, pp. 1–10, DOI: 10.1016/j.envres.2023.115790.

9. Basu, Niladri, Bastiansz, Ashley, Dórea, José G., Fujimura, Masatake, Horvat, Milena, Shroff, Emelyn, Weihe, Pal, Zastenskaya, Irina. Our evolved understanding of the human health risks of mercury. Ambio. 2023, vol. 52, iss. 5, pp. 877–896.Masten Rutar, Jasmina, Strojnik, Lidija, Nečemer, Marijan, Bontempo, Luana, Ogrinc, Nives. Determining the authenticity of Spirulina dietary supplements based on stable isotope and elemental composition. Foods. 2023, vol. 12, no. 3, pp. 562-1-562-20. ISSN 2304-8158. DOI: 10.3390/foods12030562. [COBISS.SI-ID 140894723].

10. Cenikj, Gjorgjina, Strojnik, Lidija, Angelski, Risto, Ogrinc, Nives, Koroušić-Seljak, Barbara, Eftimov, Tome. From language models to large-scale food and biomedical knowledge graphs. Scientific Reports. 2023, vol. 13, article no. 7815, pp. 1–14, DOI: 0.1038/s41598-023-34981-4.

Awards and Appointments

1. GMOS-Train Science to Policy Workshop, 6–8 March 2023, Hereon, Hamburg, Germany.
2. Meeting of the Advisory Body of the SURFBIO Innovation Center, 8th March 2023.
3. TunTwin Summer School: Analysis of Light Stable Isotopes in Environmental and Food Samples: Technical Analysis and Validation of Methods, 18–20 April 2023, Ljubljana, Slovenia.
4. 2nd ISO-FOOD Symposium: From Food Sources to Health, in collaboration with the International Post-graduate School of the Jožef Stefan Institute, 24–27 April 2023, Piran, Slovenia.
5. Round Table for the Development of the SURFBIO Innovation Center, 20th June 2023.
6. Mercury and Human Health Workshop, as part of the GMOS-Train project, 18–20 September 2023, IFREMER, Nantes, France.
7. FoodTraNet Workshop & Teambuilding: The Barilla Experience, 3–5 October 2023, Parma, Italy.
8. Atmospheric Reactive Mercury Project New Measurement Methods Workshop, co-organized with the University of Reno, Reno, Nevada, USA, 9–15 October 2023.
9. Co-creation Living Labs Workshop: Pilots' Contextual Analysis, 10th October 2023, Florence, Italy.
10. Mercury: Bridging Science, Policy, and the Minamata Convention through Doctoral Training, Knowledge Lab, as part of COP5, 3rd November 2023, Geneva, Switzerland.
11. Opening of the SURFBIO Innovation Center for Colloid Biology and Surface Biology, 9th November 2023, Ljubljana, Slovenia
12. Winter School: Exploring Microbial Cell-Surface and Cell Colloid Interactions: Advanced Analytical Methods, 10th November 2023, Ljubljana, Slovenia

Organization of conferences, congresses and meetings

1. Polona Klemenčič was awarded the Krka Award for her master thesis on "Exposure to Cadmium in the Slovenian Population" in Novo mesto, September 2023.
2. Adna Alilović received the ERASS prize in the Specialty Section Award, Chemical Risk Assessment Research category, at the EUROTOX 2023 conference for her research on methyl mercury after ingesting tuna in Ljubljana, September 2023.
3. Dr Ana Kovačič and Dr Lidija Strojnik achieved Summa Cum Laude, a prestigious distinction at the Jožef Stefan International Postgraduate School, for their extraordinary academic excellence in Ljubljana, July 2023.
4. Cathrine Terro received the award for the best contribution at the 15th Jožef Stefan IPSS Conference in Kamnik, June 2023.
5. Anja Vehar was honored with the 10th Saubermacher Environmental Award for the best Master's thesis in the field of energy and the environment, titled "Monitoring the Efficiency of the Removal of Bisphenols from Wastewater in a Municipal Wastewater Treatment Plant" in Kidričevo, May 2023.
6. The CitieS-Health Project received an Honorary Mention in the European Union Citizen Science Award in Linz, Austria, September 2023.
7. Eirini Andreasidou won 1st Place in the Science Slam of the ISO-FOOD Symposium: From Food Source to Health in Portorož, Slovenia, April 2023.
8. Eirini Andreasidou was the winner of the Public Engagement Activity Competition at the FoodTraNet Summer School 2 in Almeria, Spain, June 2023.
9. Dr Aleš Lapanje and Dr Tomaž Rijavec achieved third place in the University of Ljubljana's Rector award for Best Innovation in the Researchers category, recognizing their outstanding work on the GumGuardian project in Ljubljana, October 2023.
10. Klara Žagar received an award for her contribution at the ISO-FOOD conference for her work on $\delta 18O$ and $\delta 2H$ fingerprinting of tap water, Portorož, April 2023.
11. Dr Žiga Tkalec and colleagues received Excellent in Science 2023 award for their paper "Suspect and non-targeted screening-based human biomonitoring identified 74 biomarkers of exposure in urine of Slovenian children", Ljubljana, November 2023

INTERNATIONAL PROJECTS

1. EMPIR - EDC-WFD; Metrology for Monitoring Endocrine Disrupting Compounds Under the Water Framework Directive
   Prof. Ester Heath
   Euramet E.v.
2. LIFE18 ENV/SI; LIFE HIDAQUA
   Prof. Radmila Milačič Ščančar
   European Commission
3. EMPIR; STELLAR; Stable Isotope Metrology to enable Climate Action and Regulation
   Prof. Nives Ogrinc
   Euramet E.v.
4. EMPIR; Si-Hg; Metrology for Traceable Protocols for Elemental and Oxidised Mercury Concentrations
   Prof. Milena Horvat
   Euramet E.v.
5. EMPIR - Food-MetNet; Support for a European Metrology Network on Food Safety
   Prof. Nives Ogrinc
   Euramet E.v.
6. EMPIR - MetroCycleEU; Metrology for the Recycling of Technology Critical Elements to support Europe's Circular Economy Agenda
   Prof. Radojko Jaćimović
   Euramet E.v.
7. Authenticity of High-Quality Slovenian Food Products Using Advanced Analytical Techniques; Implementation of Nuclear Techniques for Authentication of Foods with High-Value Labelling Claims (INTACT Food) (D52042)
   Prof. Nives Ogrinc
   IAEA - International Atomic Energy Agency
8. Isotope Variability of Rain for Assessing Climate Change Impacts; Trends in Isotopic Composition of Precipitation in Slovenia under Climate Change
   Prof. Sonja Lojen
   IAEA - International Atomic Energy Agency
9. TC Regional Project RER/7/014: Improving Environmental Monitoring and Assessment for Radiation Protection in the Region
   Asst. Prof. Marko Štrok
   IAEA - International Atomic Energy Agency
10. Training Fees for Hosting Ms. Kasiet Salymbekova, 02.03.2020 - 31.12.2020, ICTP/IAEA STEP Programme
    Prof. Milena Horvat
    ICTP - Centro Internazionale Di Fisica Teorica
11. COST CA19120; WATSON - WATer isotopeS in the critical zONe: from groundwater recharge to plant transpiration
    Dr. Polona Vreča
    COST Association Aisbl
12. COST CA19123; PHOENIX - Protection, Resilience, Rehabilitation of Damaged Environment
    Prof. Aleš Lapanje
    COST Association Aisbl
13. Training Fees for Hosting Ms. Nurgul Nursapino, Kazakhstan, ICTP/IAEA STEP Programme
    Asst. Prof. Marko Štrok
    ICTP - Centro Internazionale Di Fisica Teorica
14. H2020 - GREENER; InteGRated systems for Effective ENvironmEntal Remediation
    Prof. Aleš Lapanje
    European Commission
15. H2020 - EURAD; European Joint Programme on Radioactive Waste Management
    Prof. Milena Horvat
    European Commission
16. H2020 - FNS-Cloud; Food Nutrition Security Cloud
    Prof. Nives Ogrinc
    European Commission
17. H2020 - A-CINCH; Augmented Cooperation in Education and Training in Nuclear and Radiochemistry
    Asst. Prof. Marko Štrok
    European Commission
18. H2020 - TUNTWIN; TWINING Towards Advanced Analytical Strategies for Capacity Building and Innovation for the Tunisian Economy: Application to Three Industrial Key Sectors in Tunisia
    Prof. Nives Ogrinc
    European Commission
19. H2020 - MERFISH; Health-Benefit Understanding of Mercury-Selenium Interactions from Fish to Human
20. Prof. Milena Horvat
    European Commission
21. H2020 - URBANOME; Urban Observatory for Multi-participatory Enhancement of Health and Wellbeing
22. Dr. David Kocman
    European Commission
23. H2020 - GMOS-Train; Global Mercury Observation and Training Network in Support to the Minamata Convention

Prof. Milena Horvat
European Commission
24. H2020 - SurfBio; Innovation Hub for Surface and Colloid Biology Research
    Prof. Aleš Lapanje
    European Commission
25. H2020 - FoodTraNet; Advanced Research and Training Network in Food Quality, Safety and Security
    Prof. Nives Ogrinc
    European Commission
26. H2020 - STROMASS; Rapid 90Sr Determination Using Laser Ablation ICP-QQQ-MS
    Asst. Prof. Marko Štrok
    European Commission
27. AlgFer - Lactic Acid Fermentation to increase Microalgae Nutritional and Bioactive Components
    Prof. Nives Ogrinc
    Slovenian Research Agency
28. Graphitic Carbon Nitride Nano-Carrier Loaded with Curcumin for Treatment of Highly Potent Synergistic Anticancer Treatment
    Dr. Raghuraj Singh Chouhan
    Slovenian Research Agency
29. Tin Isotope Fractionation During the Transformation of Organotin Compounds as a Tool to Study their Behaviour and Distribution in the Marine Environment
    Prof. Tea Zuliani
    Slovenian Research Agency
30. Valorisation of Olive Oil Waste Material by Microbial Multispecies Biocatalytic Aggregates
    Prof. Aleš Lapanje
    Slovenian Research Agency
31. HE - PARC; Partnership for the Assessment of Risks from Chemicals
    Prof. Milena Horvat
    European Commission
32. HE - AgroServ; Integrated SERvices supporting a sustainable AGROecological transition
    Prof. Nives Ogrinc
    European Commission
33. HE - INQUIRE; Identification of Chemical and Biological Determinants, Their Sources, and Strategies to promote Healthier Homes in Europe
    Dr. David Kocman
    European Commission
34. HE - SECURE; Strengthening the European Chain of sUpply for next generation medical RadionuclidEs
    Asst. Prof. Marko Štrok
    European Commission
35. HE - BIOSYSMO; BIOremediation systems exploiting SYnergieS for improved removal of Mixed pOllutants
    Prof. Aleš Lapanje
    European Commission
36. HE - PIANOFORTE; European Partnership for Research in Radiation Protection and Detection of Ionising Radiation: Towards a Safer Use and Improved Protection of the Environment and Human Health
    Asst. Prof. Marko Štrok
    European Commission
37. HE - EIRENE PPP; Environmental Exposure Assessment Research Infrastructure Preparatory Phase Project
38. Prof. Milena Horvat
    European Commission
39. HE - THEROS; An Integrated Toolbox for Improved Verification and Prevention of Adulterations and Non-Compliances in Organic and Geographical Indications Food Supply Chain
    Dr. David Kocman
    European Commission
40. HE - WASTELESS; Waste Quantification Solutions to Limit Environmental Stress
    Dr. Lidija Strojnik
    European Commission
41. HE - FishEUTrust; European Integration of New Technologies and Social-Economic Solutions for Increasing Consumer Trust and Engagement in Seafood Products
42. Prof. Nives Ogrinc
    European Commission
43. HE - BPEC-DW; Development of Novel Technology Based on a Hybrid of Bio-Photo-Electrochemical Detritiation Light-Water for Tritium Separation and Simultaneously H2 Generation
    Asst. Prof. Marko Štrok
    European Commission
44. LIFE+, LIFE IP RESTART - Boosting Waste Recycling into Valuable Products by Setting the Environment for a Circular Economy in Slovenia
    Prof. Radmila Milačič Ščančar
    European Commission
45. PRIMA; PROMEDLIFE - Novel food products for the PROmotion of MEDiterranean LIFEstyle and healthy diet
    Prof. Nives Ogrinc
    Prima Foundation - Partnership For Research And
46. EMPIR; MetroPOEM - Metrology for the Harmonisation of Measurements of

Environmental Pollutants in Europe
Prof. Tea Zuliani
Euramet E.v.

47. EMPIR - STANBC; Standardisation of Black Carbon Aerosol Metrics for Air Quality and Climate Modelling
Prof. Milena Horvat
Euramet E.v.

48. RadoNorm-SLO: Citizen Science as Support to Increasing Radon Testing and Mitigation in Bela Krajina, Slovenia
Dr. David Kocman
Sck • cen - Studiecentrum Voor Kernenergie/

49. Measurements and Reporting on Certified Materials BCR-462, BCR-646 and ERM-CA400
Prof. Tea Zuliani
European Commission

50. Element Measurements of ERM-CZ130; Analysis - ICP-MS (As, Cd, Pb, Ni) and Anaysis - k0-INAA (As)
Prof. Tea Zuliani
European Commission

51. Training Fees for Hosting Mrs. Dorice Seif, ICTP/IAEA STEP Programme
Asst. Prof. Marko Štrok
ICTP - Centro Internazionale Di Fisica Teorica

52. Training Fees for Hosting Dr. George Melikadze, IAEA Reference Number: SV-RER7013-2205050; From 08 to 12 May 2023
Dr. Polona Vreča
IAEA - International Atomic Energy Agency

53. Measurements and Reporting on Certified Reference Materias ERM-CE101
Prof. Milena Horvat
European Commission

54. Measurements and Reporting on Certified Reference Material ERM-CE477
Prof. Tea Zuliani
European Commission

55. Measurements and Reporting on Certified Reference Material ERM-CA403
Prof. Tea Zuliani
European Commission

56. Radiochemistry Training for NRRC
Asst. Prof. Marko Štrok
Nuclear and Radiological Regulatory Commission

RESEARCH PROGRAMMES

1. Design of novel (nano) material properties & Applications
2. Dr. Doris Potočnik
3. Modelling and environmental impact assessment of processes and energy technologies
   Asst. Prof. Marko Štrok
4. Cycling of substances in the environment, mass balances, modelling of environmental processes and risk assessment
   Prof. Milena Horvat

R&D GRANTS AND CONTRACTS

1. Impact of endocrine disruptors (bisphenols, parabens, triclosan) and potentially toxic and essential chemical elements on childbirth, infertility and ovarian cancer in Slovenia
   Prof. Milena Horvat
2. Monitoring of the clinical and immune response to improve the outcome of combined electrochemotherapy and IL-12 gene therapy in dogs with spontaneous peripheral tumours
   Asst. Prof. Tina Kosjek
3. Indentifying the genetic determinants of chemical toxicity in the green alga Chlamydomonas reinhardtii
   Prof. Milena Horvat
4. CRIME – CRemation or Inhumation of ancientpopulations? A Multidisciplinary question at the European level
   Dr. Doris Potočnik
5. The unrevegled information on soil biodiversity in leached waters
   Prof. Nives Ogrinc
6. Subglacial carbonate deposits - a new source for studying the presence of glaciers in a glaciokarstic environment
   Prof. Sonja Lojen
7. Algal technologies for green products – ALGreen
   Prof. Ester Heath
8. Oaks for future forests and forestry in Slovenia: Quercus robur versus Quercus petraea
   Dr. Bor Krajnc
9. Climate changes and ectomycorrhizal fungi - how far can we go with an assisted migration of truffles?
   Dr. Lidija Strojnik
10. Nanofibers for codelivery of selected microbiota cocktails and antimicrobials for local treatment of vaginal infections
    Prof. Nives Ogrinc

11. Preclinical development of new Mitochondrial ion channel inhibitors for Cancer therapy
    Asst. Prof. Tina Kosjek
12. Investgation of selected invasive plant from genus Fallopia as reliable sources of bioactive compounds
    Prof. Aleš Lapanje
13. Denuded caves of the Nullarbor Plain
    Prof. Sonja Lojen
14. Supporting Holocene Climate Reconstruction with High-Resolution Cryospheric Proxies from the Kast Ice Caves of Slovenia
    Dr. Polona Vreča
15. Novel approaches for the estimation of the use of psychoactive pharmaceuticals and illicit drugs by wastewater analysis
    Prof. Ester Heath
16. Novel proxies of the Holocene climate variability in stalagmites in Slovenia
    Prof. Sonja Lojen
17. Cost-efficient separation of tritium from water with bio-based systems – BIOTRISEP
    Asst. Prof. Marko Štrok
18. Innovative isotopic techniques for identification of sources and biogeochemical cycling of mercury in contaminated sites – IsoCont
    Prof. Milena Horvat
19. Quality, Safety and Authenticity of INsect PROtein-Based Food and Feed Products
    Dr. David John Heath
20. New biofertilization approach based on the microbial multispecies biocatalytic aggregates
    Asst. Prof. Tomaž Rijavec
21. Valorisation of olive oil waste material by microbial multispecies biocatalytic aggregates
    Prof. Aleš Lapanje
22. Validation of catchment-scale contaminant transport models using stable isotopes and multi-element measurements
    Prof. Radmila Milačič Ščančar
23. Plasma-assisted removal of emerging genotoxic contaminants from wastewater
    Prof. Ester Heath
24. WellBEEing: IoT monitoring of bee colonies in the presence of external stressors
    Dr. Janja Vidmar
25. Trace metals disorder as biomarker in biliary tract cancers
    Prof. Janez Ščančar
26. CAEmissionMonitor - Determination of primary carbonaceous aerosol emission rates and formation rate of secondary organic aerosol
    Prof. Janja Vaupotič
27. Authentich high-quality product and sustainable pig production (A-SUS)
    Prof. Nives Ogrinc
28. Hydro-ecologically based operation of run-of-river reservoirs for effective sediment management and energy production
    Prof. Radmila Milačič Ščančar
29. „Uptake": agricultural reuse of wastewater and sewage sludge: uptake and distribution of contaminants of emerging concern in tomato plant as a model
    Prof. Ester Heath
30. Investigation of the fate of chromium from industrial and urban sources using chromium stable isotopic tracers and advanced chromatography and mass spectrometry-based techniques: environmental and health concerns
    Dr. Stefan Marković
31. Assessment of the potential impact of incineration and co-incineration of waste on human health effects: a model study on the case of the Salonit Anhovo cement plant
    Prof. Milena Horvat
32. The presence of mercury in drinking water in the area of ??the Municipality of Idrija
    Asst. Prof. Jože Kotnik
33. EPOS-SI (EPOS-European Plate Observing System)
    Prof. Janja Vaupotič
    Slovenian Research Agency
34. METROFOOD
    Prof. Nives Ogrinc
    Slovenian Research Agency
35. Smart mobility measures for sustainable mobility in Slovenia – SmarMOVE
    Asst. Prof. Davor Kontić
    Institute for Spatial Policies
36. High-performance and sustainable breeding of runners of the Krškopolski pig breed with the help of precision control machines
    Dr. Doris Potočnik
    Agency for Agricultural Markets and Rural Development
37. Optimization of consumptionof energy in raising brown cattle
    Dr. Doris Potočnik
    Ministry of Agriculture, Forestry and Food
38. Cofinancing of LIFE18 ENV/SI; LIFE HIDAQUA: Sustainable Water Management in High Water Demanding Industries
    Prof. Radmila Milačič Ščančar
    Ministry of the Environment and Spatial Planning
39. Design of novel (nano) material properties & Applications
    Dr. Doris Potočnik
    Slovenian Research Agency
40. Assessment of the potential impact of incineration and co-incineration of waste on

human health effects: a model study on the case of the Salonit Anhovo cement plant
Prof. Milena Horvat
Ministry of Health

41. Measurements of mercury in air and precipitation for 2021 and 2022
Prof. Milena Horvat
Ministry of the Environment and Spatial Planning

42. Radioactivity Monitoring in Drinking Water for the Year 2023 - PART 2
Asst. Prof. Marko Štrok
Ministry of Health

43. Analyses of Tributyltin and Dibutyltin Compounds in Seawater
Prof. Tea Zuliani
Ministry of the Environment, Climate and Energy

44. Human Biomonitoring Program in 2023
Prof. Milena Horvat
Ministry of Health

45. Analysis of official samples for the content of elements and stable isotopes for the year 2023.
Prof. Nives Ogrinc
Ministry of Agriculture, Forestry and Food

46. The presence of mercury in drinking water in the area of the Municipality of Idrija
Asst. Prof. Jože Kotnik
Ministry of Health

47. Services; Determination of the Isotopic Composition of Carbon in Sugar Samples
Prof. Nives Ogrinc

48. Small Services for the Years 2023 and 2024
Dr. Tjaša Kanduč

49. Determination of the Isotopic Composition of Oxygen and Hydrogen
Dr. Polona Vreča

50. Analyses of Metals, TBT and DBT in Sediments, Mussels and Fish
Prof. Janez Ščančar

51. CROSSING - Crossing Borders and Scales - An Interdisciplinary Approach
Prof. Aleš Lapanje
Helmholtz-Zentrum Dresden-Rossendorf E.v.

52. H2020 - GMOS-Train; Global Mercury Observation and Training Network in Support to the Minamata Convention
Prof. Milena Horvat
European Commission

53. Monitoring of the Environmental Fingerprint in Graviera Naxou PDO Product for Certification of Authenticity and Geographical Origin - Sr Isotopes and H, O, C, N Stable Isotopes
Prof. Tea Zuliani
Agricultural Cooperatives Union of

54. Radon Mapping and Radon Risk Assessment in Georgia
Prof. Janja Vaupotič
Ivane Javakhishvili Tbilisi State University

55. Supporting Research Activities in Environmental Sciences/Organic Analysis
Prof. Ester Heath
Sherwin-williams Company

56. Measurements of TBT Concentrations in Seawater Extracts and Hg Concentrations in Water Samples; Water Analyses of the Northern, Central and Southern Adriatic Sea
Prof. Janez Ščančar
Institut „Ruđer Bošković"

57. Analysis of Trace Elements in River Water Samples
Prof. Radmila Milačič Ščančar
Technische Universität Wien

58. Mercury Analysis of Marine Water Samples
Prof. Milena Horvat
Istituto Per Lo Studio Degli Impatti Antropici

NEW CONTRACTS

1. Qualitative and quantitative monitoring of groundwater in the impact area of the dam for HPP Mokrice
Dr. Tjaša Kanduč
Irgo Consulting d. o. o.

2. Elemental analysis by mass spectrometry for the characterisation of biological drugs
Prof. Janez Ščančar
Lek d. d.

3. LOT 1: Measurements of gaseous effluents - Specific analyzes of H-3 and C-14 in 2022, 2023, 2024 and 2025; LOT 2: Measurements of gaseous effluents - Gamma spectrometry and analysis of strontium Sr-89/90 in 2022, 2023, 2024 and 2025
Asst. Prof. Marko Štrok
Krško Nuclear Power Plant

4. Environmental radioactivity monitoring in the vicinity of the Krško Nuclear Power Plant in connection with Hydro Power Plant Brežice for the years 2022 and 2023
Asst. Prof. Marko Štrok
Krško Nuclear Power Plant

5. Agricultural reuse of wastewater and sewage sludge: Uptake and distribution of contaminants of emerging concern in tomato plant
Prof. Ester Heath
Komunala Kranj d. o. o.

6. Agricultural reuse of wastewater and sewage sludge: Uptake and distribution of contaminants of emerging concern in tomato plant
Prof. Ester Heath
Jp CČN Domžale-kamnik d. o. o.

7. Agricultural reuse of wastewater and sewage sludge: Uptake and distribution of contaminants of emerging concern in tomato plant
Prof. Ester Heath
Komunala d. o. o.

8. S17981Agricultural reuse of wastewater and sewage sludge: Uptake and distribution of contaminants of emerging concern in tomato plant
Prof. Ester Heath
Občina Krško

9. Agricultural reuse of wastewater and sewage sludge: Uptake and distribution of contaminants of emerging concern in tomato plant
Prof. Ester Heath
Komunala Novo Mesto d. o. o.

10. Agricultural reuse of wastewater and sewage sludge: Uptake and distribution of contaminants of emerging concern in tomato plant
Prof. Ester Heath
Komunalno Podjetje Velenje d. o. o.

11. Agricultural reuse of wastewater and sewage sludge: Uptake and distribution of contaminants of emerging concern in tomato plant
Prof. Ester Heath
Ksd d. o. o.

12. Conduct of the independent environmental audit
Asst. Prof. Davor Kontić
Unior Kovaška Industrija d. d.

13. Investigation of the fate of chromium from industrial and urban sources using chromium stable isotopic tracers and advanced chromatography and mass spectrometry-based techniques: environmental and health concerns
Dr. Stefan Marković
Unior Kovaška Industrija d. d.

VISITORS FROM ABROAD

1. Klaudia Block, University of Gdansk, Gdansk, Poland, 1. 1.–3. 3. 2023 & 1.–14. 6. 2023
2. Marija Petrović, University of Belgrade, Belgrade, Serbia, 12. 2.–7. 3. 2023
3. Dorice Seif, Ministry of education, science and technology, Dodoma, Tanzania, 27. 3.–24. 6. 2023
4. Olfa Kallech ep Ziri, INRAP, Ariana, Tunis, 16.–23. 4. 2023
5. Mohsen Ben Alaya, INRAP, Ariana, Tunis, 16.–30. 4. 2023
6. Sassi ep Souissi, INRAP, Ariana, Tunis, 16.–30. 4. 2023
7. Emna Jridette ep Dougari, INRAP, Ariana, Tunis, 16.–30. 4. 2023
8. Manel Haraketi ep Hosni, INRAP, Ariana, Tunis, 16.–30. 4. 2023
9. Riadh Hamdi, INRAP, Ariana, Tunis, 16.–30. 4. 2023
10. Dr Houyem Abderrazak ep Snani, INRAP, Ariana, Tunis, 16.–30. 4. 2023
11. Dr Alejandro Cifuentes, Foodomics, CIAL, Madrid, Spain, 22.–26. 4. 2023
12. Dr George Melikadze, Georgian Geothermal Association, Tbilisi, Georgia, 8.–12. 5. 2023
13. Namrata S. Kumar, Indian embassy, Ljubljana, 27. 6. 2023
14. Dr Donata Canu, OGS Trieste, Italy, 1. 8. 2023
15. Ginevra Roseti, OGS Trieste, Italy, 1. 8. 2023
16. Dr Casimo Salidoro, OGS Trieste, Italy, 1. 8. 2023
17. Dr Stefano Salon, OGS Trieste, Italy, 1. 8. 2023
18. Mara Antonietta Carrera, EEZA-CSIC, Almeria, Spain, 15. 8.–30. 9. 2023
19. Dr Alexandre Soares Leal, CDTN, Belo Horizonte, Brasil, 16. 8. 2023
20. Dr Bahriddin Nishonov, Scientific Research Hydrometeorological Institute, Tashkent, Uzbekistan, 22. 8. 2023
21. Dr Igor Nicoara, Institute of Geology and Seismology of Moldavian State University, 22. 8. 2023
22. Nayyer Rehman, WRG Europe, Exeter, Great Britain, 1. 9.–15. 10. 2023
23. Dr Maria Angela de Barros Correia Menezes, CDTN, Bello Horizonte, Brasil, 14. 9.–7. 10. 2023
24. Petra Škvorova, Czech University of Life Sciences Prague, Prague, Czech Republic, 18. 9.–18. 10. 2023
25. Allen Anies, University of Antwerp, Antwerp, Belgium, 18. 9.–31. 10. 2023
26. Aseel Husain Almohammad, Jordan Atomic Energy Commission, Aman, Jordan, 2.–6. 10. 2023
27. Dr Lubertus Bijlsma, Universitat Jaume I, Valencia, Spain, 16.–19. 10. 2023
28. Niki Simonović, Institut Ruđer Bošković, Zagreb, 2. 11.–3. 12. 2023
29. Samira Bejaoui ep Jelassi, INRAP, Ariana, Tunis, 20. 11.–3. 12. 2023
30. Dr Martina Furdek Turk, Institut Ruđer Bošković, Zagreb, Croatia, 22.–24. 11. 2023

31. Dr Maja Ivanić, Institut Ruder Bošković, Zagreb, Croatia, 22.–24. 11. 2023
32. Dr Vesna Despotović, Faculty of Sciences, University of Novi Sad, Novi Sad Serbia, 3.–8. 12. 2023

33. Dr Daniela Šojić Merkulov, Faculty of Sciences, University of Novi Sad, Novi Sad Serbia, 3.–8. 12. 2023

STAFF

Researchers
1. Dr. Raghuraj Singh Chouhan
2. Asst. Prof. Ingrid Falnoga
3. Dr. David John Heath
4. Prof. Ester Heath
5. **Prof. Milena Horvat, Head**
6. Prof. Radojko Jaćimović
7. Dr. Tjaša Kanduč
8. *Dr. Norbert Kavasi, left 01.09.23*
9. Dr. David Kocman
10. Asst. Prof. Davor Kontić
11. Asst. Prof. Tina Kosjek
12. Asst. Prof. Jože Kotnik
13. Prof. Aleš Lapanje
14. Prof. Sonja Lojen
15. Dr. Darja Mazej
16. Prof. Radmila Milačič
17. Dr. Griša Močnik*
18. Prof. Nives Ogrinc
19. Asst. Prof. Tomaž Rijavec
20. DR. Tayebeh Sharifi
21. Prof. Borut Smodiš
22. Janja Snoj Tratnik, B. Sc.
23. Prof. Janez Ščančar
24. *Asst. Prof. Zdenka Šlejkovec, retired 01.07.23*
25. Asst. Prof. Marko Štrok
26. Prof. Janja Vaupotič
27. Dr. Janja Vidmar
28. Dr. Polona Vreča
29. Prof. Tea Zuliani
30. Dr. Dušan Žigon

Postdoctoral associates
31. *Anatolii Abalymov, Dr. left 20.08.23*
32. Dr. Ermira Begu
33. Dr. Jan Gačnik
34. Dr. Marta Jagodic Hudobivnik
35. *Dr. Ana Kovačič, on leave since 01.11.22*
36. Dr. Bor Krajnc
37. Dr. Katarina Marković
38. Dr. Stefan Marković

39. Dr. Marjeta Mencin
40. Dr. Doris Potočnik
41. Dr. Leja Rovan Stiplošek
42. *Dr. Agneta Annika Runkel, on leave since 01.05.23*
43. Dr. Anja Stajnko
44. Dr. Lidija Strojnik
45. Dr. Žiga Tkalec
46. Dr. Igor Živković

Postgraduates
47. Saeed Waqar Ali, M. Sc.
48. Eirini Andreasidou, M. Sc.
49. *Teodor-Daniel Andron, M. Sc., left 01.09.23*
50. Katja Babič, B. Sc.
51. *Dominik Božič, B. Sc., left 16.10.23*
52. Pia Leban, B. Sc.
53. *Jasmina Masten Rutar, B. Sc., left 15.11.23*
54. Dr. Rok Novak
55. Neža Palir, B. Sc.
56. Brina Pavlovič, B. Sc.
57. Žan Rekar, B. Sc.
58. Janko Stankić, B. Sc.
59. Cathrine Terro, M. Sc.
60. Anja Vehar, B. Sc.
61. Dr. Taja Verovšek
62. Sreekanth Vijayakumaran Nair, M. Sc.
63. Maja Zugan, B. Sc.
64. Klara Žagar, B. Sc.
65. Tjaša Žerdoner, B. Sc.

Technical officers
66. Jure Ftičar, B. Sc.
67. Polona Klemenčič, B. Sc.
68. Karolina Trentelj, B. Sc.
69. Vanja Usenik, B. Sc.
70. Tina Vrabec, B. Sc.

Technical and administrative staff
71. Barbara Svetek, B. Sc.
72. Stojan Žigon

Note:

* part-time JSI member

DEPARTMENT OF AUTOMATION, BIOCYBERNETICS AND ROBOTICS E-1

The research strategy within our department (http://abr.ijs.si/) combines the fields of robotics (including robot learning, intelligent control, humanoids, cognitive robotics, and robot vision), industrial robotics and automation, factories of the future, biomechanics, biocybernetics, ergonomics and environmental physiology. The common theme of our research endeavours to date has been optimizing the behaviour of man and machine, accounting for the interactions with the environment. An additional synergy is provided by the research topic human-robot collaboration. Our research strategy supports a variety of multi- and interdisciplinary research projects. By combining engineering and life sciences, we have been able to make breakthroughs in robot learning based on imitation and deep neural networks, development of a planetary habitat simulation facility, reconfigurable robotic workcells, humanoid robotic systems, exoskeletons, manikins enabling the evaluation of protective garments for industry and recreation, and new strategies for physical human-robot interaction.

The department maintains the programme group Automation, robotics and biocybernetics. Members of the department participate in numerous EU projects in the areas of robotics and artificial intelligence, factories of the future, health, and space technologies. For example, in collaboration with the European Space Agency we launched a new programme Long-Term Hypoxic Bed Rest with Resistance Vibration Exercise. In 2023 we also coordinated the Horizon 2020 project ReconCycle, developing new reconfigurable and adaptive robotic systems in the domain of recycling. We are also continuously active in transferring our research results to applications through direct collaborations with industry, currently taking place within the scope of large-scale collaboration program DGITOP.

Research in the area of humanoid robotics and robot learning is primarily conducted within the Humanoid and Cognitive Robotics Lab (https://hcr.ijs.si), which operates within the department. The aim of this laboratory is to create robots that can acquire new knowledge through continuous learning and collaborate with people in their natural environments. Another laboratory that operates within the department is the Laboratory for Neuromechanics and Biorobotics (https://nbr.ijs.si). The main focus of this lab is to integrate the results of biomechaniscs, neurophysiology, and robotics to study human motor control and develop new robot systems that can effectively assist people with their daily activities.

Head:
Prof. Aleš Ude

By maintaining a critical mass of researchers in the areas of robotics, automation and life sciences within one department, we have managed to foster exciting multidisciplinary projects.

During the past year, our research focused on the development of new robot learning methodologies primarily based on kinesthetic teaching, reinforcement learning and deep learning, human-robot collaboration, development of new control methods for robotic assistive devices such as exoskeletons, reconfigurable robotic systems for factories of the future, automation of production processes in manufacturing, studies of human physiology in extreme environments, evaluation of protective equipment, as well as development of biomedical methods.

Robotics

In 2023 we were coordinating the Horizon 2020 project **ReconCycle** (self-reconfiguration of a robotic workcell for the recycling of electronic waste, http://www.reconcycle.eu/). The main aim of the project is to introduce **self-reconfigurable hardware and software for the disassembly of electronic devices**, based on a reconfigurable robotic cell developed within the ReconCell project, http://www.reconcell.eu/, which was also coordinated

Figure 1: Robotic cloth folding

by our group. The challenge of this project is to provide methodologies for a re-design of the recycling cell including the location of robots and other elements in the workcell and the choice of grippers and sensing systems. On the software side, approaches to **fast re-programming and adaptation of manipulation actions** for soft robots and

grippers suitable for recycling tasks need to be provided. Soft components make grasping and compliant control easier, but they can be problematic for the assembly tasks that usually rely on high-precision position control. However, high precision is less important for disassembly operations, typical for the domain of recycling electronic devices, where physical constraints guide compliant robot movements to successfully accomplish a desired task.

In the ARIS funded project Robot Textile and Fabric Inspection and Manipulation – RTFM (https://abr.ijs.si/rtfm/) we are developing methodologies of handling deformable materials, with a focus on textiles. It is an important area of robotics research that has applications both in industry and in homes. Yet, advances in the robotic manipulation of such deformable objects have lagged behind those of rigid objects due to their far more complex dynamics and configuration space. In cooperation with the Faculty of Computer Science from the University of Ljubljana, we are developing approaches to first segment and characterize textiles, and then effectively manipulate them towards a predefined goal state, e.g., a folded shirt. In 2023 we developed and tested **vision-to-motion approaches** that effectively flatten out textile materials, as well as **learning approaches** to fold textiles in simulation. We continue our work towards an autonomous textile inspection and folding robotic cell.

> **In the H2020 project ReconCycle coordinated by our department we aim at substantially increasing the degree of automation in recycling by introducing new robot learning technologies.**

In 2023 we successfully concluded the SWITCH project (Learning by Switching Roles in Physical Human-Robot Collaboration), which was a collaborative effort with Idiap in Switzerland and co-funded by the SNSF (https://switch-project.github.io/). The primary aim in the final year of the SWITCH project was to develop an innovative control strategy for humanoid robots. This strategy enabled effective adaptation to human partners, as demonstrated through experiments involving assistance with standing up using a humanoid robot. By analysing the collected data, we formulated models that accurately describe the **behaviors of both the assisting agent and the assisted individual**. This data was crucial in furthering the development of a new quasi-passive mechanism, which led to a successful patent registration with the Slovenian Patent Office. The integration of this mechanism into a knee exoskeleton was achieved, followed by an evaluation of its practical application.

Our work within the BodyCoM project – Rethinking Dynamic Whole-Body Multicontact Interaction: Towards Next Generation of Collaborative Robots (http://cobotat.ijs.si/projects/bodycom/) aims to improve manipulation accuracy through physical interaction with the robot's structure, such as using environmental support for elbow placement. Within this project, we introduced a **novel calibration method for collaborative robots** that utilizes physical contacts, making calibration possible without the need for expensive and highly accurate equipment. Our pioneering approaches to controlling humanoid robots and harnessing physical interactions stand to significantly advance human-robot collaboration, paving the way for enhanced precision in manipulation and seamless cooperation between humans and robots in the future.

> **We developed a new quasi-passive mechanism, which was integrated into a knee exoskeleton and patented.**

In 2023 we continued our work in the field of robotic task learning, where robots interact with the environment. We formalized our approach into a **multi-level hierarchical learning scheme**. At the top hierarchical level, we use reinforcement learning to determine the optimal strategy for the task, which we formalize through directed graph representations. The middle hierarchical level is dedicated to autonomously generating graphs through exploration, while the lowest level comprises control algorithms that adapt to environmental constraints independently. Furthermore, we focused on algorithms ensuring the robustness of previously learned assembly and disassembly procedures. The primary challenge was to ensure a smooth task execution, even when the workpiece may move during the assembly process without being detectable by sensors.

Figure 2: JSI-KneExo, a knee exoskeleton that can function in either active or passive mode

In our recent work on curriculum learning, we focused on enhancing the speed of the acquisition of manipulation skills. Our research primarily involved multi-objective reinforcement learning, where we designed multiple reward functions and **adjusted their weights using multiple curriculum learning algorithms** based on the agent's performance in completing a task. To evaluate the effectiveness of our approach, we applied it to a robotic pick-and-place task. Our experiments demonstrated that all three curriculum learning algorithms via reward weighting achieve a near-perfect success rate in less than four hours of an interaction with the environment, a significant improvement over some baselines that were unable to solve the task after 16 hours of training.

We started to work on a new Horizon Europe project SWAG – Soft Wearable Assistive Garments for Human Empowerment (https://swag-project.eu) in collaboration with 12 other research and industry partners. The project aims to replace traditional rigid materials found in exoskeletons, with high-strength, inflatable fabrics and sensing films to create smart, human-assistive, soft and lightweight garments. Our primary role in the project will be to evaluate the effectiveness of the newly developed SWAG exoskeleton prototype.

Another Horizon Europe project that started in 2023 was DS4Health (https://www.digitalskills4health.eu), which will design and deliver an international Master's programme in digital health. The goal is to provide **higher education for healthcare professionals in digital skills** and deepen the insight into the design, use, and development of digital technologies to form a modern, ethically responsible, efficient and citizen-centred healthcare. As one of the research institutes, we will provide practical training to students in advanced technologies with a clear view on the digital transformation of healthcare towards a clinical digital ecosystem.

In 2023 we started to work on two new Horizon Europe projects, focusing on exoskeletons (SWAG) and education program for healthcare professionals (DS4HEALTH).

In our research on human motor learning, we focus on how different types of errors and perturbations (visual vs. proprioceptive) and daily experiences affect the motor learning process. We assess the effectiveness of various learning strategies, such as haptic guidance, and investigate **decoding neural correlates of error processing in complex motor tasks**. We experimentally disassociated low-level motor and high-level strategic errors to probe the impact of prior low-level error detection on high-level error processing, employing a controlled visuomotor rotation paradigm. Our results demonstrate that it is possible to accurately differentiate between these types of errors. Furthermore, prior low-level error processing significantly influences feedback signals, with the superior parietal cortex playing the key role in high-level error processing. These findings highlight the potential for implementing more specific feedback signals in adaptive brain-machine interface control based on implicit human error detection.

Automation and robotics in industrial and other applications

In 2023 we launched a new research program DIGITOP – digital transformation of robot-supported factories of the future (https://digitop.info/en/digitop/), coordinated by our department. The main goal of the DIGITOP program is the introduction of advanced digital technologies, such as robotics, artificial intelligence (AI), information and communication technologies (ICT), Industry 4.0 and 5.0, into manufacturing companies for the automation and optimization of production processes. The program includes nine research and development projects, which are at various stages of technological readiness, focusing on **digital transition and strategic autonomy**. The goal of the program is to maintain industrial production in Slovenia and the EU, with participating research organizations and industrial partners, who partially support the research with their own resources.

Figure 3: Interaction between human and humanoid robot, where humanoid robot helps human to stand up

In 2023 we continued our work on the Stellaverde project. The goal of the project was **to design and develop a five-legged climbing robot**. We were working on the design and implementation of the mechanical components, control algorithms, algorithms for calculating the kinematics and dynamics of the robot, path planning and implementation of the entire application which combines those algorithms into a working system. In 2023 we presented the robot at two exhibitions. The first one, called Konsekvence, took place in March at the Cukrarna Gallery in Ljubljana. The second one, Ars-Electronica, was held in September in Linz, Austria. During those exhibitions, the robot was operating for ca. 8 hours daily – watering the plants in a vertical garden.

Within the DIGITOP program coordinated by our department, we work on transferring our expertise on robot learning and reconfigurable workcell design to industrial applications.

In the past years, our department was working towards the implementation of **Smart Specialization Strategy S4** and recently also **S5**. As part of the Strategic Research and Innovation Partnership of the Factory of the Future (SRIP FoF), we **chaired** the SRIP FoF Board of Directors, and **coordinated** the Robotics SRIP FoF horizontal network, thus providing support for the introduction of advanced robotic technologies into factories of the future, being developed by the Slovene industry. In 2023 SRIP FoF continued with the implementation of a new program to foster cooperation of manufacturing companies with the research departments in academia and transfer the latest robotics research results into the industrial practice.

Environmental physiology and ergonomics

Life-science research in our department focuses on the physiology and pathophysiology of humans in extreme environments. We contribute to the development of new strategies and equipment to mitigate the effects of environmental factors on human health and well-being, and enhance the safety and productivity of workers in industrial, military and space environments.
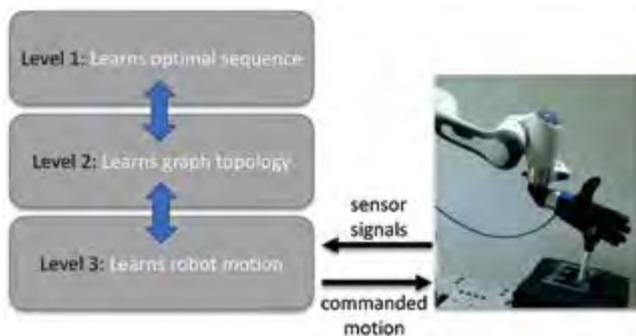
Countermeasures for deep space missions: The Jožef Stefan Institute maintains the European Space Agency ground-base research facility Plan-

Figure 4: Hierarchical scheme for learning contact policies represented by graphs

Figure 5: Autonomous learning of assembly and disassembly of a car license plate light

Figure 6: Autonomous five-legged robot designed for vertical gardening. Photo: Katja Goljat, Matjaž Rušt

Figure 7: JSI researcher in the horizontal resistance vibration exercise device

etary Habitat Simulation (PlanHab) in Planica (Rateče, Slovenia). Within the framework of the ESA BRAVE project we assessed the efficacy of resistance vibration exercise (RVE) combined with artificial gravity as a potential countermeasure for preventing loss of muscle and bone mass, and cardiovascular deconditioning during missions to Mars.

As a prelude to the European Space Agency (ESA) project "Long-term hypoxic bed rest with resistance vibration exercise", which was launched in September 2022, we focused on several issues that needed to be resolved prior to the start of this project. These studies were supported by ESA:

i.) *Effect of vibration on muscle activation.* Using magnetic resonance imaging (MRI) we conducted studies to assess the effect of vibration on muscle activation during resistance exercise. This study was conducted in collaboration with the Institute of Clinical Physiology at the Faculty of Medicine (University of Ljubljana).

ii.) *Vibration transmission.* We assessed the transmission of vibration from the feet to the head, to determine the magnitude of vibration transmission to different body regions. In this manner we determined the optimal and safe frequencies for resistance vibration exercise. This study was a collaborative project with the Faculty of Sport, University of Ljubljana.

iii.) *Horizontal Resistance Vibration Exercise device.* With partner Mak d.o.o., we designed and constructed a novel exercise device that is able to mimic the gravitational forces experienced during RVE on the short-arm human centrifuge.

iv.) *Exercise programme for Resistance Vibration Exercise (RVE).* The focus of a successful pilot study was to establish an exercise programme for RVE conducted on the short-arm human centrifuge. The aim was to develop a programme that could be successfully performed by subjects participating in a 60-day bed rest study. The developed exercise programme was approved by the ESA Bedrest Advisory Committee.

v.) *Feasibility study (FAVE).* We tested the ability of the participants to conduct the established exercise programme (iv) with artificial gravity (i.e., on the short-arm human centrifuge) during a 2-wk course. The results were compared with those of the subjects participating in a similar (iv) 2-wk training programme, but conducting upright RVE. In both studies, we used the vibration characteristics determined in (i).

vi.) *Feasibility study 2 (FAVE 2).* Following the construction of the novel Horizontal Resistance Vibration Exercise device (iii) we conducted the second feasibility study (FAVE 2). Using the same protocol as in FAVE (v) we compared the results of the group of subjects conducting upright RVE with those of the group conducting the training using the prototype Horizontal Resisance Vibration Exercise (HRVE) device.

vii.) *Energy demand of RVE.* To establish an appropriate nutritional intake during the 60-d bed rest, we determined the energy demand of the RVE exercises. The oxygen uptake measured during RVE with and without artificial gravity (on the horizontal exercise device) will be used in the planning of the meals for the subjects, ensuring an appropriate daily energy intake. This study is part of a larger project being carried out in collaboration with another partner, the University of Nottingham.

viii.) *Effect of centrifugation (artificial gravity) on the regulation of vasomotor activity.* The regulation of the vasomotor activity in peripheral vascular beds is regulated by the physiological systems regulating the body temperature and arterial pressure. The manner in which these two physiological systems interact in the regulation of peripheral vasomotor tone in the presence of elevated head-to-foot gravitational load in thermoneutral and hot, hypoxic and normoxic conditions was the focus of the ESA-INTREPID project. This project was conducted in partnership with the University of Caen (France).

ix.) *Motion sickness during exercise on the short-arm human centrifuge (SAHC).* Exercise on the short-arm human centrifuge causes motion sickness. There is a paucity of data regarding the effect of repeated

exposure to a motion sickness-inducing stimulus. The aim of this study was to determine whether a daily exercise conducted over a 2-wk period (v) would ameliorate the aetiology of motion sickness or exacerbate it.

Spaceflight Associated Neuro-Ocular Syndrome (SANS): Our previous work had focused on evaluating the effects of spaceflight-associated factors (i.e., inactivity/unloading, hypoxia, hypercapnia, exercise, age, gender, etc.) on the retina and intraocular pressure. Those studies had been designed to determine whether, and to what extent, such factors contribute to the aetiology of SANS. However, they had been of a short duration and thus had not been able to adequately predict the contribution of the tested factors to SANS. With partner C3M, and the support of ESA, we developed a biomechanical model of the eye, incorporating all our findings to date, and allowing a simulation of long-term effects of the investigated factors on the eye.

The aim of the studies conducted in 2023 was to address a variety of unresolved issues regarding resistance vibration exercise conducted with and without artificial gravity. These studies were essential for the preparation of the ESA-BRAVE project (Long-term hypoxic bed rest with resistance vibration exercise).

Protective clothing: With partner Prevent Deloza d.o.o. we continued the development of a ventilated vest that can provide efficient cooling of the torso, particularly when worn under a ballistic vest. The evaluation of the vest under simulated hot environmental conditions in our climatic chamber, confirmed that the prototype vest provides sufficient ventilation, significantly reducing the absorption of sweat by the near-to-skin layers of clothing, which resulted in improved wearer's comfort.

Predicting the cardiovascular function during exposure to a hot ambient. Climate change has increased the frequency, intensity, and duration of summer heat waves, imposing an additional strain on workers with underlying cardiovascular diseases. We validated equations for predicting stroke volume (SV) based on blood pressure measurements and applied these equations to monitoring the cardiac index of subjects conducting assembly line tasks during a simulated 3-d heat wave (HW). On the basis of these results we were able to rank the equations according to their predictive power. Future work will focus on establishing a new model for predicting stroke volume and ultimately cardiac index that could be used by workers exposed to hot ambient conditions. This study was conducted in collaboration with colleagues from the University of Innsbruck.

Some outstanding publications in the past year

1. T. Petrič, L. Žlajpah, Kinematic model calibration of a collaborative redundant robot using a closed kinematic chain, Scientific Reports, 2023, vol. 13, pp. 17804-1–17804-12.
2. T. Kunavar, X. Cheng, D. W Franklin, E. Burdet, J. Babič, Explicit learning based on reward prediction error facilitates agile motor adaptations, PLOS ONE, 2023, vol. 18, no. 12, pp. e0295274-1-e0295274-23.
3. M. Deniša, A. Ude, M. Simonič et al., Technology modules providing solutions for agile manufacturing, Machines, 2023, vol. 11, no. 9, pp. 877-1–877-28
4. J. Čamernik, R. Kropivšek Leskovar, T. Petrič, Leader–follower dynamics in complex obstacle avoidance task, International Journal of Social Robotics, 2023, vol. 15, no. 1, pp. 59–70.
5. U. Ciuha, T. Valenčič, L. G. Ioannou, I. B. Mekjavić, Efficacy of cooling vests based on different heat-extraction concepts: The HEAT-SHIELD project, Journal of Thermal Biology, 2023, vol. 112, pp. 103442-1–103442-10.
6. T. Mlinar, T. Debevec, J. Kapus, P. Najdenov, A. McDonnell, A. Ušaj, I. B. Mekjavić, Igor B., P. Jaki Mekjavić, Retinal blood vessel diameters in children and adults exposed to a simulated altitude of 3,000 m, Frontiers in Physiology, 2023, vol. 14, art. no. 1026987.

Awards and Appointments
1. Gal Sajko: Prešeren Award for students, Ljubljana, Faculty of Electrical Engineering, University of Ljubljana, a climbing robot spider

Organization of conferences, congresses and meetings
1. The 32nd International Conference on Robotics in Alpe-Adria-Danube Region, RAAD 2023, Bled, Slovenia, 14–16 June 2023
2. H2020 ReconCycle Meeting, Ljubljana, Slovenia, 5–6 July 2023
3. ReconCycle Summer School, Cala Ratjada, Spain, 23–26 October 2023

INTERNATIONAL PROJECTS

1. PERI SiteStruct
   Prof. Aleš Ude
   Peri Se
2. FlexHex Patent „Cardon Joint"
   Asst. Prof. Igor Kovač
   Flex Hex Aps
3. H2020 - TRINITY; Digital Technologies, Advanced Robotics and increased Cyber-Security for Agile Production in Future European Manufacturing
   Prof. Aleš Ude
   European Commission
4. H2020 - ReconCycle; Self-reconfiguration of a Robotic Workcell for the Recycling of Electronic Waste
   Prof. Aleš Ude
   European Commission
5. Effects of robotically induced local gravity rendering on human motor control in various environmental gravities
   Prof. Jan Babič
   Slovenian Research Agency
6. Expanding Model Predictive Control of Humanoid Robots with Pre-Learned Dynamics
   Prof. Andrej Gams
   Slovenian Research Agency
7. Ergonomic Human-Robot Interaction Through Machine Learning Optimization
   Prof. Jan Babič
   Slovenian Research Agency
8. Human Motor Adaption and Feedback Modulation in Whole Body Movements
   Prof. Jan Babič
   Slovenian Research Agency
9. HE - EUROfusion; WP17: RM_HE-FU
   Prof. Aleš Ude
   European Commission
10. HE - euROBIN; European ROBotics and AI Network
    Prof. Aleš Ude
    European Commission
11. HE - SWAG; Soft Wearable Assistive Garments for Human Empowerment
    Prof. Jan Babič
    European Commission
12. Optimising Athletic Performance in the Environmental Heat Stress Conditions of the Paris 2024 Olympic Games
    Dr. Urša Ciuha
    Sveriges Olympiska Kommitté
13. DIGITAL EU; DS4Health - Digital Skills for Healthcare Transformation
    Prof. Jan Babič
    European Commission
14. ERASMUS+; AgeWell - Multimodal Physical Activity and Health Education for Healthy Ageing
    Dr. Adam Mcdonnell
    Léargas, The Exchange Bureau
15. ESA - INTREPID; Interaction of Human Temperature and Blood Pressure Regulation in the Responses of Regional Peripheral Perfusion During Exposure to Artificial Gravity on the Short Arm Human Centrifuge
    Prof. Igor Mekjavić
    ESA/ESTEC.
16. ESA - BRAVE; Bed Rest, Artificial Gravity, Vibration, Exercise
    Prof. Igor Mekjavić
    ESA/ESTEC.
17. ESA – CORA
    Prof. Igor Mekjavić
    ESA/ESTEC.

RESEARCH PROGRAMME

1. Avtomation, robotics and biocybernetics
   Prof. Igor Mekjavić

R&D GRANTS AND CONTRACTS

1. Mechanisms of hypoxia (in)tolerance in prematurely born individuals
   Prof. Tadej Debevec
2. Intermittent exogenous ketosis: a novel strategy to improve hypoxic tolerance and adaptation
   Prof. Tadej Debevec
3. Adaptation and sensorimotor processing during increased gravity gradients
   Dr. Adam Mcdonnell
4. Learning by Switching Roles in Physical Human-Robot Collaboration (SWITCH)
   Prof. Tadej Petrič
5. The use of Resistive Vibration Exercise (RVE) to mitigate hypoxic inactivity induced cartilage degeneration: implications for Covid-19 patients
   Dr. Adam Mcdonnell
6. Rethinking Dynamic Whole-body Multicontact Interaction: Towards Next Generation of Collaborative Robots
   Prof. Tadej Petrič
7. Robot Textile and Fabric Inspection and Manipulation (RTFM)
   Prof. Andrej Gams
8. NOO-DIGITOP; Digital transformation of robot-supported factories of the future
   Prof. Aleš Ude
   Slovenian Research Agency
9. Keep on moving
   Prof. Jan Babič
   University of Primorska
10. Robot garden - technical and professional support in the development and set-up of the production, the manufacturing of a robotic spider and a dedicated vertical wall
    Prof. Jan Babič
    Mladinski Center Velenje
11. Development of multispectral camouflage for vehicles, equipment and soldiers.
    Dr. Urša Ciuha
    Ministry of Defence
12. Stimulators for Foreign Customers
    Prof. Aleš Ude
    Customer Service – Abroad
    Prof. Aleš Ude

VISITORS FROM ABROAD

1. Elena Paris Quijada, University of Twente, Netherlands, 13 January to 3 February 2023
2. Pasquale Mottola, University of Naples Federico II, Naples, Italy, 3 May to 10 November 2023
3. Raffaella Mancino, University of Naples Federico II, Naples, Italy, 3 May to 10 November 2023
4. Antonio Bicchi, University of Pisa, Italy, 17–19 April 2023
5. Andrej Čilag, University of Novi Sad, Serbia, 16 June to 17 September 2023
6. Florentin Wörgötter, University of Göttingen, Germany, 5–6 July 2023
7. Sebastian Ruiz, University of Göttingen, Germany, 5–6 July 2023
8. Jurgen Schulz, ElectroCycling GMbH, Germany, 5–6 July 2023
9. Riccardo Persichini, qbrobotics srl, Pisa, Italy, 5–6 July 2023
10. Hamid Sadehian, Technical University of Munich, Germany, 5–6 July 2023
11. Manuel Catalano, Italian Institute of Technology (IIT), Genoa, Italy, 5–6 July 2023
12. Vinicio Tincani, Italian Institute of Technology (IIT), Genoa, Italy, 5–6 July 2023
13. Myrthe Stalman, University of Leuven, Belgium, 8–16 September 2023
14. Sebastian Ruiz, University of Göttingen, Germany, 11–15 September 2023
15. Ana Salve Machuca, University of Twente, Netherlands, 16 September to 16 December 2023
16. Ron Goerz, University of Vienna, Austria, 27–29 September 2023
17. Mirko Raković, University of Novi Sad, Serbia, 22–24 November 2023

STAFF

Researchers
1. Prof. Jan Babič
2. Dr. Urša Ciuha
3. Prof. Tadej Debevec*
4. Prof. Andrej Gams
5. Prof. Polonca Jaki Mekjavić*
6. Asst. Prof. Igor Kovač
7. Dr. Adam Mcdonnell
8. Prof. Igor Mekjavić
9. Prof. Bojan Nemec
10. Prof. Tadej Petrič
11. Dr. Anton Ružić
12. *Prof. Blaž Stres*, left 01.10.23*
13. **Prof. Aleš Ude, Head**
14. Asst. Prof. Leon Žlajpah

Postdoctoral associates
15. Dr. Tilen Brecelj
16. *Dr. Jernej Čamernik, left 06.02.23*
17. Dr. Miha Deniša
18. *Dr. Miha Dežman, on leave since 01.05.21*
19. Dr. Leonidas Ioannou
20. Dr. Marko Jamšek
21. Dr. Rok Pahič*
22. Dr. Mihael Simonič
23. Dr. Lydia Tsoutsoumpi
24. Dr. Nina Verdel

Postgraduates
25. Martin Bem, B. Sc.
26. Victorien Olivier Faivre-Rampant, M. Sc.
27. Benjamin Fele, B. Sc.
28. Jason Thomas Fisher, M. Sc.
29. Jack Patrick Fortune, B. Sc.
30. Tjaša Kunavar, B. Sc.
31. Boris Kuster, B. Sc.
32. Dr. Zvezdan Lončarević
33. Matija Mavsar, B. Sc.

34. Luka Mišković, M. Sc.
35. Benjamin Jonathan Narang, M. Sc.
36. Peter Nimac, B. Sc.
37. Sara Podgornik, B. Sc.
38. Gal Sajko, B. Sc.
39. Kristina Savevska, B. Sc.
40. Riccardo Sorrentino, M. Sc.
41. Jan Šifrer, B. Sc.

Technical officers
42. Niko Kroflič, B. Sc.
43. Matevž Majcen Hrovat, B. Sc.
44. Simon Reberšek, B. Sc.
45. Saša Repanšek, B. Sc.
46. Bogomir Vrhovec, B. Sc.

Technical and administrative staff
47. Tanja Ivančič, B. Sc.
48. Petra Movh, B. Sc.

Note:

* part-time JSI member

DEPARTMENT OF SYSTEMS AND CONTROL
E-2

The Department of Systems and Control is engaged in the analysis, control and optimization of systems and processes. The activities are focused on the research of new methods and algorithms for automatic control, the development of procedures and tools to support the design of control systems, the development of specific measurement and control modules, and the development and construction of complete systems for the control and supervision of machines, devices and industrial processes.

Head:
Asst. Prof. Gregor Dolanc

Research and projects in 2023 were devoted to the following sub-areas: modelling of complex dynamic systems, advanced control methods, prognostics and diagnostics and tools and building blocks for control systems implementation. With these methodologies we addressed open problems in the fields of industrial production, energy, ecology, as well as in the fields of medicine and social and economic sciences.

In the field of the **modelling of complex dynamic systems** our research focused on the simulation of approximated autoregressive models and modelling using methods of decision trees and Gaussian-process models.

For the project ''Sources, Transport and fate of persistent air pollutants in the environment of Slovenia'', we developed a surrogate Gaussian process model that shows the dispersion of sulphur dioxide in the air above the Šoštanj thermal power plant.

For the project ''Modelling the dynamics of short-term exposure to radiation'', we improved, analysed, and published a surrogate model for predicting short-term exposure to radiation. In particular, we analysed the accuracy and computational complexity of the method for modelling and predicting radiological radiation in the area around NEK Krško.

After an ERC project application, we obtained national research project, entitled "Air in karst underground as a sink of greenhouse gases". Methane is a major greenhouse gas that was found to swiftly decompose in the air that enters the underground. Using measurements, modelling, and theory, we will quantify the flow rate of air through the karst underground, which is a major source of uncertainty in quantifying the role of the underground as a methane sink.

In the field of **advanced process control** and in collaboration with partners we continued the project ''Stability of nuclear reactors in load follow mode of operation'' and research of the feasibility and the limitations of using nuclear energy as a dispatchable electrical power source for covering the daily fluctuations of the energy production from photovoltaic panels. Research was performed as a simulation study on a digital twin of a nonlinear pressurised water reactor (PWR) based on a nonlinear model with 2-point neutron kinetics. The contribution of our team is a new method of reactor control considering the actuator nonlinearity, which was done for the configuration with two groups of control rods and also for the configuration with one group of control rods and adjusting the boric acid concentration.

In **Clean Environment** we used regression models based on random forests to model the indicators of a wastewater treatment plant's (WWTP) operation. Research in wastewater treatment is also focused on the development of simplified models and the application of optimisation methods to improve operational indicators such as effluent quality and energy consumption.

In the scope of the project ''Supervisory control system for plant-wide optimization of wastewater treatment plant operation'' we investigated the most important influencing variables of the WWTP benchmark simulation

Figure 1: International project HYPER: electrified hydrogen peroxide production and electric grid balancing

model with respect to the effluent-quality and operating-costs criteria was performed using the random-forests method. An optimisation algorithm was developed and tested by simulation to optimise the selected criteria using a fuzzy model and a simple predictive controller. The performance of the controllers of the three real wastewater-treatment plants was monitored and analysed, tuning of the controllers was performed and specifications for the improved controllers were prepared to improve the operational criteria.
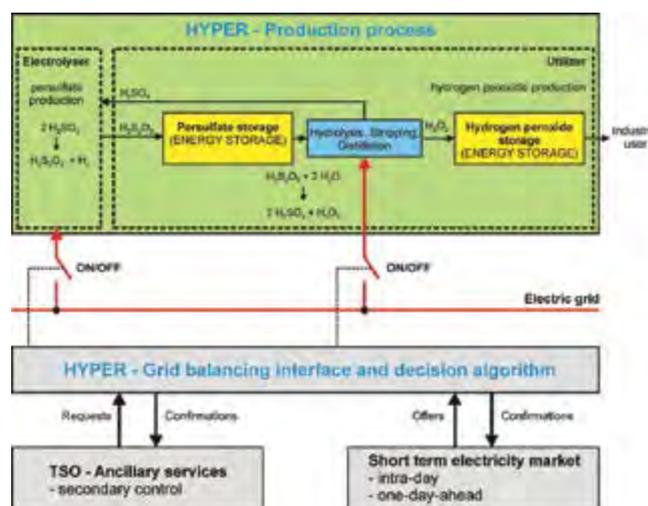
In the project ''UPTAKE – Agricultural reuse of wastewater and sewage sludge: Uptake and distribution of contaminants of emerging concern in tomato plant as a model'' we modelled the uptake of contaminants of emerging concern in tomatoes. Using a classification method and experimental data, we confirmed the influence of the physical and chemical properties of the contaminants on their uptake in tomato fruit and identified the properties that have the greatest influence on the uptake.

In the field of **smart factories** we were researching and developing self-learning systems for the monitoring of production equipment, based on the analysis of signals generated by production systems.

In the project ''Minimum-Invasive Self-Evolving Diagnostic Systems: An ultimate component of the Factories of the Future'', we were developing individual building blocks, which perform the segmentation and comparison of repeatable segments based on the measured time series of process operation. We also developed methods for the identification of discrete-event systems (DESs) in the operation of production equipment. The aim of the project is to develop methods and algorithms for the detection of faults in industrial production processes based on signals from general-purpose or simply embedded sensors.

In cooperation with the Polycom company we started developing algorithms for the predictive maintenance of injection-moulding equipment. The developed algorithms focus on the detection of deviations of the current operating points and the detection of the medium-term drift of process variables.

Following the initiative of the Republic of Slovenia for the establishment and operation of strategic innovative partnerships within the framework of the Slovenian Smart Specialization Strategy S4, the Strategic Innovative Partnership of the Factory of the Future **SRIP ToP** is operating. Our department plays an active role in SRIP ToP in the area Control Technologies and in the implementation of its Multi-Annual Action Plan. The members of the department are representatives of the SRIP ToP network in the European associations **Processes4Planet** and **Made in Europe**.

Figure 2: Project WASTELESS: System for weighing and categorising food waste (smart scale & app)

In the field of **energy and hydrogen technologies** in the frame of research project ''Optimisation based control of a P2G converter connected to a hydropower plant'', we designed and developed a decision-support tool for the future design and investment in hydrogen technologies in a hydropower plant, taking into account both technical and economic aspects of their implementation. Such a tool enables more efficient selection of the size of hydrogen-system components and gives an estimate of the economic benefits of hydrogen production.

In this area we continue to coordinate a related research project ''Multifunctional hydrogen technologies supporting power system balancing, energy storage and market'' in the field of using hydrogen technologies in the energy sector. Using models and simulation we are exploring the feasibility and economy of using a hybrid system comprising an electrolyser, hydrogen storage, fuel-cell, and a battery for grid balancing via ancillary services (secondary control) and market mechanisms. The developed digital twin will be used for system dimensioning and for the tuning of a coordination algorithm controlling the system. The participating partners in the project are the Faculty of Electrical Engineering, Computer Science and Informatics of Maribor and the hydro power plant operator company Dravske elektrarne, which also co-finances the project.

We started a new project ''Probabilistic and explainable data-driven modelling of Solid-oxide fuel cells''. High-temperature solid-oxide fuel cell (SOFC) technology offers efficient and clean energy generation from various types of fuel, but operating under suboptimal conditions can lead to degradation and reduced lifetimes.
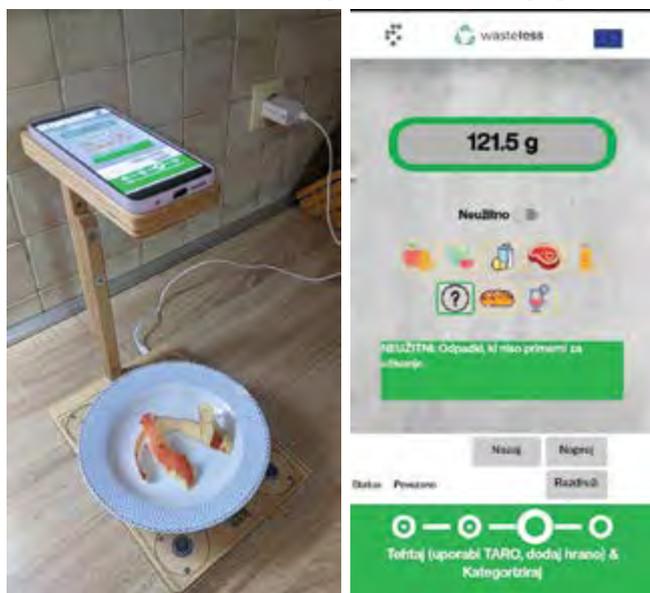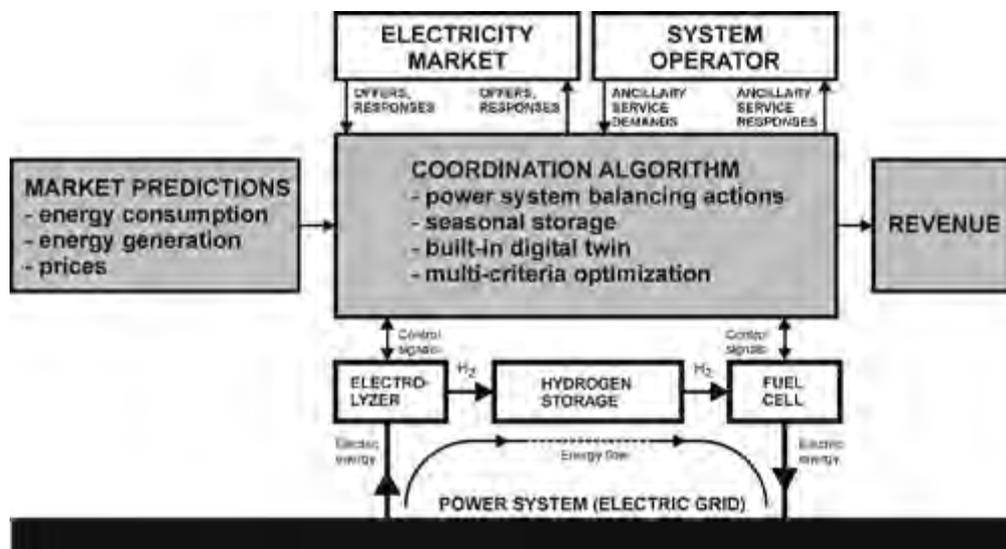

Figure 3: Concept of integration of hydrogen technologies with electric power system and market

This project aims to develop new methods for predicting the remaining useful life of SOFC systems by models that account for uncertainties and limited data sets. Modelling is based on expertise from SOFC technology and experimental data. The result of the research will be a novel probabilistic data-driven modelling approach that goes beyond traditional methods.

In the field of the **battery systems**, we are continuing the project "Precise physics-based state of health assessment of lithium-ion batteries based on low-frequency impedance measurements with stochastic excitation". We are developing new, physics-based impedance models for graphite anodes and complete lithium-ion batteries. We investigate the relation between electrochemical impedance spectroscopy (EIS) and state of health (SOH) for individual commercial batteries. We are developing an electronic measurement module (DRBS-EIS) based on the chirp wavelet transform (CWT). Ultimately, the project seeks to improve the accuracy of the relationship between EIS and SOH and establish a dependable, non-invasive method for diagnosing and predicting battery health.

We also continue with research in **medicine**. We are carrying out a research project entitled "Synchronized cardio-respiratory coronary rehabilitation". The mentioned method is intended for the rehabilitation of cardiac patients and is based on slow movement coordinated with breathing. The study we are conducting in this regard will compare the effectiveness of this method with the standard method of continuous aerobic/interval exercise (CAIE) and a hybrid approach that combines the two. Together with partner research organizations, we will evaluate patients' physiological processes and cardiovascular-respiratory interactions to determine whether SCR can improve the survival rate and quality of life for cardiac patients.

In the field of **social and economic sciences** we continued the collaboration with the Faculty of Economics in Ljubljana within the new research project "Investments as the key to building a sustainable business: building a theoretical model and multi-methodological empirical analysis" aimed at building a theoretical framework for sustainable companies, determining the types of investments required, and evaluating the existing and required investments to achieve the sustainability.

Figure 4: Project REACTT - Electronic module for non-invasive diagnostics of solid-oxide electrolysers (SOEC).

We also started participating in a new project "The impact of artificial intelligence on the labor market: economic analysis, reducing the competence gap and ensuring labour law protection". The project focuses on artificial intelligence (AI) in the labour market, and aims to raise awareness of the use of AI solutions and identify and manage risks in employment processes.

We participate and coordinate numerous international research projects.

We successfully completed the coordination of the project "H2020 Inevitable", which is focused on the optimization in metal industry by using digitalization techniques. The project is focused to steel industry, in the Slovenian part of the project it is a multifaceted optimization of the process in the electric arc furnace and the cold rolling process.

In 2023, together with several other departments at IJS, we launched the WASTELESS project, which aims to develop and test various innovative tools and methodologies to measure and monitor food-waste quantities. We are developing a methodology and a supporting tool for the automatic assessment of food waste in households.

The international project "AI Redgio5.0" also started. The project aims to demonstrate and test artificial intelligence solutions in industrial production. We are focused on the technology of non-invasive real-time monitoring of assembly production processes. This includes the development of a service-oriented platform using micro-computers (ESP & RaspberryPi) and the development of control algorithms.

We have started to implement a large new international project "HYPER" in the field of energy, green transition and digitization. The aim of the project is to develop a method for the green production of hydrogen peroxide. The classic process is based on the use of natural gas and consequently causes CO_2 emissions. The new, proposed process produces hydrogen peroxide from water by using electricity from renewable sources and thus largely eliminates CO_2 emissions. The role of our department, together with the National Institute of Chemistry, is the development and automation of an important part of the technological process, as well as the coupling of the system with the electricity market in order to use cheap energy in periods of energy surplus.

Figure 5: Automatic end-of-line quality inspection system type ZKG for the company Domel (development and fabrication stage at JSI)

The "RUBY" project pursues the development of advanced techniques and dedicated hardware for the monitoring, diagnosis, prognosis and optimizing the control of PEM and SOFC fuel cells with the aim to maximize efficiency and durability. Our team developed a set of diagnostic algorithms for the active and passive diagnosis of the solid-oxide fuel-cell systems. A particular contribution of our team concerns the probabilistic approach to the

diagnostic fusion, which combines all the available symptoms in order to produce a ranked list of suspected faults with the associated probability mass.

In the related project "REACTT" we developed an embedded technological platform that supports the optimal performance, durability and economic exploitation of solid-oxide electrolysers (SOE and rSOC) while ensuring portability, scalability and easy operability. The most notable contribution of our team is an innovative electronic module for the external excitation of stacks for the purpose of real-time electrochemical impedance spectroscopy. It is designed as a current generator that operates in series with the default (voltage) power supply. It is capable of exciting the stack with an arbitrary waveform in the frequency range up to 18 kHz and simultaneously providing up to 200 A of DC component current to the stack.

In the "HECAT" project, together with partners, we developed the innovative **www.MyLabourMarket.com** platform, aimed at enhancing visibility and understanding of the labour market for citizens. This platform, created in collaboration with the Slovenian Public Employment Service, integrates advanced labour-market data analytics to assist individuals in navigating their personal labour-market conditions, including job demand and supply, pay rates, and the stability of various occupations.

We also carried out **contractual projects for Slovenian industry**. In 2023 we started developing a new diagnostic system (type ZKG) for the end-of-line quality inspection of larger brushless DC electric motors for our long-standing industrial partner Domel. The new device is characterized by an extremely high degree of flexibility, which enables the diagnosis of variants of electric motors with different electrical and geometric parameters. Adaptations for different motor types are carried out by software, which has brought our devices even closer to the concepts of Industry 4.0 and Smart Factories.

Figure 6: Minimum-Invasive Self-Evolving Diagnostic Systems of production lines installed in an industrial environment

Educational and training activities

Some members of the department are giving lectures and practical courses at different faculties and universities: Faculty of Electrical Engineering, University of Ljubljana, the Faculty of Logistics, University of Maribor, Faculty of Industrial Engineering Novo mesto, University of Nova Gorica and the "Jožef Stefan" International Postgraduate School.

Some outstanding achievements in the past year

1. Stržinar, Žiga, Pregelj, Boštjan, Škrjanc, Igor. Soft sensor for non-invasive detection of process events based on Eigenresponse Fuzzy Clustering. Applied soft computing. [Online ed.]. Jan. 2023, vol. 132, str. 1-12, ilustr. ISSN 1872-9681. DOI: 10.1016/j.asoc.2022.109859. [COBISS.SI-ID 131913475]
2. Pavšek, Aljaž, Horvat, Martin, Kocijan, Juš. Dynamical and statistical properties of estimated high-dimensional ODE models : the case of the Lorenz '05 type II model. Chaos online. Jul. 2023, vol. 33, iss. 7, [article no.] 073127, str. 073127-1-073127-14 DOI: 10.1063/5.0151252. [COBISS.SI-ID 159462659]
3. Gerkšič, Samo, Vrančić, Damir, Ćalić, Dušan, Žerovnik, Gašper, Trkov, Andrej, Kromar, Marjan, Snoj, Luka. A perspective of using nuclear power as a dispatchable power source for covering the daily fluctuations of solar power. Energy. 2023, vol. 284, december, 14 str. DOI: /10.1016/j.energy.2023.128531. [COBISS.SI-ID 161858307]
4. Perne, Matija, Kocijan, Juš, Božnar, Marija, Grašič, Boštjan, Mlakar, Primož. Hybrid forecasting of wind for air pollution dispersion over complex terrain. Journal of environmental informatics. 2023, 41, 2, str. 88-103. DOI: 10.3808/jei.202300489. [COBISS.SI-ID 154495235]
5. Vrančić, Damir, Moura Oliveira, Paulo, Bisták, Pavol, Huba, Mikuláš. Model-free VRFT-based tuning method for PID controllers. Mathematics. Feb. 2023, vol. 11, iss. 3, [article no.] 715, str. 1-29, ilustr. ISSN 2227-7390. DOI: 10.3390/ math11030715. [COBISS.SI-ID 140811523]
6. Hvala, Nadja, Mlakar, Primož, Grašič, Boštjan, Božnar, Marija, Perne, Matija, Kocijan, Juš. Surrogate tree ensemble model representing 2D population doses over complex terrain in the event of a radiological release into the air. Progress in nuclear energy. [Online ed.]. Apr. 2023, vol. 158, [article no.] 104594, str. 1-16. DOI: 10.1016/j.pnucene.2023.104594. [COBISS.SI-ID 145531651]

Some outstanding achievements in the past year

1. Results of collaboration with industry, i.e., the design and implementation of a new and advanced end-of-line quality-inspection system for the company Domel.
2. Acquisition of new international research projects.

INTERNATIONAL PROJECTS

1. H2020 - RUBY; Robust and Reliable General Management Tool for Performance and Durability Improvement of Fuel Cell Stationary Units
   Prof. Đani Juričić
   European Commission
2. H2020 - HECAT; Disruptive Technologies Supporting Labour Market Decision Making
   Prof. Pavle Boškoski
   European Commission
3. H2020 - INEVITABLE; Optimization and Performance Improving in Metal Industry by Digital Technologies
   Dr. Dejan Gradišar
   European Commission
4. H2020 - REACTT; REliable Advanced diagnostics and Control Tools for increased lifetime of solid oxide cell Technology
   Prof. Đani Juričić
   European Commission
5. Photoluminescence of Calcite: Development of a Potentially Field-Deployable Tool for Paleothermometry
   Asst. Prof. Matija Perne
   Slovenian Research Agency
6. HE - AI REDGIO 5.0; Regions and (E)DIHs Alliance for AI-at-the-Edge Adoption by European Industry 5.0 Manufacturing SMEs
   Dr. Miha Glavan
   European Commission
7. HE - HYPER; An electrochemically produced oxidiser for modular, onsite generation of HYdrogen PERoxide
   Asst. Prof. Gregor Dolanc
   European Commission
8. HE - WASTELESS; Waste Quantification Solutions to Limit Environmental Stress
   Dr. Dejan Gradišar
   European Commission

RESEARCH PROGRAMME

1. Program systems and control
   Prof. Đani Juričić

R&D GRANTS AND CONTRACTS

1. Synchronised cardiorespiratory coronary rehabilitation
   Prof. Pavle Boškoski
2. Corporate investment as the key to building a sustainable company: building a theoretical model and multimethod empirical analysis
   Prof. Pavle Boškoski
3. Accurate physics-based State-of-Health estimation of Lithium ion batteries based on ultra-low frequency impedance measurements with stochastic excitation
   Prof. Pavle Boškoski
4. Air in karst underground as a sink of greenhouse gases
   Asst. Prof. Matija Perne
5. Probabilistic and explainable data-driven modelling of Solid-oxide fuel cells
   Prof. Pavle Boškoski
6. Optimization based control of P2G converter connected to hydro power plant
   Asst. Prof. Gregor Dolanc
7. Stability of nuclear reactors in load follow mode of operation
   Dr. Boštjan Pregelj
8. Modelling the Dynamics of Short-Term Exposure to Radiation
   Prof. Juš Kocijan

9. Supervisory control system for plant-wide optimization of wastewater treatment plant operation
   Dr. Darko Vrečko
10. Minimum-Invasive Self-Evolving Diagnostic Systems: An ultimate component of the Factories of the Future
   Prof. Đani Juričić
11. Multifunctional hydrogen technologies supporting power system balancing, energy storage and market
   Dr. Janko Petrovčič
12. „Uptake": agricultural reuse of wastewater and sewage sludge: uptake and distribution of contaminants of emerging concern in tomato plant as a model
   Dr. Nadja Hvala
13. The impact of artificial intelligence on the labour market: economic analysis, reducing the competence gap and providing labour law protection
   Prof. Pavle Boškoski
14. The impact of artificial intelligence on the labour market: economic analysis, reducing the competence gap and providing labour law protection
   Prof. Pavle Boškoski
   Government Digital Transformation Office
15. NOO-DIGITOP; Digital transformation of robot-supported factories of the future
   Dr. Miha Glavan
   Slovenian Research Agency

NEW CONTRACTS

1. Development of a system for monitoring equipment operation based on real-time data analysis
   Dr. Miha Glavan
   Polycom Škofja Loka d. o. o.
2. Modelling the Dynamics of Short-Term Exposure to Radiation
   Prof. Juš Kocijan
   Nuklearna Elektrarna Krško d. o. o.
3. Supervisory control system for plant-wide optimization of wastewater treatment plant operation
   Dr. Darko Vrečko
   JP CČN Domžale-Kamnik d. o. o.
4. Supervisory control system for plant-wide optimization of wastewater treatment plant operation
   Dr. Darko Vrečko
   Kolektor Sisteh d. o. o.
5. Supervisory control system for plant-wide optimization of wastewater treatment plant operation
   Dr. Darko Vrečko
   Komunala Novo Mesto d. o. o.
6. Supervisory control system for plant-wide optimization of wastewater treatment plant operation
   Dr. Darko Vrečko
   Komunala Kranj d. o. o.
7. Multifunctional hydrogen technologies supporting power system balancing, energy storage and market
   Dr. Janko Petrovčič
   Dem d. o. o.
8. Minimum-Invasive Self-Evolving Diagnostic Systems: An ultimate component of the Factories of the Future
   Prof. Đani Juričić
   Domel, d. o. o.
9. Implementation of the system for testing ZKG motors
   Asst. Prof. Gregor Dolanc
   Domel, d. o. o.

STAFF

Researchers
1. Prof. Pavle Boškoski
2. **Asst. Prof. Gregor Dolanc, Head**
3. Dr. Samo Gerkšič
4. Dr. Miha Glavan
5. Dr. Giovanni Godena
6. Dr. Dejan Gradišar
7. Dr. Nadja Hvala
8. Prof. Đani Juričić
9. Prof. Juš Kocijan
10. Asst. Prof. Matija Perne
11. Dr. Janko Petrovčič
12. Dr. Boštjan Pregelj
13. Prof. Damir Vrančić
14. Dr. Darko Vrečko

Postgraduates
15. Viktor Andonovikj, B. Sc.
16. Martin Brešar, B. Sc.
17. Žan Gorenc, B. Sc.
18. Žiga Gradišar, B. Sc.
19. Dr. Tadej Krivec*
20. Jernej Mlinarič, B. Sc.
21. Aljaž Pavšek, B. Sc.
22. Matic Rutnik, B. Sc.
23. Žiga Stržinar, B. Sc.
24. Luka Žnidarič, B. Sc.

Jožef Stefan Institute

Technical officers
25. Stanislav Černe, B. Sc.
26. Primož Fajdiga, B. Sc.
27. Viktor Govže, B. Sc.
28. David Jure Jovan, B. Sc.

Technical and administrative staff
29. Maja Janežič, B. Sc.
30. Miroslav Štrubelj

Note:

* part-time JSI member

DEPARTMENT FOR ARTIFICIAL INTELLIGENCE E-3

The Department for Artificial Intelligence (http://ailab.ijs.si/) is concerned mainly with the research and development of information technologies with an emphasis on artificial intelligence. Our main areas of research are: data analysis with an emphasis on text, web and cross-modal data; scalable real-time data analysis; machine learning; analysis and modelling of large networks; visualization of complex data; semantic technologies, language technologies; reasoning methods and knowledge management. The Department for Artificial Intelligence has employees and students with an international background and expertise in different areas of artificial intelligence. In addition to publishing their research results in international publications and presenting their work at international events, our researchers have also developed numerous software tools for multimodal data analysis. These tools include: Text-Garden (https://ailab.ijs.si/tools/text-garden/), a suite of text mining tools; OntoGen (https://ailab.ijs.si/tools/ontogen-2/), a tool for ontology learning; Document-Atlas (https://ailab.ijs.si/publications/past-projects/documentatlas/), a tool for complex visualization; Atlas of Slovenian Science (http://scienceatlas.ijs.si/), a web portal for analyzing the scientific community; Enrycher (http://enrycher.ijs.si/), a system for semantic enrichment of textual data; SearchPoint, a portal for visual and contextualized web browsing; OntoPlus (https://ailab.ijs.si/tools/ontoplus/), a methodology for semi-automatic ontology extension; Contextify, a tool for contextualized e-mail and contact management; Qminer (http://qminer.ijs.si/), a data analytics platform for processing large-scale real-time streams containing structured and unstructured data; NewsFeed (https://ailab.ijs.si/tools/newsfeed/), a clean, continuous, real-time aggregated stream of semantically enriched news articles from RSS-enabled sites across the world; Event Registry (http://eventregistry.org/), a system for identifying world events in news media including the DarkNET component of Event Registry; Wikifier (http://wikifier.org), a system for document annotation with links to relevant Wikipedia concepts; StreamStory, an exploratory data stream analysis tool offering an alternative type of visualization by representing the multivariate data stream using a Markovian model; Videolectures Explorer, a tool enabling users to search through the videolectures and find similarities between them; EDSA dashboard, a tool aggregating demand data (job postings around Europe) and supply data (training materials) in data science; nextPin, a system for the analysis of time varying data of geographic locations; Connection tool, a tool based on Event Registry news data, which allows a user to follow business and personal named entities in time and establish broad relations between named entities (based on shared Wikipedia concepts from news articles) as well as to view the changes in these relations; Graph Based Analytics, a service for business relation identification from a text which enables identification of business relations, such as mergers & aquisitions, bankruptcy, earnings, dividends, et al., based on the sentence level; streamfusion, a universal system for the preprocessing of heterogenous stream data; ELEXIS ER, a lexicography-adapted version of Event Registry; a public procurement anomaly detection tool; a service for processing, analysing and searching through the environmental legal documents; Infominer, a tool for interactive data analysis, Water Observatory (http://naiades.ijs.si/), a system for automatic generation of commonsense descriptions; MultiCOMET (https://multicomet.ijs.si/); Smell Tracker (https://odeuropa.ijs.si/); Smell Explorer (https://explorer.odeuropa.eu/), monitoring the use of AI in manufacturing; EUJapan Observatory (https://eujapan.ijs.si/); the Slovenian Terminology Hub, part of the European network of terminology portals and a tool for converting time series into system states (http://atena.ijs.si:8080/); and the Slovenian AI Observatory (http://siai.ijs.si). The Department's strategy is to combine scientific excellence with strong industrial collaboration, enabling the transfer of research results into real-world

Head:

Prof. Dunja Mladenić

We successfully concluded five EU H2020 projects: FACTLOG (Energy-Aware Factory Analytics for Process Industries); STAR (Safe and Trusted Human Centric Artificial Intelligence in Future Manufacturing Lines); INFINITECH (Tailored IoT & BigData Sandboxes and Testbeds for Smart, Autonomous and Personalized Services in the European Finance and Insurance Services Ecosystem); ODEUROPA (Negotiating Olfactory and Sensory Experiences in Cultural Heritage Practice and Research); CLEOPATRA (Cross-Lingual Event-Centric Open Analytics Research Academy).

Members of the Department for Artificial Intelligence successfully continued participating in the EU, national and regional projects. In the last 21 years, we participated in 90 EU projects, of which 5 were concluded in 2023 and 13 were still ongoing. We also participated in 8 national projects.

In 2023 we began work on several new Horizon Europe projects in the area of Statistical Data Modelling and Machine Learning. New projects, Plooto, APRIORI and HumAIne, began, while the work on the CONDUCTOR project was still ongoing and two H2020 projects were successfully concluded: FACTLOG and STAR. The goal of the EU

Figure 1: Odeuropa Smell Explorer is an innovative online research tool that collates historical data from 23,000 images and 62,000 texts in six languages, leveraging machine learning to recognise and categorise olfactory elements. Users can explore significant smells of Europe, tracing how these were depicted, described, and experienced historically.

Horizon 2020 project FACTLOG (Energy-Aware Factory Analytics for Process Industries) was to support the process industry through the development of digital twins. As a digital representation of a factory supported by analytics systems, a digital twin supports functions such as: raising an alarm when encountering an anomaly, planning the optimal order of production and appropriately setting the parameters of production machinery. Together with other FACTLOG partners, we designed a framework in which the machine-learning models work together with domain expert models and optimization algorithms to solve industry problems. Our main contributions were software libraries for forecasting industry system states from data streams and detection of anomalies in data streams. The models developed were augmented with knowledge graphs to achieve higher generalizability for scalable industry deployment. The methods were successfully tested on an industry pilot in Tüpraş, a Turkish oil refinery. The models and analytical components were also successfully integrated into a common digital platform where they were validated with domain KPI indicators. The project successfully concluded in 2023.

The EU Horizon 2020 project STAR (Safe and Trusted Human Centric Artificial Intelligence in Future Manufacturing Lines) began in January 2021 and aimed to introduce novel AI technologies for dynamic and unpredictable manufacturing environments. AI systems are already used for improving the automation of production in the manufacturing sector; however, the STAR project aimed to improve trustworthiness in areas where systems replace human tasks in dynamic operations. The project goals were to research and integrate leading-edge technologies such as active learning, simulated reality, explainable AI, human-centric digital twins, advanced reinforcement learning and cyber-defense mechanisms. The project was successfully concluded in 2023.

Together with E7, we keep working on the EU Horizon Europe project CONDUCTOR (Fleet and Traffic Management System for Conducting future cooperative mobility) the goal of which is to design, integrate and demonstrate advanced, high–level traffic and fleet management that will allow efficient and globally optimal transport of passengers and goods, while ensuring seamless multimodality and interoperability, through dynamic balancing and priority–based management of vehicles (automated and conventional). To do so, CONDUCTOR will build upon the state-of-the-art fleet and traffic management solutions in the CCAM (Connected, Cooperative and Autonomous Mobility) ecosystem and develop the next generation of simulation models and tools at different levels, enabled by AI and data fusion, enhancing the capabilities of transport authorities and operators, becoming true conductors of future mobility networks. In the past year, we managed to develop and implement a data infrastructure for multimodal time series data integration in real-time. In the process, we designed a data model and methodology for the modelling and representation of the project data as a uniform time-space context. To design the time-space context, graph technologies were applied and methods for graph embedding designed. During the process of the technology design, the basic framework for the prediction modelling of transport demand was also set up. The analytical functionalities will be integrated and implemented in industrial pilot settings for testing and verification, namely in the SLO-IT-CR-AUT region. Use cases deployed will include integrated traffic management with demand-response transport and real-time event management.

Within the EU Horizon Europe project Plooto (Product Passport through Twinning of Circular Value Chains) the project partners are developing a circular and resilient information system (CRIS) to support manufacturers

in their transition to a circular economy. The system will enable waste reduction and the end-to-end traceability of secondary raw materials (SRM) through interconnected digital services. It will also provide a transformation framework, ICT tools for modelling products and supply chains, and a circular sustainability balanced scorecard. The solution will be piloted in three different circular supply chains. Within the project, our department is responsible for developing tools for modelling products, production processes and supply chains, as an aggregation of individual component digital twins with cognition capabilities (cognitive digital twins – CDTs) and developing educational modules and materials related to the Green Deal, climate change and sustainable development with an emphasis on a circular economy. In 2023, we developed a curriculum that is designed to introduce participants to the concept of the circular economy, its importance, key principles, and applications in various industries. The curriculum is a framework for collecting various open educational resources (OERs) on this topic that are already being collected. We have also published a call for developing these materials under the existing global mentoring program Open Education for a Better World (OE4BW.org), an international online mentoring program supporting the development and implementation of freely accessible modules and resources for online education on topics with social impact according to the UN Sustainable Development Goals (SDGs).

We successfully concluded five nationally and regionally funded projects: Slovenian Artificial Intelligence Observatory; Si-Twin; Development of Slovene in a Digital Environment (RSDO); SLOKIT project (Corpus Informer and Text Analyzer); SEMTEH (Connected Knowledge Bases for Semantic Technologies).

As part of the Marie Skłodowska-Curie Doctoral Network project APRIORI (Active PRoduct-to-Process LearnIng fOR Improving Critical Components Performance) one doctoral candidate was recruited by our department to begin work on the topic Active Learning for Explainability Manufactured Products. The main activity of the project during this first year was the recruitment of doctoral candidates. The project also held its kick-off meeting in Lueven. The Horizon Europe project HumAIne (Hybrid Human-AI Decision Support for Enhanced Human Empowerment in Dynamic Situations) began in October 2023. The aim of the project is to create an operating system for human-AI collaboration and empower the development of advanced decision-making applications across various industrial sectors. The goal is to enable AI solution integrators to create collaborative systems that outperform isolated AI systems and human efforts. The project aims to integrate four essential components: active learning, neuro-symbolic learning, swarm learning and explainable AI, which will place the human operator at the centre, offering complete control and understanding of the operations performed, and ensuring seamless collaboration between humans and AI.

In the field of Complex Systems Analysis, we concluded the nationally funded project Slovenian Artificial Intelligence Observatory and developed the first version of this Observatory. The portal for real-time monitoring of the field of artificial intelligence, both within Slovenia and in comparison with other countries, is freely accessible at http://siai.ijs.si/. It enables an analysis of a wide range of data available as visualizations, tables, and real-time generated reports through the user interface. In 2023, we upgraded the system with numerous additional, freely accessible data sources. The Observatory allows monitoring of various local indicators (e.g., in the areas of research, patents, news, funding), researchers, comparisons with other countries, companies in the field of AI, trends, and policies. In addition to the basic analytics and data exploration from various sources, the system also enables more sophisticated insights into the state of Slovenian artificial intelligence using semantic technologies.

We also concluded the nationally funded pilot project for the Slovenian Ministry of Defense, a system called Si-Twin, which represents a digital twin of Slovenia. Within this project, we implemented the architecture of the country's digital twin. The architecture enables the fusion of the data from different sensor and text sources, where the sensor data is appropriately aggregated in different phases. In the first phase, the data is aggregated in time on an hourly basis, and in the second phase, the data is aggregated in space, in case the sensor contains the GPS location. Spatial aggregation takes place at different levels: 1000×1000 m squares, municipalities, statistical regions and at the level of the entire country. The user interface allows a display of sensors on the map and the corresponding values, which are displayed on the interactive graphs. We also implemented the basic version of the chatbot to interact with a limited size dataset. We presented the prototype to the Ministry and educated potential users. The Horizon Europe project Graph-Massivizer (Massive Graph Processing of Extreme Data for a Sustainable Economy, Society, and Environment) began in January 2023 with the aim of researching and developing a high-performance, scalable, and sustainable platform for information processing and reasoning based on the massive graph representation of extreme data. One of the project goals is to deliver a toolkit of five open-source software tools and FAIR graph datasets.

In the area of Data Streams Analysis, we successfully concluded the flag ship project INFINITECH (Tailored IoT & BigData Sandboxes and Testbeds for Smart, Autonomous and Personalized Services in the European Finance and Insurance Services Ecosystem), which included 15 different pilots from the Fintech domain; one of them included the development of an analytical platform for Anti Money Laundering and Counter Financing of Terrorism (PAMLS) for the needs of the supervision of financial institutions, where our partner was the Bank of Slovenia. We have integrated the developed AI methods into the PAMLS platform and validated the functionalities using the actual

current enriched transactional data. Another important result of the project is the pseudo-anonymizer – a service for data pseudo-anonymization, which was installed and used for pseudo-anonymization of the data exchanged between different stakeholders.

The Horizon Europe project enRichMyData (The Enabling Data Enrichment Pipelines for AI-driven Business Products and Services), aims to deliver an open software toolbox – the enRichMyData toolbox – comprising practical, robust and scalable components to support organizations in enriching their data with reference data they may have limited knowledge of, as well as supporting data providers in making their data reusable and available in data enrichment processes. The Department for Artificial Intelligence is a key developer of data enrichment tools and leads one of the business cases, InnoGraph, which aims to build a knowledge graph of the AI innovation ecosystem.

Together with E6, we kept working on the EU Horizon Europe project NANCY (An Artificial Intelligent Aided Unified Network for Secure Beyond 5G Long Term Evolution) that aims to introduce an intelligent and secure architecture for beyond the fifth generation (B5G) wireless communication network via the power of AI and blockchain technology. The project began in January 2023 and was designed to enable secure and intelligent resource management, AI-powered orchestration, and flexible network architecture. In the first year of the project, we investigated and developed the architecture of NANCY and further exploited the experimental phase of the project. The Horizon Europe project FAME (Federated decentralized trusted dAta Marketplace for Embedded finance) also began in Jaunary 2023, aiming to develop a secure federated data marketplace for embedded finance (EmFi) in order to demonstrate the full potential of the data economy. FAME will develop a federated cloud environment with multiple providers of EmFi data assets, including datasets and AI/ML models. The project goal is to implement several pilots.

Figure 2: Example of a visual resource (a search for term GRAPES)

In the areas of Text and Network Analysis and Language Technologies, in 2023 we began work on two new Horizon Europe project, TWON and PREPARE. The EU Horizon Europe project TWON (TWin of Online social Networks) aims to develop a novel empirical method for systematically researching the effects of design choices of mechanisms inside Online Social Networks (OSNs) by creating digital twins of social network sites, called TWONs. It has been argued that personalization algorithms create the so-called filter bubbles and echo chambers where users' opinions are reinforced, amplifying processes of opinion polarization. Despite frequent calls for interventions to minimize such undesired effects, there is no agreed-upon method for estimating the effects of changing the parameters of the design of a social network service. Crucially, the complexity of such systems makes it hard to translate the results of isolated experiments into an estimate of the overall effects. Once developed, a TWON can be used to study counterfactuals such as: what would the effects look like, had the OSN been designed differently. The project started in April 2023 and our department is leading two work packages: the implementation of TWON as well as the work package related to legal and ethical issues.

The Horizon Europe project PREPARE (Personalized rehabilitation via novel AI patient stratification strategies) began in June 2023 with the objective of advancing personalised and holistic rehabilitation for musculoskeletal disorders. This will be done by creating methodologies for extracting relevant information from patient records, implementing novel patient stratification strategies, and providing personalized treatment recommendations. Doing so would empower the tool users, specifically doctors, enabling them to provide more effective assistance and engage in improved shared decision-making with their patients. As part of the project, the Department for Artificial Intelligence is tasked to develop a tool to convert and merge unstructured and structured health care data including textual descriptions. The primary goals of this task include development of the AI methods for detecting and extracting relevant information from health care data, incorporating multilingual support to expand the model's utility, and integrating human interactions in the model training process.

We concluded the H2020 EU Marie Skłodowska-Curie ITN project CLEOPATRA (Cross-lingual Event-centric Open Analytics Research Academy). The PhD students took part in a poster session where they showcased a poster highlighting individual research endeavors, contributions to the field of research, and prospective career plans. Additionally, two PhD theses were submitted, a chapter entitled "Analysis of Event-Centric News Spreading Barriers" was contributed for the Cleopatra OA Book and several journal and conference papers were published as a result of the research carried out during the project.

Within the scope of national and regional projects, we concluded the project Development of Slovene in a Digital Environment (RSDO). The operation was co-financed by the Republic of Slovenia and the European Union from the European Regional Development Fund. The operation was carried out within the framework of the Operational
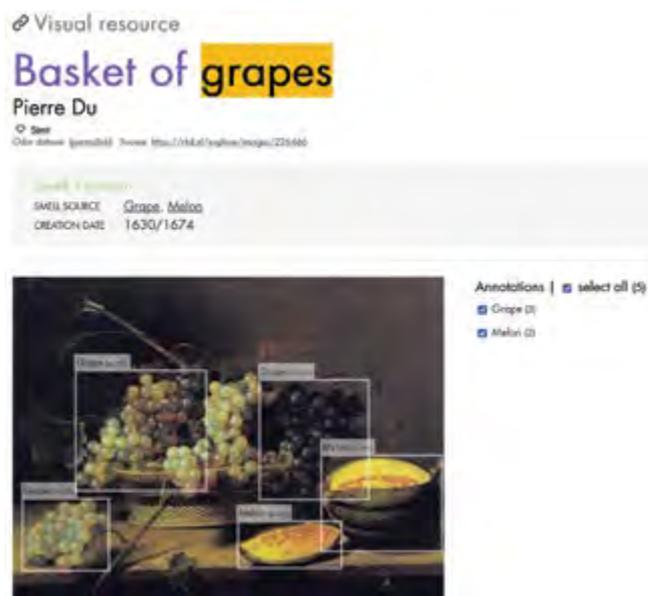
Programme for the Implementation of the EU Cohesion Policy 2014–2020. Among the results are new language resources, tools for Slovenian language processing, and applications (upgraded text corpora, speech recognition, semantic technologies, machine translation, terminology portal and maintenance of the language technology center – CLARIN.SI). We also completed the SLOKIT project (Corpus Informer and Text Analyzer). Two entirely new language tools were created within the project. The first is a corpus data summarizer, Korpusnik, which provides a quick overview of a word usage in five corpora of the Slovenian language. Users can check the usage of words in standard, contemporary, academic, online, and spoken Slovenian in one place. The second notable result of the project is an application for sentence simplification and analysis, SENTA. The application identifies and simplifies complex sentences, while leaving simple sentences unchanged. It also provides a basic statistical analysis of the text. Both resources are adapted for use by individuals with special needs. Additionally, an upgrade of the data in

the reference corpora Gigafida and the reference corpus of spoken Slovenian, Gos, was carried out within the project. Three workshops were also conducted as part of the project, aimed at presenting the resources to individuals with special needs and their professional associates. The SEMTEH project (Connected Knowledge Bases for Semantic Technologies), funded by the Ministry of Culture of the Republic of Slovenia under the Public Call for (Co)Financing Projects for the Construction and Updating of Infrastructure for the Slovenian Language in the Digital Environment 2023 (JR-infrastructure-SJ-2023) was also concluded in 2023. The first version of the semantic lexicon Open

Simon Krek and Jaka Čibej were among the authors of the best paper at the DIGIN 2023 conference. The paper was Online Notes – A Real-Time Speech Recognition and Machine Translation System for Slovene University Lectures (https://www.rtvslo.si/dostopno/kako-omogociti-digitalno-vkljucenost-vseh/684648).

Slovene WordNet (OSWN 1.0) is openly accessible on the CLARIN.SI repository. This language resource contains synsets – sets of synonymous expressions (literals) illustrating a specific concept. All of them have been manually reviewed. In version 1.0, each synset is also equipped with an English definition and its machine translation into Slovenian, along with a cross-lingual index through which Slovenian expressions can be linked to expressions in lexicons for other languages. The OSWN data is also integrated into the Digital Dictionary Database for Slovenian, which is being developed at the Center for Language Resources and Technologies at the University of Ljubljana. Links between synset IDs and meaning IDs are also openly accessible in the database.

In 2023 we continued to lead the Slovenian research infrastructure CLARIN.SI in cooporation with E8. CLARIN.SI enables easy publication and sustainable access to digital language data for researchers in humanities and social sciences. In addition to providing support for the CLARIN.SI repository, we uploaded numerous data (lexical resources, corpora, lists) and technologies for processing the Slovenian language. With the financial support from CLARIN.SI, we created a website with a comprehensive overview of the systems for annotating Slovenian corpora, the CJVT Wiki. It provides an overview of linguistic annotation in Slovenian texts and outlines the steps necessary for the development of various language technologies. The CJVT Wiki presents corpus annotation at different levels, such as tokenization, sentence segmentation, and lemmatization. In 2023, a training set of annotated, automatically extracted collocation data was created. Within the project, a training set of collocation candidates was generated, automatically extracted from the reference corpus Gigafida 2.0, and annotated according to the collocational relevance. This training set will also be integrated into the Digital Dictionary Database for Slovenian at the Center for Language Resources and Technologies at the University of Ljubljana.

In the area of Semantic Technologies and Text Mining, the H2020 project ODEUROPA (Negotiating Olfactory and Sensory Experiences in Cultural Heritage Practice and Research), which aimed at applying the state-of-the-art AI techniques to cultural heritage text and image datasets spanning four centuries of European history, identifying and tracing how 'smell' was expressed in different languages, with what places it was associated, what kinds of events and practices it characterized, was successfully concluded. In the final year of the project, the Odeuropa partners finalized development of the project tools, organized and participated in smell related events (workshops, conferences, dissemination to public) and discovered a significant number of smell textual and visual resources from the available data sources. In particular, the Department for Artificial Intelligence contributed to the extraction of smell-related knowledge from the Slovenian Odeuropa corpora. We developed a methodology for fine-grained emotion detection and extracted the emotions related to smell in English, French, Dutch and Italian languages. In November 2023, our department participated in final Odeuropa event – Odeuropa Smell Culture Fair. The event attracted researchers in the area of smell, historians, IT professionals from different European institutions and provided the foundation for evaluation and validation of Odeuropa outcomes – Smell Explorer, Encyclopedia of Smell History and Heritage, Olfactory Storytelling Toolkit and Nosebooks Demonstrators.

In the area of Knowledge Management and Sustainability, the group's main focus includes research and development using methods and tools from the broader Artificial Intelligence area in real business settings in sustainable and responsible ways. The Horizon 2020 project HumanE-AI-Net (Making artificial intelligence human-centric) brings together the leading European research centres, universities and industrial enterprises into a network of centres of excellence. The project that started in September 2020 is encouraging global artificial intelligence (AI)

laboratories to collaborate with the key players in areas such as human-computer interaction, cognitive, social and complexity sciences. In 2023 the Department for Artificial Intelligence collaborated on a micro-project focusing on developing new AI methods for analysing the patient report data and providing interpretable explanations and new knowledge for rare diseases. A specific focus was the Kleefstra syndrome cohort retrieved from the Genida registry (Genetics of Intellectual Disability and Autism Spectrum Disorders registry), collecting caregiver-reported data, as the rare-disease patients covered are children and/or adults with intellectual disabilities. The aim was to show what information the collected data contains, and how to present this data to the clinicians in a structured, insightful, and helpful way.

Figure 3: Slovenian AI Observatory including a graphical representation of local indicators. The graph displays the number of published scientific articles on the topic of 'machine learning.' The publications listed have at least one author from each country for the period between 1985 and 2022. The data source is Microsoft Academic Graph.

The new Horizon Europe project ELIAS (European Lighthouse of AI for Sustainability) began in September 2023 and aims to be the European Lighthouse of AI for Sustainability. It builds on and expands the highly successful and internationally recognized European Laboratory for Learning and Intelligent Systems (ELLIS). ELIAS will develop the excellence criteria and the pillars within ELLIS and implement the actions that will support AI researchers and young talents at different stages of their careers. Furthermore, ELIAS will develop a science entrepreneurship track, with the purpose of attracting and empowering talents at the interface of scientific innovation and business, and establish original AI solutions that move towards a sustainable long-term future of our planet, contribute to a cohesive society, and respect individual rights. The Department for Artificial Intelligence in involved in one use case, through the work on IRCAI's SDG Observatory which defines the use case specifications and requirements that will be considered in order to demonstrate the AI solutions developed within the other tasks. We are also developing emergent behaviors from LLMs enabling geopolitics agent simulations.

The Horizon Europe project AI4Gov (Trusted AI for Transparent Public Governance fostering Democratic Values) started in January 2023 and has been introducing novel and unbiased AI technologies for the context of policy making. The aims of the project are to introduce solutions and frameworks towards a two-fold sense, facilitate policymakers for the development of automated, educated and evidence-based decisions and increase the trust of citizens in democratic processes and institutions. The project will leverage the capabilities of the state-of-the-art tools for providing un-bias, discrimination-free, fair, and trusted AI. These tools will be validated in terms of their ability to provide technical and/or organizational measures, causal models for bias and discrimination, and standardized methodologies for achieving fairness in AI.

The promotion of science is continually present in the efforts of our department. In 2023 members of the Department for Artificial Intelligence were very active in promoting artificial intelligence and science in general. Some examples are included below:

- Marko Grobelnik gave numerous talks and several interviews on the topic of artificial intelligence and the revolution of large language models, including "The genie escaped from the bottle" for the Slovenian multimedia portal 24 ur.com; "Will artificial intelligence surpass humans? ChatGPT between opportunity and threat" for RTVSLO, Studio at 5 pm; "ChatGPT simulates a smart interlocutor well, but it does not understand texts, so it gets lost in them" for The Current Topic; "From tool to author: navigating the field of artificial intelligence after its boom" for the Faculty of Arts & STA.
- Dunja Mladenić gave a talk at the OECD event: AI foresight: anticipating what lies ahead.
- Dunja Mladenić had a presentation on AI to tackle the shortage in human resources for health at the High-Level Meeting on Strengthening the Healthcare Systems in South-Eastern Europe. Dunja Mladenić delivered several keynote speeches on AI opportunities and challenges for both professionals and the general public at several events in Slovenia, including Responsible Future of Media AI & Sustainability Conference, and AI: get ready for the future! organized by Slovenian magazine Finance.
- Dunja Mladenić participated in several panels on AI including "IT tour – a journey into the world of artificial intelligence: opportunities and pitfalls" at IT Tour 2023, "Roundtable discussion by business leaders" at IEDC's Annual Presidents' Forum 2023 and "AI the decision maker of tomorrow?" at Confindustria Udine.
- Jože Rožanec presented his research papers at 4 international conferences.
- Inna Novalija participated in a webinar Applying AI to Cultural Heritage Text Analysis within the Odeuropa project, Artificial Intelligence Solutions in Libraries.
- Erik Novak gave a talk on the Fundamentals in AI at the AI4Gov Training Workshop: Bias in AI.
- Erik Novak participated at 2 roundtable discussions, one on the topic of AI and libraries, the other on the topic of AI and finance.

- Erik Novak gave several lectures on various AI topics including two lectures at Slovenian high schools and one for the Ministry of Public Administration.
- Erik Novak was a panellist at the Open Education for a Better World Eduscope 2023.
- Simon Krek was a keynote speaker at a conference in Tallinn, presenting a lecture entitled Digital Dictionary Database for Slovenian: unstructured, semi-structured and structured data in modern lexicography.

Together with the Centre for Knowledge Transfer in Information Technologies (CT3), we continued to use the Videolectures.NET portal to promote artificial intelligence, the Jožef Stefan Institute and Slovenian research in general. We are also among the main organizers and supporters of the annual national ACM Computer Science Competition for secondary-school students; in 2023, 129 students from 31 schools participated in the competition. We have also been active in promoting women in science, providing a virtual exhibition about female PhD holders in the area of computer science and electrical engineering in Slovenia. We are also constantly updating our publicly available resources related to women-in-science issues and related international news (http://ScienceWithArt.ijs.si/).

Gender equality to unlock research potential is the topic of the H2020-CSA project Athena in which we focused on monitoring the implementation of Gender Equality Plans (GEPs) at the institutional level. Several accomplishments of the past year demonstrate the Institute's commitment to advancing gender equality. Notably, we changed the criteria for scientific progression that were identified as the key obstacle in the career progression and retention of women researchers. Substantial progress was made by adopting gender-sensitive language, which is most prominently reflected in the language of the revised Statute of the Institute, adopted on 8 December 2023. The first JSI Annual Gender Equality Assessment Report was approved by the JSI Board of Governors at its meeting on 27 February 2023.

In 2023 the International Research Center on Artificial Intelligence under the auspices of UNESCO – IRCAI, a laboratory within the Department for Artificial Intelligence, received funding for the Horizon Europe project RAIDO (Reliable AI and Data Optimisation) and will act as its primary coordinator when the project begins in 2024. RAIDO will give rise to a powerful framework designed to support the development of trustworthy and green AI. Throughout the past year, IRCAI has also been brought on board for six other Horizon Europe projects. IRCAI's NAIXUS project (Network of AI Researchers on AI and the United Nations SDGs) convened a significant meeting during the Deep Learning Indaba 2023 in Ghana. The purpose of this meeting was to discuss the progress of the project, share insights, and plan future actions to strengthen the network's impact on advancing the United Nations Sustainable Development Goals (SDGs) through AI research. It also hosted a workshop aimed to foster collaboration among AI researchers and practitioners to address the challenges posed by the United Nations Sustainable Development Goals (SDGs). In 2023, IRCAI and AWS launched the Compute for Climate Fellowship to fund new tech solutions addressing the climate crisis. It is the first-of-its-kind global program supporting entrepreneurs and start-ups applying advanced cloud computing and artificial intelligence to create new solutions that address the climate crisis. The program selected and fully funded proofs of concept for new ideas leveraging advanced computing in the cloud, including generative AI and complex systems modeling and simulation, to help solve some of the biggest challenges in the fight against climate change. IRCAI also continued its traditional yearly activities, including the latest edition of the international list of artificial intelligence innovations for sustainable development for the benefit of humanity, comprising stakeholders working to achieve 17 Sustainable Development Goals, covering multiple sectors and every geographic region of the United Nations. Additionally, the IRCAI Award for 2023 was presented to researchers for the outstanding achievements of their projects in the field of artificial intelligence solutions in tackling development issues.

The paper Fostering Research & Innovation in AI through Regulatory Sandboxes co-authored by Jože Rožanec was selected as the third-best paper at the 16th International Technology Transfer Conference.

Some outstanding publications in the past year

1. Bai, Chongyang, Chen, Haipeng, Kumar, Srijan, Leskovec, Jurij, Subrahmanian, V. S. M2P2: multimodal persuasion prediction using adaptive fusion. IEEE Transactions on Multimedia. 2023, vol. 25, pp. 942–952, illustr. ISSN 1941-0077 Rei, Luis, Mladenić, Dunja. Detecting fine-grained emotions in literature. Applied Sciences. Jul. 2023, vol. 13, iss. 13, [article no.] 7502, pp. 1–26

2. Rei, Luis, Mladenić, Dunja, Dorozynski, Mareike, Rottensteiner, Franz, Schleider, Thomas, Troncy, Raphaël, Sebastián Lozano, Jorge, Gaitán Salvatella, Mar. Multimodal metadata assignment for cultural heritage artifacts. Multimedia Systems. [Online ed.]. Apr. 2023, vol. 29, iss. 2, pp. 847–869

3. Sebastián Lozano, Jorge, Alba Pagán, Ester, Martínez Roig, Eliseo, Gaitán Salvatella, Mar, León Muñoz, Arabella, Sevilla Peris, Javier, Vernus, Pierre, Puren, Marie, Rei, Luis, Mladenić, Dunja. Open access to data about silk heritage: a case study in digital information sustainability. Sustainability. Oct. 2023, vol. 15, iss. 19, pp. 1–30

Jožef Stefan Institute

4. Rožanec, Jože Martin, Novalija, Inna, Zajec, Patrik, Kenda, Klemen, Fortuna, Blaž, Mladenić, Dunja, et al. Human-centric artificial intelligence architecture for industry 5.0 applications. International Journal of Production Research. 2023, vol. 61, iss. 20, pp. 6847-6872

5. Swati, Swati, Mladenić, Dunja, Grobelnik, Marko. An inferential commonsense-driven framework for predicting political bias in news headlines. IEEE Access. 2023, vol. 11, pp. 1–17

6. Swati, Swati, Mladenić Grobelnik, Adrian, Mladenić, Dunja, Grobelnik, Marko. A commonsense-infused language-agnostic learning framework for enhancing prediction of political bias in multilingual news headlines. Knowledge-Based Systems. [Online ed.]. 2023, vol. 277, [article no.] 110838, pp. 1–15

7. Bobrowski, Omer, Škraba, Primož. A universal nulldistribution for topological data analysis. Scientific Reports. 2023, vol. 13, article no. 12274, pp. 1–13, illustr. ISSN 2045-2322

Awards and Appointments

1. Jose Martin Rožanec: Third-best paper at the 16th International technology transfer conference, 16th International Technology Transfer Conference, Fostering Research & Innovation in AI through Regulatory Sandboxes, JSI, Ljubljana

Organization of Conferences, Congresses and Meetings

1. Policy dialogue: Stronger Together through the power of Artificial Intelligence, 7 March 2023 (virtual)
2. 8th Multi-stakeholder Forum on Science, Technology and Innovation for the Sustainable Development Goals. Side event: Artificial Intelligence and Data Science for society and the public good: technologies, applications, and governance, 2–3 May 2023 (virtual)
3. European Parliament - EuroGPT Forum, Brussels, Belgium, 25 May 2023
4. Visit of defence diplomatic representatives of the Republic of Slovenia abroad, 8 June 2023
5. IRCAI and Amazon Web Services (AWS) Launch Compute For Climate Fellowship to Fund New Tech Solutions Addressing the Climate Crisis, Ljubljana, 25 July 2023
6. Naixus workshop "Building a Global Network of AI Researchers", Accra, Gana, 3–9 September 2023
7. Multi-factor Authentication delegation visit to South African Republic, 4–8 October 2023
8. SiKDD, Slovenian KDD Conference, Ljubljana, 9 October 2023 (hybrid)
9. Digital for Development (D4D) Hub AI, working group meeting, 27 October 2023 (virtual)
10. IRCAI hosting ASEFClassNet16, "Leading Change: Digital Transformation of Education in the Era of AI", Ljubljana, 12–16 November 2023
11. AI and Disinformation Scoping Workshop, D4D Hub and the Department for International Partnerships, Brussels, Belgium, 14-15 December 2023

INTERNATIONAL PROJECTS

1. D4D HUB AI; D4D Hub Artificial Intelligence
   Mihajela Črnko
   Deutsche Gesellschaft Für Internationale
2. LDS Workshop; A Common European Language Data Space
   Asst. Prof. Simon Krek
   Dfki Gmbh - Deutsches Forschungszentrum Fuer
3. ERASMUS+: BRIDGES - Bridging Educational Emergency to Digital Pedagogies
   Kim Sevšek
   Agenzia Nazionale Erasmus Plus Indire
4. COST CA18209; European Network for Web-Centred Linguistic Data Science
   Asst. Prof. Simon Krek
   COST Association Aisbl
5. COST CA18231; Multi3Generation: Multi-Task, Multilingual, Multi-Modal Language Generation
   Marko Grobelnik
   COST Association Aisbl
6. H2020 - Cleopatra; Cross-Lingual Event-Centric Open Analytics Research Academy
   Marko Grobelnik
   European Commission
7. H2020 - INFINITECH; Tailored IoT&BigData Sandboxes and Testbeds for Smart, Autonomous and Personalized Services in the European Finance and Insurance Services Ecosystem
   Marko Grobelnik
   European Commission
8. H2020 - FACTLOG; Energy-aware Factory Analytics for Precess Industries
   Prof. Dunja Mladenić
   European Commission

9. H2020 - HumanE-AI-Net; HumanE AI Network
   Marko Grobelnik
   European Commission
10. H2020 - STAR; Safe and Trusted Human Centric Artifical Intelligence in Future Manufacturing Lines
    Marko Grobelnik
    European Commission
11. H2020 - ODEUROPA: Negotiating Olfactory and Sensory Experiences in Cultural Heritage Practice and Research
    Prof. Dunja Mladenić
    European Commission
12. H2020 - ATHENA; Implementing Gender Equality Plans to Unlock Research Potential of RPOs and RFOs in Europe
    Prof. Dunja Mladenić
    European Commission
13. HE - CONDUCTOR; Fleet and Traffic Management Systems for Conducting Future Cooperative Mobility
    Prof. Dunja Mladenić
    European Commission
14. HE - enRichMyData; Enabling Data Enrichment Pipelines for AI-Driven Business Products and Services
    Marko Grobelnik
    European Commission
15. HE - Graph-Massivizer; Massive Graph Processing of Extreme Data for a Sustainable Economy Society and Environment
    Marko Grobelnik
    European Commission

16. HE - Plooto; Product Passport through Twinning of Circular Value Chains
Mitja Jermol, M. Sc.
European Commission
17. HE - Ai4Gov; Trusted AI for Transparent Public Governance Fostering Democratic Values
Mitja Jermol, M. Sc.
European Commission
18. HE - FAME; Federated decentralized trusted dAta Marketplace for Embedded finance
Marko Grobelnik
European Commission
19. HE - NANCY; An Artificial Intelligent Aided Unified Network for Secure Beyond 5G Long Term Evolution
Marko Grobelnik
European Commission
20. HE - APRIORI; Active PRoduct-to-Process LearnIng fOR Improving Critical Components Performance
Prof. Dunja Mladenić
European Commission
21. HE - TWON; TWin of Online social Networks
Marko Grobelnik
European Commission
22. HE - PREPARE; Personalized Rehabilitation via Novel AI Patient Stratification Stategies
Marko Grobelnik
European Commission
23. HE - ELIAS; European Lighthouse of AI for Sustainability
Prof. John Stewart Shawe-Taylor
European Commission
24. EIT Climate-KIC; UP SCALE - Urban Pioneers - Systemic Change Amid Livable Environments
Prof. Dunja Mladenić
Cinea - European Climate, Infrastructure
25. HE - HumAIne; Hybrid Human-AI Decision Support for Enhanced Human Empowerment in Dynamic Situations
Marko Grobelnik
European Commission
26. AIRISE - International Policy Observatory Framework
Prof. John Stewart Shawe-Taylor
Iceed - International Council On Environmental
27. COST CA21167; UniDive - Universality, Diversity and Idiosyncrasy in Language Technology
Asst. Prof. Simon Krek
Cost Association Aisbl
28. Stronger Together
Mihajela Črnko
The British Council

RESEARCH PROGRAMME

1. Knowledge Technologies
Prof. Dunja Mladenić

R&D GRANTS AND CONTRACTS

1. Correlating desired phenotypic traits using behavioural, physiological and anatomical features with genetic markers in Lipizzan horse
Dr. Aljaž Košmerlj
2. Defining a framework to ensure public trust in systems and applications of Artificial Intelligence
Marko Grobelnik
3. A framework for measuring the potential of artificial intelegence implementation in Slovenia with an in-depth analysis of the situation in Slovenia and the EU and a multi-method approach to analysis of status and trends in Slovenia
Prof. Dunja Mladenić
Government Digital Transformation Office
4. Proteverb - Legal, ethical and technological aspects of processing textual and speech

data for scientific, research and development purposes
Asst. Prof. Simon Krek
Government Digital Transformation Office
5. Slovenian Artificial Intelligence Observatory
Prof. Dunja Mladenić
Government Office for the Protection of Classified Information
6. Slo2World - Connecting cultures, information and learning through open educational resources and artificial intelligence
Prof. John Stewart Shawe-Taylor
7. Clarin
Asst. Prof. Simon Krek
Institut Jožef Stefan
8. FAIR
Asst. Prof. Simon Krek
Slovenian Research Agency
9. A framework for measuring the potential of artificial intelegence implementation in Slovenia with an in-depth analysis of the situation in Slovenia and the EU and a multi-method approach to analysis of status and trends in Slovenia
Prof. Dunja Mladenić
Služba Vlade Republike Slovenije
10. Proteverb - Legal, ethical and technological aspects of processing textual and speech data for scientific, research and development purposes
Asst. Prof. Simon Krek
Služba Vlade Republike Slovenije
11. Defining a framework to ensure public trust in systems and applications of Artificial Intelligence
Marko Grobelnik
Služba Vlade Republike Slovenije
12. Elexis Association
Asst. Prof. Simon Krek
13. SLOKIT: Upgrade of CLARIN.SI: Corpus informer and text analyzer
Dr. Iztok Kosem
Ministry of Culture
14. IRCAI - International Research Center for Artificial Intelligence – UNESCO
Mitja Jermol, M. Sc.
Ministry of Higher Education, Science and Innovation
15. SEMTEH - Linked Knowledge Bases for Semantic Technologies
Asst. Prof. Simon Krek
Ministry of Culture
16. Digitization of analytical support in the national crisis management center
Marko Grobelnik
Ministry of Defence
17. Slovenian Artificial Intelligence Observatory
Prof. Dunja Mladenić
Ministry of Public Administration
18. Slovenian Artificial Intelligence Observatory
Prof. Dunja Mladenić
Ministry of Foreign and European Affairs
19. Slovenian Artificial Intelligence Observatory
Prof. Dunja Mladenić
Government Office for the Protection of Classified Information
20. Slovenian Artificial Intelligence Observatory
Prof. Dunja Mladenić
Ministry of Higher Education, Science and Innovation
21. Slo2World - Connecting cultures, information and learning through open educational resources and artificial intelligence
Prof. John Stewart Shawe-Taylor
Ministry of Foreign and European Affairs
22. Management of the European Statistics Award for Web Intelligence - LOT 1
Marko Grobelnik
European Commission
23. Management of the European Statistics Award for Nowcasting - LOT 2
Marko Grobelnik
European Commission
24. Slovenian Innovation Ecosystem Watch
Marko Grobelnik
Google Ireland Limited

VISITORS FROM ABROAD

1. Franco Spicciariello, Amazon Web Services, Paris, France, 8-10 March 2023
2. Sasha Rubel, Amazon Web Services, Paris, France, 8-10 March 2023
3. Sargis Ghazaryan, Amazon Web Services, Paris, France, 8-10 March 2023
4. Umida Tukhtasheva, Deputy Director of the Anti-Corruption Agency, Tashkent, Uzbekistan, 21 March 2023
5. Makhtumjon Akhmedov, Head of the Internal security division, Tashkent, Uzbekistan, 21 March 2023
6. Akmal Muratov, Lead Inspector of the international cooperation Department, Tashkent, Uzbekistan, 21 March 2023
7. Bakhramjan Burkhanitdinov, Lead Inspector of the Department for public relations, Tashkent, Uzbekistan, 21 March 2023
8. Sanatulla Yunusov, Lead Inspector of the Department for income and asset declaration of civil servants, Tashkent, Uzbekistan, 21 March 2023

9. Hudayberdi Tursunbekov, Senior prosecutor of the Scientific-educational Center for fighting against corruption of the Academy, Tashkent, Uzbekistan, 21 March 2023
10. Natalya Goncharova, Interpreter, Tashkent, Uzbekistan, 21 March 2023
11. Aziz Eshbekov, RD Program Specialist, Tashkent, Uzbekistan, 21 March 2023
12. Franco Spicciariello, Amazon Web Services, Paris, France, 13-14 April 2023
13. Sasha Rubel, Amazon Web Services, Paris, France, 13-14 April 2023
14. Sargis Ghazaryan, Amazon Web Services, Paris, France, 13-14 April 2023
15. Charles Ange Ginesy, President of the Alpes Maritimes and Mercantour National Park department, Sophia Antipolis, France, 15 May 2023
16. David Konopnicki, Vice-President Smart Deal, Departement des Alpes Maritimes, Sophia Antipolis, France, 15 May 2023
17. Yannick Bernard, President of Green deal, Departement des Alpes Maritimes, Sophia Antipolis, France, 15 May 2023
18. Mr. Lombardo, President of Territorial Attractiveness Commission, Departement des Alpes Maritimes, Sophia Antipolis, France, 15 May 2023
19. Christophe Picard, Departement des Alpes Maritimes, Sophia Antipolis, France, 15 May 2023
20. José Ammendola, SICTIAM, Sophia Antipolis, France, 15 May 2023
21. Isabelle Galy, Director, House of Artificial Intelligence, Sophia Antipolis, France, 15 May 2023
22. Mr. Fabris, Public policy officer, Departement des Alpes Maritimes, Sophia Antipolis, France, 15 May 2023
23. Hanna Kisrane, Chief of staff, Departement des Alpes Maritimes, Sophia Antipolis, France, 15 May 2023
24. Tawfik Jelassi, Deputy Director General UNESCO, Paris, France, 27-30 August 2023

STAFF

Researchers
1. Asst. Prof. Špela Arhar Holdt*
2. Dr. Kaja Dobrovoljc*
3. Prof. Branko Kavšek*
4. Dr. Iztok Kosem*
5. Asst. Prof. Simon Krek
6. Prof. Jurij Leskovec
7. **Prof. Dunja Mladenić, Head**
8. Prof. John Stewart Shawe-Taylor
9. Asst. Prof. Primož Škraba

Postdoctoral associates
10. Dr. Krisztian Antal Buza
11. Dr. Jaka Čibej*
12. Dr. Blaž Fortuna
13. *Dr. Blaž Fortuna*, left 19.08.23*
14. Dr. Alenka Guček
15. Dr. Luka Stopar
16. Dr. Oleksandra Topal

Postgraduates
17. *Swati, M. Sc., left 30.01.23*
18. Rayid Ghani, M. Sc.
19. *Jakob Jelenčič, B. Sc., left 01.10.23*
20. Mitja Jermol, M. Sc.
21. Klemen Kenda, B. Sc.
22. Mark D Minevich, M. Sc.
23. Erik Novak, B. Sc.
24. Dr. Jose Martin Rožanec
25. Dr. Abdul Sittar
26. Jan Šturm, B. Sc.

Technical officers
27. Dr. Luka Bradeško

28. Dr. Janez Brank
29. Erik Calcina, B. Sc.
30. Dr. Miha Cimperman
31. Dr. Wayne Holmes
32. Dr. Matej Kovačič
33. Dr. Gregor Leban*
34. Jose Luis Machado Rei, M. Sc.
35. M Besher Massri, B. Sc.
36. Dr. Inna Novalija
37. Dr. Ervin Pfeifer*
38. Matej Polzelnik, B. Sc.
39. Dr. Jan Rupnik*
40. Dr. Polona Škraba Stanič
41. Maja Škrjanc, B. Sc.
42. Dr. Tanja Zdolšek Draksler

Technical and administrative staff
43. Aleš Buh
44. Mihajela Črnko, B. Sc.
45. Jasna Franko, B. Sc.
46. Marko Grobelnik
47. Mojca Kregar, B. Sc.
48. Monika Kropej, B. Sc.
49. Blaž Novak, B. Sc.
50. *Kim Sevšek, B. Sc., left 01.03.23*
51. Špela Sitar, B. Sc.
52. Mateja Škraba, B. Sc.
53. Martina Vilhar, B. Sc.

Note:
* part-time JSI member

LABORATORY FOR OPEN SYSTEMS AND NETWORKS E-5

The main activities of the laboratory are R&D in the area of next-generation networks, internet technologies, components and integrated systems, information-society services, mechanisms, and applications, especially those that enable better privacy protection of citizens and increased security and trustworthiness of the information and communication technologies and services.

The research in 2023 was performed within the research programme *Future Internet Technologies: concepts, architectures, services and socio-economic issues*, funded by the Slovenian Research and Innovation Agency. In addition, research was carried out within the EU Horizon 2020 projects CONCORDIA, DE4A, BD4OPEM and iFlex, the EU Horizon Europe project RESONANCE, the SiQUID project from the EU Digital Europe programme, and the national project *Cybersecurity and large language models*. Research on digital skills for older people was carried out within the Erasmus+ project DIGIBLEND, and activities on gender equality in the EU Horizon 2020 project ATHENA.

Members of the laboratory teach at the undergraduate and postgraduate levels at the Jožef Stefan International Postgraduate School, the DOBA Faculty, and the Faculty of Commercial and Business Sciences. The laboratory is a member of European Cyber Security Organisation (ECSO).

Head:
Asst. Prof. Tomaž Klobučar

Concepts and architectures of the secure internet, internet technologies and information systems

Research in the first area was related to security infrastructure and trusted services in the areas of public administration and industrial systems.

The main goal of the **DE4A** ("Digital Europe for All") project, which was successfully completed in 2023, was to facilitate migration towards secure European digital public services co-delivered across borders, across sectors and with different participants, and implement the latest EU directives and regulations (e.g., eIDAS, Single Digital Gateway). The project simplified the cross-border user's interaction with the selected procedures, systems and platforms, and demonstrated in practice the benefits for different stakeholders of realizing across borders the principles of Once-Only and Digital-by-Default. Our main role in the project was to coordinate the Studying Abroad pilot, one of the three project pilots, and analyse the current eGovernment landscape. The pilot has implemented and validated the cross-border higher-education procedures for the Single Digital Gateway Regulation, in particular applications to higher-education institutions, applications for study grants, and the recognition of diplomas. In 2023, with the help of students from Spain and Portugal, we tested a secure cross-border

> We have created building blocks for security infrastructures and secure internet services, supporting the process of digitalization in the public sector.

grant-application service that allows students to use their national eIDs to access the service and explicitly request the use of the DE4A technical system to have their evidence required by the service transferred electronically from an authentic source in their home country. In this way, students no longer have to search for evidence and fill in the necessary application forms by themselves. We further collected feedback on the usefulness of the common components and specifications, analysed the benefits of the piloted services for students, higher-education institutions, and Member States, identified lessons learnt in the analysis, design, customization, and integration phases, and formulated suggestions for adoption. Other Slovenian partners in the project were the Ministry of Education, Science and Sport, the Ministry of Public Administration, and the University of Maribor.

Over the past year, our focus on security architectures and critical infrastructure has been widened by exploring the design and application of digital twins within the cybersecurity domain. This encompassed the entire system life cycle, from inception to implementation and management, with a holistic perspective on security, covering aspects of detection, protection, response and analysis. Our findings were documented in two scientific publications: *Securing critical infrastructures with a cybersecurity digital twin* and *Taxonomy-based risk analysis with a digital twin*. The former introduces a pioneering methodology for crafting a security-centric digital twin tailored to cyber-physical critical systems. This method adopts an architectural security-by-design approach, applicable to both new and existing systems, resulting in a comprehensive asset catalog structured within a cybersecurity architecture viewpoint. This facilitates the selection of appropriate countermeasures based on the desired security objectives, ensuring the integrity of the digital twin design while providing practitioners with clear modeling guidelines aligned with existing standards for critical infrastructure security. We validated this methodology through application to real-world cases, such as Cooperative Intelligent Transport Systems (C-ITS) and Industrial Automation and Control

Systems in road tunnels, which yielded targeted cyber-attack scenario analyses and corresponding risk-mitigation countermeasures.

Building on these findings, we proposed a framework that integrates the human-centric aspect of security assurance through taxonomy-based risk analysis with a digital twin. We demonstrated how taxonomies, digital enterprise models, and visual modeling tools can be harnessed to conduct risk analysis and risk management, effectively bridging the communication gap between technical and non-technical stakeholders. By involving all
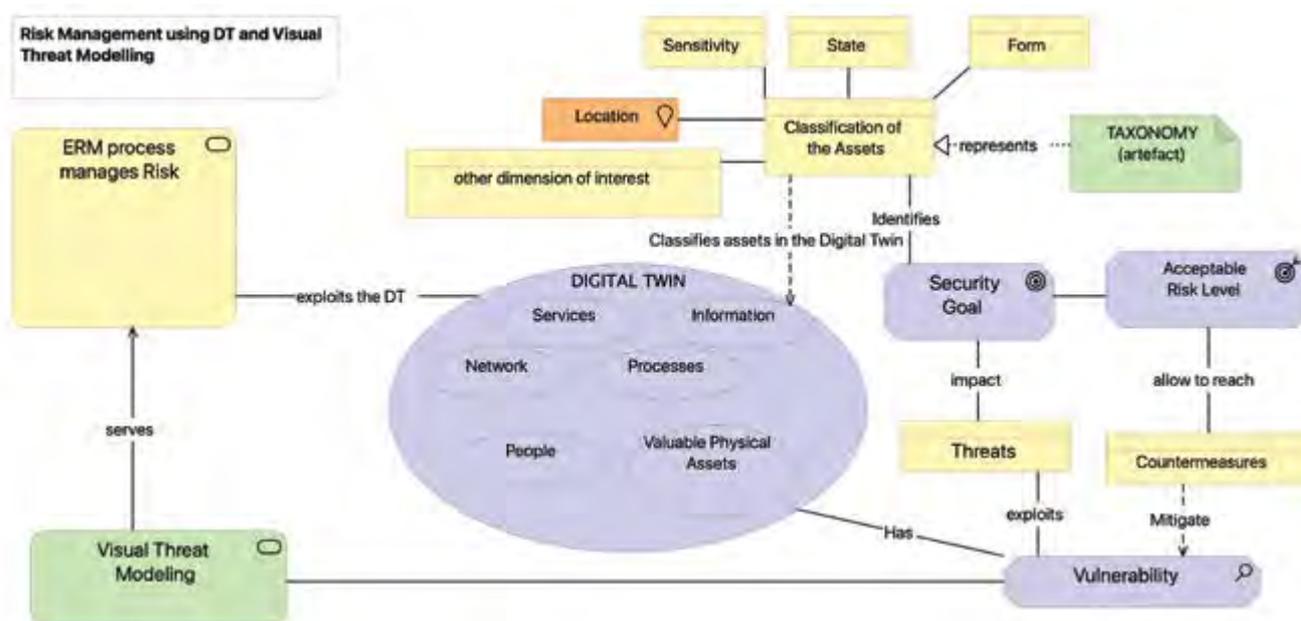
Figure 1: Risk management using a digital twin and visual threat modelling

relevant parties in the decision-making process related to enterprise risk management, we addressed a critical need in today's organizations, where security expertise is increasingly scarce.

As part of the **infrastructure programme in research organizations** we continue to provide support services that enable better communication among members of various research programmes, as well as students and their mentors from geographically dispersed institutions. The equipment needed to organize large and interactive online events is available for institute members as well for governmental and public, non-profit institutions. In addition, the infrastructure programme provides GoToMeeting licences and, together with the Centre for Network Infrastructure, additional Zoom licences. The services and licences were provided to 31 departments, laboratories, centres and other organizational units of the Institute.

Digital services and internet technologies in energetics

A large share of the projects is related to the planning, implementation and use of digital services and internet technologies in the energy sector.

The **BD4OPEM** (Big Data for Open Innovation Energy Marketplace) project uses a data-centric approach to innovate between the needs of energy stakeholders and the solutions being developed. A data flow through the marketplace enables the development of analytic services to boost business processes. To date, the laboratory has focused on predictive maintenance, non-technical loss analysis, flexibility prediction in the distribution network, and the privacy and security of the marketplace and services. A module for service provision and automated service management has been developed and deployed in the local cloud environment. Services were fine tuned for the environment and the environment integrated with the project marketplace. The department

> **Internet technologies facilitate the integration of end-users in the electricity market and help power distributors in market operations.**

services were tested and evaluated in Slovenian, Spanish and Turkish pilots. Two JSI departments, our laboratory and the Department of Communication Systems, participate in the project, while Elektro Celje is a key Slovenian partner from the energy sector.

The **iFlex** (Intelligent Assistants for Flexibility Management) project focuses on the design, development and evaluation of supporting tools for consumers' successful participation in various flexibility services of the smart grid of the future and for their easier pursuit of sustainability goals in their premises. A strong Slovenian consortium is

participating in the project: Elektro Celje, Elektro Celje Energija, Smart Com, Slovene Consumers Associations, and the JSI Laboratory for Open Systems and Networks. The tasks of the laboratory include security and privacy of the project solutions, data analytics, consumer profiling, development of the digital twin of the consumer premises and optimal, multicriteria control of consumers' power consumption in their homes. In 2023 we used the developed and locally deployed basic data-management service for pilot consumers and continued developing a digital twin of a household with a heat pump and a storage boiler. The digital twin was improved with a methodology for identifying household physical construction parameters based on the standard RC model and the family of Neural ODE models. The developed services are currently being tested and evaluated as part of the Slovenian pilot.

The **Resonance** (Replicable and Efficient Solutions for Optimal Management of Cross-sector Energy) is developing a catalogue of hardware and software solutions for the efficient management of energy consumption and production for a wide range of end users. The end users supported are households, apartment buildings, office buildings, shopping centres, and industry. The elements of the catalogue are being developed at three levels: resource manager, customer energy manager, and aggregation. The developed catalogue solutions are evaluated in pilots in six countries: France, Germany, Sweden, Finland, Greece, and Slovenia. A strong Slovenian consortium is involved in the project: ECE, Elektro Celje, SmartCom, Amibit, and the JSI. The initial focus of the Slovenian pilot is on households with heat pumps and renewables, price-based demand response, and aggregation for imbalance management and renewables balancing. In the second piloting cycle, the solutions developed in other pilots will be evaluated: apartment-building heating, the network batteries and electric-vehicle charging, and optimization of solutions for energy efficiency. In the project we are leading the work package on the resource-manager catalogue and the tasks related to secure and privacy-preserving data management.

Mechanisms for security and privacy provision in information systems

Advanced technologies that promise more effective cybersecurity provision include artificial intelligence (AI), which is especially useful in analysing and processing a large number of security-relevant events and in detecting and responding to unknown threats and forms of cyber-attacks. In the **Cybersecurity and large language models** project, we started to investigate the possibility of using large language models (LLMs) to enhance cybersecurity and to locally deploy and fine-tune an open source LLM for cybersecurity needs. The results will enable a better understanding of the role, potential and performance requirements of LLM-based systems in cybersecurity, and facilitate the integration of such systems into existing IT systems and with other security solutions, such as firewalls, intrusion detection systems, etc.

Furthermore, in the scientific journal *Information fusion*, with an impact factor of more than 18, we presented a new taxonomy of AI methods for cybersecurity and described use cases of AI for cybersecurity. Based on a literature
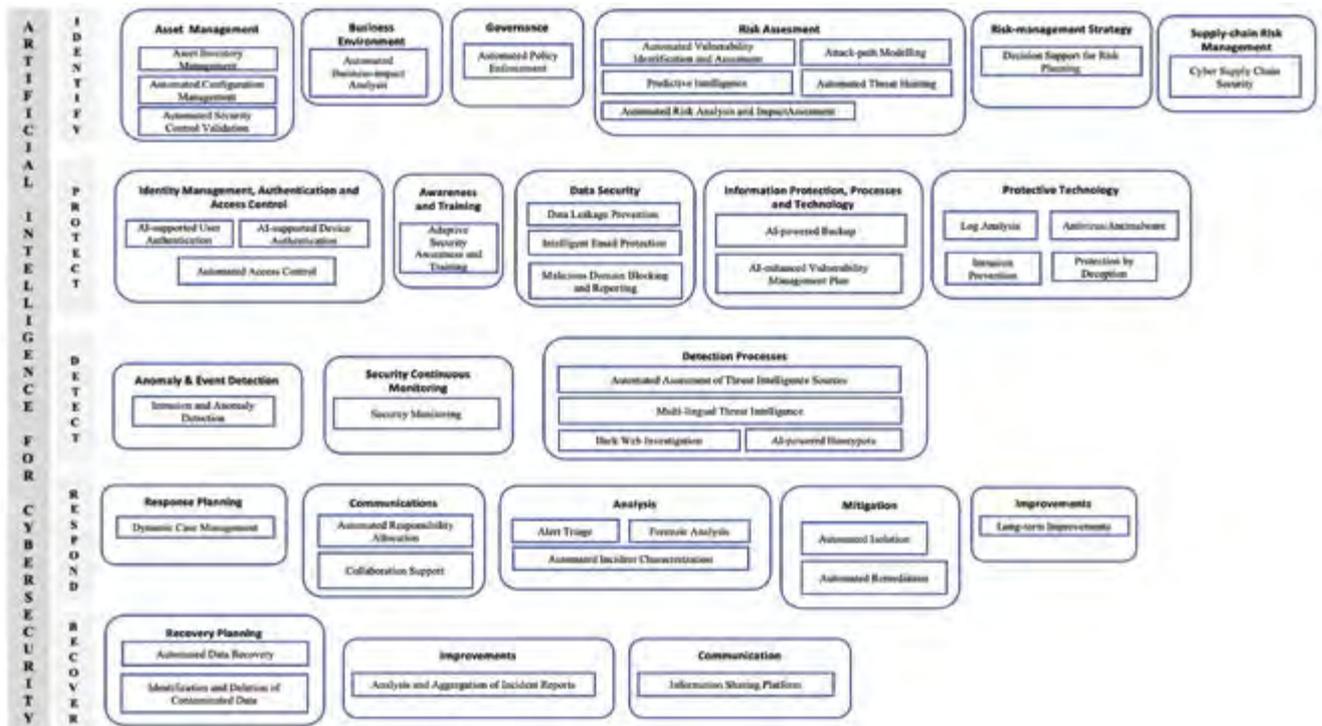

Figure 2: AI-based use cases for cybersecurity

analysis, we created a list of research and development gaps, which were classified into four groups: i) new areas of AI use in cyber security, (ii) data sources and presentation, (iii) advanced AI methods for cyber security, and (iv) research and development of new infrastructure.

The Laboratory for Open Systems and Networks was a member of **CONCORDIA** (Cyber security competence for research and innovation), one of the four European centres of excellence in cyber security from the H2020 programme with leading competences in research, technology, industry and the public domain. The centre provided research and development solutions for a safe, resilient and trustworthy European ecosystem. In 2023 we completed an important part of the planned programme. Based on a comprehensive international survey on the state and needs of secondary-school students in the EU, a modern, flexible and interactive educational programme was developed for teaching secondary-school students and for improving the knowledge of computer-science teachers

> **Our research and development activities and results enable a more secure and trustworthy information society.**

in the area of cybersecurity. The survey showed that cybersecurity topics are missing from educational programmes and that high school teachers lack this knowledge. The new cybersecurity education programme, which includes e-resources for interactive learning and school exercises similar to the real environment, as well as educational games, was implemented in

the first school semester of 2023 in 9 schools across Europe. A total of 330 students from Slovenia participated. The impact of the newly developed programme was evaluated by organizing an international Catch the Flag competition online. Some 19 teams from schools in Romania, Croatia and Slovenia took part in the competition, with the best Slovenian team coming fifth. The program was found to have been successful in bringing cybersecurity skills and knowledge to EU high-school students and teachers.

From the beginning of 2023 we have been involved together with several other research departments and centres at the JSI (F1, F5, E6, CMI) in an important project **SiQUID** (Slovenian Quantum Communication Infrastructure Demonstration). Its aim is to establish quantum key distribution (QKD) links among multiple government nodes in Slovenia, while also creating a test-bed quantum network for advanced quantum-communication protocols among research institutions in Ljubljana. Our laboratory is involved in collecting use cases and defining system security requirements, as well as in assessing the risks of deploying QKD technology and interconnections with existing security systems. Based on this research, we will also propose necessary adjustments to existing security policies
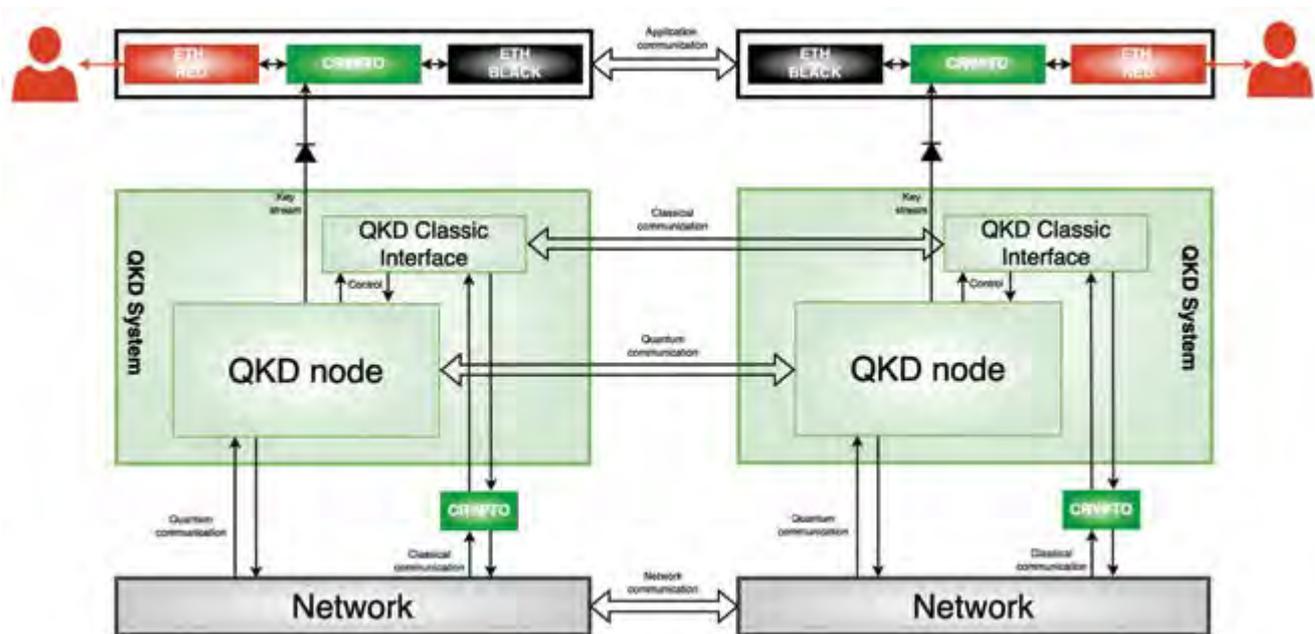
Figure 3: Quantum key distribution for network protection

to mitigate risks. In the first year, we defined the requirements that must be met by the SiQUID system, including security, QKD, functional, integration, and cross-border interoperability requirements. Moreover, we proposed an architecture design to ensure that the system's security objectives are achieved. We have also identified the key challenges and open research questions in the field of quantum networks, and presented potential solutions to enable the realization of secure and trustworthy quantum networks. As quantum networks continue to evolve, addressing these challenges will be crucial to realizing their full potential for secure communication and computation. The results were published in a scientific paper in the journal "IEEE Access".

Information-society services, applications and socio-economic issues

Successfully teaching basic digital skills to older adults requires an approach that is tailored to their needs and abilities. Within the scope of the ERASMUS+ project Improving adult digital literacy through innovative gamified blended learning (**DIGIBLEND**) we continued our research in crafting a novel instructional paradigm for enhancing basic digital competencies among older adults. We formulated an experimental protocol aimed at scrutinizing the efficacy of a knowledge-assessment board game. Building upon the insights from this preliminary study, we proceeded to innovate further by conceptualizing an integrated approach that combines the physical and digital gaming world by developing a hybrid board game to be played both in physical and online modalities. Concluding the year, we outlined a subsequent study to evaluate the attributes and efficacy of the refined game.

The Laboratory for Open Systems and Network is involved with several other research departments and the Director's Office at the Jožef Stefan Institute in the Athena project, aiming at removing barriers to the recruitment, retention and career progression of female researchers, lowering gender imbalances in decision-making processes and generating a cultural change needed to avoid gender bias and discriminatory practices through the implementation of Gender Equality Plans (GEPs). In 2023, training was provided for the Institute's employees on GEP to make appropriate contributions for ensuring systemic institutional change. In parallel, an inclusive cooperation process was set up, the goal of which was to understand the needs and wishes of the employees of the institute, on the one hand, and to familiarize them with selected topics related to equal treatment of the genders on the other. In 2023, language requirements ensuring gender equality were included in the new JSI statute, and the Scientific Council adopted a new version of the required condition for career advancement of JSI researchers, which now ensures a more flexible implementation of the required postdoctoral studies abroad.

Figure 4: Knowledge assessment with board games

Some outstanding publications in the past three years

1. Kaur, R., Gabrijelčič, D., Klobučar, T. Artificial intelligence for cybersecurity: literature review and future research directions. *Information fusion*. [Online ed.]. Sep. 2023, vol. 97, [article no.] 101804, pp. 1-29.
2. Bajrić, S. Building a sustainable ecosystem for eHealth in Slovenia: opportunities, challenges, and strategies. *Digital health*. 2023, vol. 9, pp. 1-8.
3. Masi, M., Sellitto, G. P., Aranha, H., Pavleska, T. Securing critical infrastructures with a cybersecurity digital twin. *Software and systems modeling*. [Online ed.]. Apr. 2023, vol. 22, iss. 2, pp. 689-707.

Organization of conferences, congresses and meetings

1. Organization of a meeting with students of Bežigrad High School, 13 June 2023

INTERNATIONAL PROJECTS

1. ERASMUS+; DigiBlend - Improving Adult Digital Literacy Through Innovative Gamified Blended Learning
   Dr. Martin Mihajlov
   European Commission
2. H2020 - DE4A; Digital Europe for All
   Asst. Prof. Tomaž Klobučar
   European Commission
3. H2020 - BD4OPEM; Big Data for Open Innovation Energy Marketplace
   Dr. Dušan Gabrijelčič
   European Commission
4. H2020 - iFLEX; Intelligent Assistants for Flexibility Management
   Dr. Dušan Gabrijelčič
   European Commission
5. H2020 - ATHENA; Implementing Gender Equality Plans to Unlock Research Potential of RPOs and RFOs in Europe
   Prof. Borka Džonova Jerman Blažič
   European Commission
6. HE - RESONANCE; Replicable and Efficient Solutions for Optimal Management of Cross-Sector Energy
   Dr. Dušan Gabrijelčič
   Cinea - European Climate, Infrastructure
7. DIGITAL EU; SiQUID - Slovenian Quantum Communication Infrastructure Demonstration

Dr. Samed Bajrić
European Commission
8. COST CA21107; Work Inequalities in Later Life Redefined by Digitalization
   Dr. Martin Mihajlov
   Cost Association Aisbl

RESEARCH PROGRAMME

1. Future Internet Technologies: concepts, architectures, services and socio-economic issues
   Prof. Borka Džonova Jerman Blažič

R&D GRANTS AND CONTRACTS

1. Cybersecurity and large language models
   Asst. Prof. Tomaž Klobučar
2. Slovenian Quantum Communication Infrastructure Demonstration
   Dr. Samed Bajrić
   Government Information Security Office
3. Cybersecurity and large language models
   Asst. Prof. Tomaž Klobučar
   Government Information Security Office

VISITORS FROM ABROAD

1. Oliver Popov, Stockholm University, Department of Computer and Systems Sciences, Sweden, May 2023
2. Victor Tikhonov and Olena Tykhonova, State University of Intellectual Technologies and Telecommunications, Odesa, Ukraine, 13 December 2023

STAFF

Researchers
1. Dr. Ramanpreet Kaur
2. Asst. Prof. Rok Bojanc*
3. Prof. Borka Džonova Jerman Blažič
4. Dr. Dušan Gabrijelčič
5. **Asst. Prof. Tomaž Klobučar, Head**
6. Dr. Martin Mihajlov
7. Dr. Tanja Pavleska

Postdoctoral associates
8. Dr. Samed Bajrić
9. Dr. Primož Cigoj*

10. Dr. Andrej Jerman Blažič

Postgraduates
11. Jan Kincl, B. Sc.
12. **Technical officers**
13. Davud Topalović, B. Sc.

Technical and administrative staff
14. Tatjana Martun, B. Sc.

Note:
* part-time JSI member

DEPARTMENT OF COMMUNICATION SYSTEMS

E-6

The core activities of the Department of Communication Systems comprise the research, development and design of heterogeneous communication, computer and sensor networks, wireless technologies and next-generation communication services; the design of new procedures for the parallel and distributed computing of computationally intensive problems in various high-performance computing architectures and time-sensitive problems in edge devices; and the integration of sensor, communication, computing and data technologies to support digitalization and smart infrastructures. Within these activities our research includes the development and investigation of new methods and architectures, software tools and libraries, pilot deployments and experimental testbeds.

Head:
Prof. Mihael Mohorčič

The research and development activities at the department are carried out in three laboratories, the *Communication Technology Laboratory (CTL),* the *Parallel and Distributed Systems Laboratory (PDSL)* and the *Networked Embedded Systems Laboratory (NESL).* The research work of the three laboratories is complementary, which is reflected in the joint applied projects.

The introduction of intelligence into communication networks was an important part of the research activities of the **Communication Technology Laboratory** this year. Today, communication networks enable interactions between people, smart devices and access to various services. Like with user devices we are witnessing the introduction of artificial intelligence also in communication networks, in particular in wireless networks. The actions in intelligent wireless networks should be performed based on the experience and results of previous actions as well as the latest information about the status of the wireless radio environment. Our research is limited to the tasks related to the physical layer, in particular to the support of environmental information for channel state information (CSI) estimation and prediction, focusing on indoor wireless communications. In this context, we have developed a novel method that enables the prediction of wireless channel characteristics beyond what was previously available by taking advantage of environmental information, measured CSI, and information about the wireless nodes. Based on a survey of the system requirements of environmentally aware intelligent wireless networks, we have developed a system architecture that uses model- and data-driven approaches to predict CSI from environmental information and CSI estimates from training symbols. We have proposed and evaluated new, advanced methods, algorithms and approaches that enable the intelligent and environmentally friendly (for nature and people) utilisation of radio resources considering environmental information for indoor communication. Our focus is on algorithms for

Figure 1: Experimental setup for range-estimation localization with AoA using IEEE 802.15.4 TSCH communication technology.

the localization of radio nodes, the classification of the radio environment using the measured CSI and extensive measurement databases, and algorithms that complement the CSI and environmental information. Next, we have demonstrated the proposed concept on a Log-A-Tec testbed by applying UWB radio technology, and evaluated the proposed solution in terms of energy efficiency, environmental friendliness and intelligence in a real environment. By augmenting the estimation of CSI from training symbols with environmental information, we were able to improve the accuracy of the CSI prediction and consequently increase the net capacity of the communication link, reduce the energy consumption and consequently reduce the human exposure to non-ionised radio waves. In addition, the data-driven classification of the radio environment shortens the time for the CSI estimation and contributes to achieving the goal of future networks. This research was the subject of the basic research project J2-2507, "Towards the environment-aware intelligent wireless communications".

In wireless channel modelling we have continued the work started in previous years and dealt with deterministic channel modelling in terrestrial communication systems, especially for indoor environments, and statistical channel modelling in satellite communication systems. Among the deterministic channel models, ray tracing is the most widely used, but the electromagnetic properties of the reflective materials are generally unknown, so the ray-tracing models need to be calibrated by the channel measurements. In this context we have developed devices

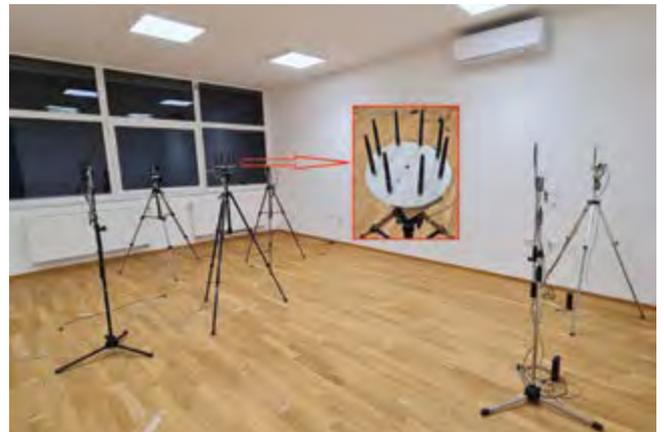for CSI estimation that can measure the angle of arrival (AoA) of the radio signal in addition to estimating the channel impulse response (CIR). We have focused on the 2.4 GHz band, but the concepts proposed can also be applied to higher frequency bands. The developed devices were used to collect data sets in different indoor environments. In addition, the radar channel measurements were performed in an urban-intersection environment using a frequency-modulated continuous-wave measurement system in the 77 GHz band. The measurements were used to calibrate the ray-tracing tools, which enable reliable virtual software-in-the-loop and hardware-in-the-loop testing of wireless communication system designs.

The ray-tracing method models only a subset of the known radio-wave propagation mechanisms and in its current form does not provide adequate radio channel models for next-generation communications. The reduction in the effective geographical area of the radio cells and the increase in computing power have opened up the possibility of solving the fundamental Maxwell equations numerically. We have investigated such techniques for modelling telecommunication channels in complex environments as part of the basic research project J2-3048, "Advanced modelling of radio channels

We developed a phase-based distance estimation that is integrated into the IEEE 802.15.4 TSCH communication.

using ray-optical and numerical meshless methods". Based on the investigation of numerical mesh and meshless methods, it was recognised that these methods are too computationally intensive for the mmWave and THz bands. Therefore, we have focused on quantum algorithms for modelling electromagnetic propagation, which promise a speedup far beyond that of classical algorithms. We have examined current progress by reviewing recent proposals in this area. We took a closer look at the potentially advantageous quantum architectures, ranging from mainstream gate-level computing and short-term, medium-scale, noisy architectures with limited capabilities to adiabatic and annealing approaches that are already in commercial use. We have analysed the weaknesses and strengths of recent proposals. We have found that quantum computers can overcome the temporal and spatial limitations of classical methods for larger computational domains, and to some extent solve the problems of dispersion and stability in finite-difference approximations. We have also identified the most promising techniques and scenarios that hold the greatest potential.

Future wireless services will often require environment sensing as part of the application functionality. Therefore, the coexistence of communication, sensing and localization is foreseen in 6G systems. In this context we have investigated the parameters of the propagation channel and the applicability of THz electromagnetic waves for integrated communications and sensing, and explored new challenges and differences that arise when starting from systems operating at frequencies below the THz bands, namely severe path loss due to the small wavelength and smaller antenna aperture, larger Rician K-factor, a decrease in RMS delay spread that increases with the propagation distance, and the sparsity of the channel in the angular domain. The research was conducted as part of the basic research project J2-4461 "Terahertz radio waves for sensing and localization in future 6G communication systems".

We also continued research on the Internet of Things (IoT), focusing on localization and positioning. We have developed two new methods of phase-based ranging for wireless technologies based on the 6TiSCH (IPv6 over TSCH mode of IEEE 802.15.4e) standard. The proposal improves known algorithms by reducing the number of phase samples required without reducing the accuracy and sensitivity of the algorithm, while increasing energy efficiency. We have also developed a uniform circular antenna array with 12 monopole antennas and RF switches to select the active antenna for estimating the direction of arrival (DoA) of the signal for Bluetooth Lower Energy (BLE) systems. The system was tested in a semi-controlled environment and achieved a direction-of-arrival estimation error of less than 1 degree. We extended the wireless experimentation platform with features that support experiments with BLE technology.

We proposed a non-intrusive, privacy-preserving approach to presence monitoring based on Wi-Fi wireless technology. The method makes it possible to monitor the presence and movements of individuals or crowds in a given area and can thus provide valuable insights into actual behavioural patterns and trends. The method preserves individual privacy through a novel de-randomization technique that detects individual devices by grouping similar network management messages and corresponding radio channel characteristics using a novel clustering and matching method. The results show that the proposed de-randomization method is able to correctly detect more than 96% of devices in rural and indoor environments.

In the area of signal processing, we also performed extensive statistical analysis on the signals obtained from 3 years of beacon measurements from the Alphasat satellite at 19.7 GHz and 39.4 GHz. We have analysed the tropospheric scintillation fading and compared it with the ITU-R P.618-13 model.

The laboratory also continued with active participation in several working groups of the COST Action CA 20210 INTERACT "Intelligence-enabling radio communications for seamless inclusive interactions". The aim of this action is to achieve scientific breakthroughs by introducing novel design and analysis methods to make future radio-communication networks intelligent, i.e. aware, adaptive, and parsimonious, and to contribute to the creation of intelligent environments.

In the **Parallel and Distributed Systems Laboratory** we continued developing local mesh-free methods for the numerical solving of systems of partial differential equations (PDEs).

In 2023 we experimented with our hp-adaptive solution procedure based on an iterative solve–estimate–mark–refine paradigm and published the findings in a paper titled "Strong form mesh-free hp-adaptive solution of linear elasticity problem" in the prestigious journal Engineering with Computers.

We continued our research on a hierarchical algorithm for the generation of quasi-uniform and variable density spatial nodes on domains whose boundaries are represented as computer-aided design (CAD) models, more specifically non-uniform rational B-splines (NURBS). We provided evidence that the node sets generated by our algorithm meet the requirements in terms of local regularity and separation distances. In addition, we introduced a hybrid regular-scattered node-positioning algorithm to improve the computational efficiency. We have demonstrated that the generated node sets are well-suited (both in terms of accuracy and numerical stability) for meshless radial basis function generated finite differences (RBFFD) analysis by solving several problems ranging from Poisson's equation to Navier-Stokes and Navier-Cauchy equations, in both 2D and 3D.

We have made further progress in our investigations regarding the oscillatory behaviour of the RBF-FD solution accuracy under increasing stencil size. We have expanded our analyses to a much greater set of problem configurations and confirmed

Figure 2: Concept of efficient use of transformers leveraging the DTR technology (left) and scheme of the multi-body physical model (right).

that the observed behaviour remains. Additionally, as previously observed, a (non-trivial) connection to the pointwise error behaviour has been observed in all the considered cases. We also began applying these observations to more realistic problem setups that could arise in practice.

We have explored the application of hyperviscosity stabilisation to the RBF-FD method for simulating natural convection-driven flow, focusing on its effects as the flow approaches the turbulent regime. We introduced hyperviscosity as a higher-order Laplacian operator to introduce numerical dissipation, helping to stabilise the numerical scheme without significantly impacting the accuracy of the solution.

In the area of solidification simulations, we developed a sharp Meshless Interface Tracking (MIT) formulation of the Grain Envelope Model (GEM). In MIT, the envelope (interface) is defined as a moving domain boundary and the interface-tracking nodes are boundary nodes for the diffusion problem solved in the domain. To increase the accuracy of the method for the diffusion-controlled moving-boundary problem, an h-adaptive spatial discretization is used, thus, the node spacing is refined in the vicinity of the envelope.

In 2023, in the Nature journal Scientific Reports, we published a paper entitled "A framework for comparative study of databases and computational methods for arrhythmia detection from single-lead ECG". The paper presents ECGDL: an open-source, flexible and configurable ECG classification codebase, as one of the first efforts that includes 9 arrhythmia datasets, covering a large number of both morphological and rhythmic arrhythmias, as well as 4 deep neural networks, 4 segmentation techniques and 4 evaluation schemes. We performed a comparative analysis along these framework components to provide a comprehensive perspective into arrhythmia classification.

We developed a sharp Meshless Interface Tracking formulation of the Grain Envelope Model.

We have continued our collaboration with the Geological Survey of Slovenia and the University of Ljubljana, Faculty of Arts, Department of Geography on the ARRS project J1-2479 "Past climate change and glaciation at the Alps-Dinarides junction". One of the project goals is to model the glacier, the subglacier and the climate with enough precision to obtain a good match between a simulated and an empirically determined glacier extent. When analysing the available models, we discovered that the subglacier dynamics are an order of magnitude less influential than the climate forcings in our chosen geographical areas. Therefore, we have diverted our effort into finalising local climatological models to achieve a higher fidelity of simulation results.

We continued research within the ARRS project J7-2599 "Decay of an invasive ctenophore bloom as a perturbation to the coastal marine microbial community". In 2023 we completed our work on the new population model and summarised our conclusions in a paper entitled "Dynamic Population Modelling of Bacterioplankton Community Response to Gelatinous Marine Zooplankton Bloom Collapse and its Impact on Marine Nutrient Balance", which is under review in the scientific journal Progress in Oceanography.

In cooperation with the Faculty of Electrical Engineering (FE) and the Communication Technology Laboratory, we continued the research in the project J2-3048 "Advanced modelling of radio channels using ray-optical and numerical meshless methods". We have made some initial attempts at generalising the well-known Finite-Difference Time-Domain (FDTD) method to a meshless setting, which was again done with the Radial Basis Function generated

Finite-Differences (RBF-FD) method. We have verified that our generalisation reduces to the FDTD method for the simple case of a grid and further analysed its properties, in particular, properties related to stability and dispersion.

In cooperation with the Faculty of Sport and the Laboratory for Machine Intelligence at the Faculty of Electrical Engineering, we continued with the project J3-3115 "AiCoachU – Artificial intelligence is coaching you". During the last phase of the project, we provided technical assistance and further software improvements.

In collaboration with the Faculty of Computer and Information Science (FRI), InnoRenew (SI) and the Alfréd Rényi Institute of Mathematics (HU), we have completed the project N2-0171 "Graph Theory and Combinatorial Scientific Computing". Within the project, we further developed an algorithm for finding k-cliques in k-partite graphs, which we deployed to the National Institute of Chemistry, where it is used for the faster matching of proteins with an unknown function to known binding sites. We also used the developed framework in a combinatorial competition, where we were able to solve all of the presented problems.

In collaboration with the F1 department and the Communication Technology Laboratory, we continued the work on the project V1-2119 "Cryptographically secure random number generator". We have developed a demonstration application that generates random numbers from selected sensors on the Android and iOS operating systems. The application was used to collect data from more than twenty different modern smartphones. The data was later analysed to determine the amount of noise in the raw measurements. The application and results of the analysis were demonstrated within a project-organised workshop.
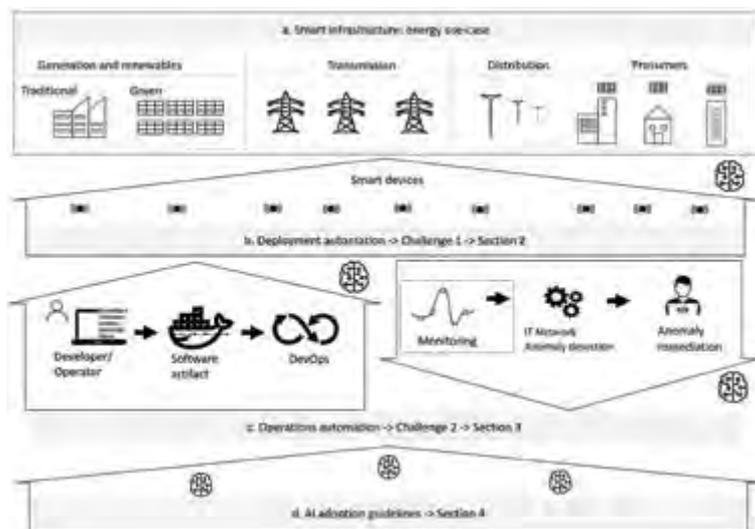

Figure 3: Smart infrastrucures: Lifecycle automation with artificial intelligence

In collaboration with the University of Wrocław we continued with the project N2-0275 "Inertial effects on fluid flow in complex porous media", where we have developed two different meshless approaches for solving the fluid-flow problem, namely the meshless Lattice-Boltzmann method and the direct solution of the Navier-Stokes equation based on the RBF-FD method. Both approaches were compared and verified on the geometry of periodic overlapping spheres, which is used for a comparison with the reference solution.

In the scope of applied research, we continued the development of DiTeR – a modular dynamic thermal rating (DTR) software designed to predict the thermal state of power lines, which is in operational use at ELES, ltd. and is marketed world-wide by the company Operato. In 2023 we continued with the maintenance of the system and performed pilot deploys for different transmission system operators. We also started a system redesign on behalf of the company Operato.

In 2023 we executed a pilot project on weather-data analysis and dynamic thermal rating evaluation to assist TransnetBW (Baden-Württemberg transmission operator) to better understand their system and maximising the use of dynamic line rating. We performed a simulation of the DTR using a CIGRE TB601-based algorithm with given weather parameters and electric current for a period of 8 years and interpreted the results for the customer.

In 2023 we started a project that deals with the downscaling of mesoscopic meteorological variables over complex terrain that is agnostic to the underlying mesoscopic model. The goal of this project is to support our other DTR-related project with weather data for specific locations, taking into account the local terrain, which is a crucial input for the DTR models.

In 2023 we successfully completed the TRAFOFLEX project, in which we developed, implemented, and validated a model for describing the thermal state of power transformers in collaboration with the Milan Vidmar Electric Power Research Institute, Elektro Gorenjska, and a subsidiary of the Slovenian transmission operator Operato. Since the project's completion, the model has been in operational use.

Research in the **Laboratory for Networked Embedded Systems** is focused on furthering the state of the art in smart infrastructures with the aim of improving their accessibility, usability, and resource efficiency. In this process, we are building on existing knowledge and solutions in signal processing and time-series modelling from the perspective of decision-making using various artificial intelligence techniques, such as representation learning, deep learning, clustering, and classification.

As part of the research program Communication Networks and Services (P2-0016), we continued studying and adapting machine learning and deep learning for advanced radio-resource management based on a data-driven approach. Furthermore, we investigated energy consumption, efficiency and automation aspects of data processing in queues and for model development in 5G mobile systems. To better position the research, we first identified the two

main challenges in the lifecycle of smart infrastructures: deployment and operation, each of which is rather generic and applies to all ICT-enabled infrastructures. We continued the work for detecting and recognizing anomalies in wireless networks, as part of their operation in large-scale IoT deployments, such as smart factories and cities, by developing new methods inspired by advances in machine vision and graph neural networks. Furthermore, we developed new methods for recognizing radio-spectrum activity from large volumes of unlabelled sweeps through feature learning and self-supervised learning techniques. We also investigated the role of deployment automation and automatic decision making through human-friendly conversational agents, zero-touch initial provisioning, resource instantiation and scaling in small premises towards O-RAN and reinforcement learning.

In addition to our work on the research programme, in 2023 we successfully completed the Horizon 2020 project BD4OPEM, continued research work on the Horizon Europe (HE) MSCA project TimeSmart, and started a new HE)project NANCY and Digital Europe Programme (DEP) project SiQUID, as well as the ARIS projects TIMIN6 and AI-ASSIST.

In the BD4OPEM project (Big Data for OPen innovation Energy Market-place) we concluded our activities with full integration of our data-driven services for grid-disturbance simulations, flexibility aggregation, energy management at the household/community level and demand estimation in the project's developed energy marketplace as well as with the preparation

We developed new methods for activity and fault/anomaly detection and identification from time series.

of a service demonstrator. These data-driven services support efficient and automatic management of distributed renewable energy sources and loads for shifting or reduction of peak energy demand and the fluctuations in transport and distribution as well as the optimization of energy consumption to fluctuating power tariffs.

In 2023, for the ongoing MSCA Individual Fellowship TimeSmart (Timeliness of Information in Smart Grids Networks), the research fellow focused on applying the Age of Information (AoI) metric in smart grids to improve the short-term energy forecasting. AoI, which measures data freshness in communication networks, was evaluated for its potential to enhance the short-term forecasting capabilities of smart grids. In parallel, we also investigated dynamic pricing for electrical energy, assessing its impact on cost reduction for smart homes with photovoltaic panels and energy-storage systems. This research aimed to identify how different pricing strategies could help smart homes manage energy consumption and production more effectively.

In January 2023 we started the SiQUID (Slovenian Quantum Communication Infrastructure Demonstration) project as the Slovenian part of the European Union's initiative to implement the infrastructure for a Europe-wide network for quantum communication. The aim of SiQUID is to perform a proof-of-principle demonstration of quantum communication and quantum key distribution (QKD) using an entanglement-based principle. The project will establish quantum communication links between multiple government nodes in Slovenia and an experimental test-bed quantum network between research institutions in Ljubljana for the research and development of advanced quantum communication protocols. In 2023 our main contributions were in system-architecture design and network-topology definition, also taking into consideration the impact of the selected underlying principle of the QKD system and the suitability of the existing QKD protocols.

In January 2023 we started the HE NANCY (An Artificial Intelligent Aided Unified Network for Secure Beyond 5G Long Term Evolution) project. The overall aim of NANCY is to introduce a secure and intelligent architecture for the beyond-the-fifth-generation (B5G) wireless network. Leveraging AI (Artificial Intelligence) and blockchain, NANCY enables secure and intelligent resource management, flexible networking, and orchestration. In this direction, novel architectures, namely point-to-point (P2P) connectivity for device-to-device connectivity, mesh networking, and relay-based communications, as well as protocols for medium access, mobility management, and resource allocation will be designed. Our role is to lead an AI-aided orchestration and intelligence work package and a resource elasticity task.

In October 2023 we also started two ARIS-funded projects, a basic project J2-50071 TIMIN6 (Timely and Sustainable Information Management in 6G Networks) and an applied project L2-50053 AI-ASSIST (Artificial intelligence based real-time power system stability assessment). In the first 3 months of the projects we focused in TIMIN6 on preparing the framework for metrics that will quantitatively define the sustainability of data generation in future networks (6G) using the concept of AoI, and in AI-ASSIST on data requirements for monitoring electric-power system stability with the support of AI methods.

Some outstanding publications in the past year

1. Novak, Roman. Quantum algorithms in electromagnetic propagation modelling for telecommunications. IEEE access. 2023, vol. 11, str. 111545-111565, ilustr. ISSN 2169-3536. https://ieeexplore.ieee.org/document/10273251, DOI: 10.1109/ACCESS.2023.3322446. [COBISS.SI-ID 168864515]
2. Kocevska, Teodora, Javornik, Tomaž, Švigelj, Aleš, Rashkovska, Aleksandra, Hrovat, Andrej. Identification of indoor radio environment properties from channel impulse response with machine learning models.

Electronics. 2023, vol. 12, [article no.] 2746, 21 f. ISSN 2079-9292. file:///C:/Users/Irena/Downloads/electronics-12-02746.pdf, DOI: doi.org/10.3390/electronics12122746. [COBISS.SI-ID 156252419]

3. Merdjanovska, Elena, Rashkovska, Aleksandra. A framework for comparative study of databases and computational methods for arrhythmia detection from single-lead ECG. Scientific reports. 2023, 13, article number 11682, str. 1-15, ilustr. ISSN 2045-2322. https://www.nature.com/articles/s41598-023-38532-9. [COBISS.SI-ID 159592451], [JCR, SNIP] kategorija: 1A2 (Z, A1/2);

4. Bertalanič, Blaž, Meža, Marko, Fortuna, Carolina. Resource-aware time series imaging classification for wireless link layer anomalies. *IEEE transactions on neural networks and learning systems*. [Print ed.]. Oct. 2023, vol. 34, iss. 10, str. 8031-8043, ilustr. ISSN 2162-237X. DOI: 10.1109/TNNLS.2022.3149091. [COBISS.SI-ID 98005507], [JCR, SNIP, WoSdo 11. 8. 2024: št. citatov (TC): 16, čistih citatov (CI): 10, čistih citatov na avtorja (CIAu): 3.33, Scopus do 25. 7. 2024: št. citatov (TC): 15, čistih citatov (CI): 10, čistih citatov na avtorja (CIAu): 3.33] kategorija: 1A1 (Z, A'', A', A1/2)

5. Fortuna, Carolina, Yetgin, Halil, Mohorčič, Mihael. Smart infrastructures : artificial intelligence-enabled lifecycle automation. *IEEE industrial electronics magazine*. [Print ed.]. Jun. 2023, vol. 17, iss. 2, str. 37-47, ilustr. ISSN 1932-4529. DOI: 10.1109/MIE.2022.3165673. [COBISS.SI-ID 106474243], [JCR, SNIP, WoS do 28. 3. 2024: št. citatov (TC): 3, čistih citatov (CI): 2, čistih citatov na avtorja (CIAu): 0.67, Scopus do 21. 3. 2024: št. citatov (TC): 3, čistih citatov (CI): 2, čistih citatov na avtorja (CIAu): 0.67] kategorija: 1A1 (Z, A', A1/2)

6. Milosheski, Ljupcho, Cerar, Gregor, Bertalanič, Blaž, Fortuna, Carolina, Mohorčič, Mihael. Self-supervised learning for clustering of wireless spectrum activity. *Computer Communications*. [Online ed.]. 1 Dec. 2023, vol. 212, str. 353-365, ilustr. ISSN 1873-703X. https://www.sciencedirect.com/science/article/pii/S0140366423003729?via%3Dihub, DOI: 10.1016/j.comcom.2023.10.009. [COBISS.SI-ID 168772867], [JCR, SNIP, WoS do 18. 8. 2024: št. citatov (TC): 1, čistih citatov (CI): 1, čistih citatov na avtorja (CIAu): 0.20, Scopus] kategorija: 1A1 (Z, A', A1/2)

Patent granted

1. Luiz A. DaSilva, Jernej Hribar, Method and system for energy aware scheduling for sensors, US 11,762,446 B2, US Patent Office, 19. 9. 2023

INTERNATIONAL PROJECTS

1. Analysis of Dynamic Thermal Rating of Overhead Power Lines
   Dr. Gregor Kosec
   Transnetbw GmbH
2. COST CA18203; ODIN - Optimising Design for Inspection
   Dr. Gregor Kosec
   Cost Association Aisbl
3. COST CA20120; INTERACT - Intelligence-Enabling Radio Communication for Seamless Inclusive Interactions
   Prof. Tomaž Javornik
   Cost Association Aisbl
4. H2020 - BD4OPEM; Big Data for Open Innovation Energy Marketplace
   Prof. Mihael Mohorčič
   European Commission
5. Machine Learning Supported Indoor Localization
   Dr. Klemen Bregar
   Slovenian Research Agency
6. HE - NANCY; An Artificial Intelligent Aided Unified Network for Secure Beyond 5G Long Term Evolution
   Dr. Carolina Fortuna
   European Commission
7. EIT Climate-KIC; UP SCALE - Urban Pioneers - Systemic Change Amid Livable Environments
   Prof. Andrej Hrovat
   Cinea - European Climate, Infrastructure
8. HE - TimeSmart; Timeliness of Information in Smart Grids Networks
   Prof. Mihael Mohorčič
   European Commission
9. DIGITAL EU; SiQUID - Slovenian Quantum Communication Infrastructure Demonstration
   Prof. Mihael Mohorčič
   European Commission

RESEARCH PROGRAMMES

1. Communication networks and services
   Prof. Mihael Mohorčič
2. Parallel and Distributed Systems
   Dr. Gregor Kosec

R&D GRANTS AND CONTRACTS

1. Past climate and glaciation at the Alps-Dinarides junction
   Dr. Gregor Kosec
2. Decay of an invasive ctenophore blooms as a perturbation to the coastal marine microbialcommunity - from molecules to ecosystem - an integrated interdisciplinary approach
   Dr. Gregor Kosec
3. Graph Theory and Combinatorial Scientific Computing
   Dr. Matjaž Depolli
4. AiCoachU – Artificial intelligence is coaching you
   Dr. Gregor Kosec
5. Towards the environment-aware intelligent wireless communications
   Prof. Aleš Švigelj
6. Advanced modelling of radio channels using ray-optical and numerical meshless methods
   Prof. Tomaž Javornik
7. Terahertz radio waves for sensing and localization in future 6G communication systems
   Prof. Andrej Hrovat
8. Inertial effects on fluid flow in complex porous media
   Dr. Gregor Kosec
9. Timely and Sustainable Information Management in 6G Networks (TIMIN6)
   Prof. Mihael Mohorčič
10. Artificial intelligence based real-time power system stability assessment (AI-ASSIST)
    Prof. Mihael Mohorčič
11. Cryptographically secure random number generator
    Dr. Matjaž Depolli
12. Slovenian Quantum Communication Infrastructure Demonstration

Prof. Mihael Mohorčič
Ministry of Public Administration
13. NOO-DIGITOP; Digital transformation of robot-supported factories of the future
Prof. Mihael Mohorčič
Slovenian Research Agency
14. Agreement on cooperation in the development and marketing of a dynamic thermal model for the assessment of transmission capacity of transmission lines
Dr. Gregor Kosec
Elektroinštitut Milan Vidmar
15. Cryptographically secure random number generator
Dr. Matjaž Depolli
Government Office for the Protection of Classified Information
16. CROSSING - Crossing Borders and Scales - An Interdisciplinary Approach

Dr. Matjaž Depolli
Helmholtz-Zentrum Dresden-Rossendorf E.v.

NEW CONTRACTS

1. Advanced concept of efficient use of transformers leveraging the DTR technology
Dr. Gregor Kosec
Operato d. o. o.
2. Downscaling meteorological variables over complex terrain
Dr. Gregor Kosec
Operato d. o. o.

VISITORS FROM ABROAD

1. Hongyu Duan, State Key Laboratory of Rail Traffic Control and Safety, Beijing Jiaotong University, Beijing, China, 30. 9. – 12. 10. 2023

2. Wu Qiang, prof. dr Guan Ke in Fan Lei, Beijing Jiaotong University, Beijing, China, 22. – 24. 12. 2023

STAFF

Researchers
1. Dr. Klemen Bregar*
2. Dr. Andrej Čampa*
3. Dr. Matjaž Depolli
4. Dr. Carolina Fortuna
5. Dr. Ke Guan
6. Dr. Jernej Hribar
7. Prof. Andrej Hrovat
8. Prof. Tomaž Javornik
9. *Dr. Arsim Kelmendi*, left 01.10.23*
10. Dr. Gregor Kosec
11. Prof. Andrej Lipej*
12. Dr. Maciej Grzegorz Matyka
13. **Prof. Mihael Mohorčič, Head**
14. Asst. Prof. Roman Novak
15. Asst. Prof. Aleksandra Rashkovska Koceva
16. Prof. Aleš Švigelj
17. Dr. Ivan Tomašić

Postdoctoral associates
18. Dr. Gregor Cerar
19. Shih-Kai Chou
20. Dr. Teodora Kocevska
21. *Dr. Sebastijan Mrak, left 01.06.23*
22. Dr. Filip Strniša
23. Dr. Nina Verdel

Postgraduates
24. Blaž Bertalanič, B. Sc.
25. Marko Hudomalj, B. Sc.
26. Mitja Jančič, B. Sc.
27. Andrej Kolar - Požun, B. Sc.
28. Ljupcho Milosheski, M. Sc.
29. Nika Mlinarič Hribar, B. Sc.
30. Grega Morano, B. Sc.
31. Miha Rot, B. Sc.
32. Aleš Simončič, B. Sc.
33. *Denis Sodin, B. Sc., left 01.07.23*
34. *Dr. Denis Sodin, left 01.07.23*
Technical officers
35. Miha Mohorčič, B. Sc.
36. *Blaž Rojc, B. Sc., left 01.02.23*
37. Miha Smolnikar, B. Sc.
Technical and administrative staff
38. Polona Anžur, B. Sc.
39. Tomaž Krištofelc
40. *Marko Mihelin*, B. Sc., left 01.04.23*
41. Nika Simčič, B. Sc.

Note:
* part-time JSI member

COMPUTER SYSTEMS DEPARTMENT
E-7

The Computer Systems Department is primarily concerned with the development of efficient optimization algorithms, intelligent massive-data processing, effective data management and visualization, and adaptive computing structures for a faster and more reliable execution of algorithms. Within this broad area, we focus on self-adaptive systems, modeling and optimization of complex, dynamic and non-deterministic systems. Our research results are used in applications for manufacturing, transportation, bioinformatics, nutrition, health, and medicine. As an integral part of our research activities, members of the department maintain close contacts and collaborations with scientists around the world through academic affiliations and industry contacts that enable us to stay at the forefront of rapidly evolving fields.

Head:
Prof. Gregor Papa

In 2023 we continued the work on our **research program** (Computer Structures and Systems – P2-0098) funded by the Slovenian Research and Innovation Agency. The program focuses on relevant research and development in areas related to reconfigurable systems: reliability, architectures for data-intensive systems, hardware/software co-design, resource planning and scheduling, adaptive and learning control methods, dynamic adaptation to changing contexts, decision and control in uncertain and changing environments. The interdisciplinary, cutting-edge research challenges combine areas of computer science, engineering, and mathematics. Our research work in 2023 was complemented by the design, development and implementation of various solutions in 18 European projects within the *Horizon 2020, Horizon Europe, ECSEL JU, PRIMA, EFSA, COST* and *Interreg* programs, as well as in 11 national projects. Our work is also actively connected to the activities of the Slovenian *Strategic Research and Innovation Partnerships* (SRIP) in the areas of *Smart Cities and Communities* (SC&C) and *Factories of the Future* (FoF).

Optimization algorithm design

Within real-world applications we carry out optimization under various criteria and constraints, involving also multiple, often time-consuming and conflicting objectives. These may require the use of computational intelligence or artificial intelligence and the support of complex numerical simulations.

In the second year of the ARIS research project *AutoOPT – Automated selection and configuration of single-objective continuous optimization algorithms* (https://cs.ijs.si/projects/199), conducted in collaboration with the Knowledge Technologies Department, we focused on collecting trajectory data obtained from running various instances of modular implementations of the Differential Evolution and Covariance Matrix Adaptation Evolution Strategy algorithms across more than 500 benchmark test problems. At the same time, extensive efforts were made to explore analytical features that can effectively capture problem characteristics that are critical for algorithm configuration and selection. Using **explainable machine learning techniques**, we can find the relationships between the characteristics of a problem instance and the performance of the optimization algorithm. In addition, we extended the OPTION ontology with the newly generated data. The main goal of our project is to enable users to obtain high-quality solutions to a given optimization problem instance without requiring in-depth prior knowledge of optimization algorithms or the specific problem instance. The research conducted within the project already resulted in numerous papers in journals and presentations at international conferences.
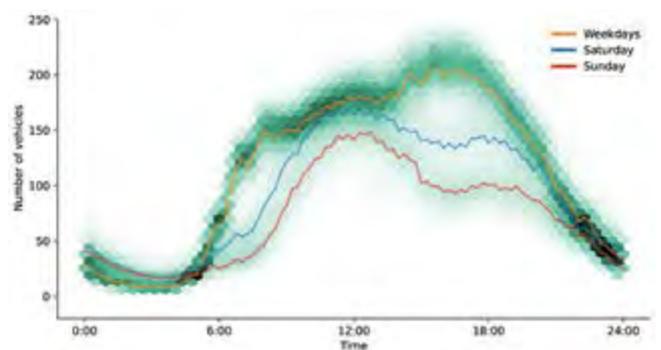
Figure 1: Differences between the morning and afternoon rush hours for traffic-flow predictions

In the context of **learning for optimization and meta-learning** (the work done within *RESPONSE – Representation Learning of Landscape Spaces for Explainable Performance of Stochastic Optimization Algorithms* (https://cs.ijs.si/projects/190), and bilateral *AutoDesign4EC – Automated Configuration, Selection, and Design of Iterative Optimization Heuristics*), we performed work to reduce the benchmarking bias in evolutionary computation (EC) by inventing, developing, implementing, and evaluating a framework for an in-depth optimization landscape analysis, which consists of methodologies that explore the expressiveness and robustness of the landscape characteristics of problems to find useful problem representations (i.e., a feature portfolio). We published a semantic model OPTION in *IEEE Transactions on Evolutionary Computation,* for storing FAIR benchmarking data within

single-objective optimization. We also developed methodologies for an in-depth optimization landscape analysis based on a synergism between representation learning, machine learning, and statistics. In addition, we proposed methods for identifying regions of optimization problems that are either easy or challenging to solve using a particular optimization algorithm, together with explanations of the characteristics that lead to these results. We also developed methodologies allowing us to solve a new optimization problem, based on its landscape representation (i.e., characteristics), by finding the most similar, already existing problem(s) and understanding which algorithm performs best. Further, this kind of knowledge (i.e., past experimental data) allows us to apply meta-learning approaches and develop algorithm-selection models to find the most suitable algorithm for new unseen optimization problems. In this case, we tested different machine-learning models using also state-of-the-art methods based on transformers, and evaluated them across different learning tasks (multi-class classification, multi-target regression,

single-target regression, pairwise classification) and different evaluation scenarios (leave-one-problem and leave-one-instance out). In addition, we tested the generalizability of an algorithm-performance-prediction model that was trained on one benchmark suite (a set of problem instances) and evaluated on another suite (problem instances not included in the training set). We published a journal article in *Expert Systems with Applications* and presented nine conference papers at top-tier optimization conferences (*GECCO*, *IEEE CEC*, *IEEE SSCI*, and *EvoApps*).

The ARIS young researcher project run by Gašper Petelin covers the topic of automatic algorithm selection and configuration, crucial in various areas of machine learning, focusing on optimization and **time series analysis**. In these areas, identifying features that effectively help in the selection of better algorithms is a major challenge. In the area of time series, the research investigates the effectiveness of the current features in forecasting the performance of specific algorithms. We identified certain features within the time series data that significantly improve the accuracy of performance predictions. In optimization, we introduced novel topology-inspired features that exhibit beneficial properties, such as resilience to various transformations – a common problem in some existing feature collections. In addition,

Figure 2: Minimizing the production cost of MAHLE electric motors

the study includes the forecasting of traffic volume in Ljubljana through a time series analysis, which further enriches this research area. We published two journal articles, in *Swarm and Evolutionary Computation* and *European Transport Research Review*, which significantly deepen our exploration of these complex areas.

Another ARIS young researcher project run by Gjorgjina Cenikj aims at the development of **representation learning methodologies** for the field of single-objective optimization as well as their application in the context of automatic selection and configuration of algorithms. This includes the development of novel trajectory-based representations for optimization problems and algorithm instances that capture the dynamics of the optimization algorithm population, as well as representations for problem instances based on deep learning architectures of neural networks such as transformer models. The evaluation of such representations is performed with respect to their performance in algorithm selection, the analysis of the generalization of the algorithm selection models based on these representations, as well as the predictive power of the constructed representations and their feature importance.

The ARIS young researcher project run by Ana Nikolikj focuses on improving Black-Box Optimization (BBO) algorithms for continuous single-objective optimization of complex problems through transfer learning and continuous learning. She investigates the potential of **transfer learning** to accelerate convergence and improve solution quality by leveraging knowledge from similar problems and addressing the challenges of strategy and problem similarity. The work also explores how continuous learning can boost the effectiveness of automated performance prediction models by incorporating data difficulty and targeting diverse problem coverage, improved robustness and generalization.

As part of the FB-DAC project (bilateral ARIS-DAAD), we investigated trajectory-based meta-features for representing reinforcement agents in dynamic algorithm configuration (DAC). DAC addresses the challenge of dynamically set hyperparameters of an algorithm for a large number of instances instead of focusing on individual tasks. Agents trained with Deep Reinforcement Learning (RL) provide a way to solve such settings. However, the limited generalization performance of these agents significantly hindered their application in DAC. Our hypothesis is that a possible bias in the training instances limits the generalization capabilities. We go a step further by selecting a representative subset of training instances to avoid overrepresentation and then retrain the agent on this subset to improve its generalization performance. In particular, when constructing the meta-features for a subset selection, we take into account the dynamic nature of an RL agent by computing time series features on the trajectories of actions and rewards generated by the agent's interaction with the environment. Through empirical evaluations of
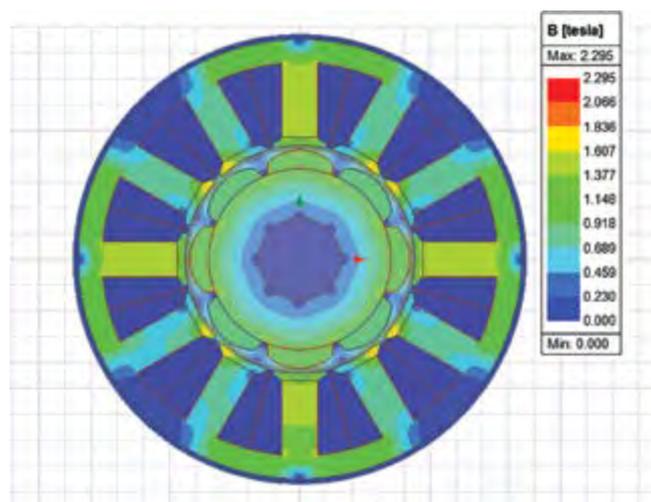
the Sigmoid and CMA-ES benchmarks from the standard benchmark library for DAC, called DACBench, we emphasize the superior performance of our selection technique compared to training on the entire instance set. Our results emphasize the effectiveness of instance selection in refining DAC policies for different instance spaces. In July 2023 we hosted a German research group, focusing on defining research problems, while during our visit in November 2023, we discussed the progress of the project results.

Within the Horizon Europe project *CONDUCTOR – Fleet and traffic management systems for conducting future cooperative mobility* (https://conductor-project.eu/), we are technically coordinating the development, integration and demonstration of an advanced, high-level **traffic and fleet management** system that will allow an efficient and globally optimal transport of passengers and goods while ensuring seamless multimodality and interoperability. Together with 15 partners from 7 countries, we will employ innovative dynamic balancing and priority-based management of automated and conventional vehicles. We are building on state-of-the-art fleet and traffic management solutions in the Cooperative Connected and Autonomous Mobility (CCAM) ecosystem and developing next-generation simulation models and tools enabled by machine learning and data fusion, to enhance the capabilities of transportation authorities and operators and enable them to become conductors of future mobility networks. In collaboration with the Artificial Intelligence Department, we developed the initial forecasting models, to be used in the demand-responsive use case led by the company GoOpti.

The industrial project *Simulation-based optimization of cogging torque in the design of electric motors* for *MAHLE Electric Drives Slovenija,* in collaboration with the Intelligent Systems Department, was successfully completed. In this project, the optimal design of a selected electric motor was determined, taking into account various constraints, with a focus on minimizing the production cost with regards to the cogging torque. Despite the inherent complexity of the motor design, the most significant challenge was the computationally intensive nature of the simulations. We overcame these challenges by employing a **multilevel optimization approach** in conjunction with surrogate optimization techniques. The proposed methodology was tested on a selected asymmetric model, and even with a limited number of simulations, we achieved a remarkable 10% reduction in the material cost while maintaining all the required motor characteristics. This improvement was compared to the optimization approach used by the Ansys software, demonstrating the importance of adapting optimization techniques to specific problem characteristics. These promising results can pave the way for future collaborations and a possible expansion of our approach to optimize other electric motors within the company. The importance of this work was widely recognized, as we received the *TARAS award* from the *Slovenian Industrial Forum* for the most successful collaboration between companies and the research sector in the area of innovation, development and technology.

The COST Action *ROAR-NET – The Randomised Optimisation Algorithms Research Network* (https://roar-net.eu/) aims to facilitate the adoption of randomized optimization algorithms by removing barriers at different levels. It focuses on the needs of practitioners and promotes the development to improve the competitiveness and wide application of these algorithms. The Action has recently started and formed working groups on several topics: Problem Modelling and User Experience, Mixed Continuous and Discrete Optimisation, Single and Multiobjective Optimisation, Optimisation under Uncertainty, Algorithm Selection and Configuration, and Benchmarking. Members of our department are actively involved, especially in the working groups Single and Multiobjective Optimisation, and Algorithm Selection and Configuration.

Our PhD student Margarita Antoniou was awarded 3rd prize at the *International Bilevel Conference* in Southampton, UK, for her work on An Evolutionary Approach to Pessimistic Bilevel Problems.

Data processing

Electronic Components and Systems (ECS) are essential to the EU economy and citizens. They support areas range from transport and mobility to medicine and energy. A key area is **improving the reliability** of increasingly complex chips and systems designed to process vast amounts of data while delivering greater processing speed and accuracy and decreasing energy consumption. We completed our work within the ECSEL JU / Horizon 2020 project *iRel40 – Intelligent Reliability 4.0* (https://www.irel40.eu) in collaboration with 75 partners from 13 countries, with the goal to reduce ECS failure rates across the value chain. The collaboration between academia, industry and knowledge institutes was established to address topics from wafer production to system integration and combine their strengths to improve reliability. As part of the iRel40 project, we contributed to the realization of a smart condition monitoring system for in-wheel electric motors from *Elaphe*. Our research within iRel40 will enable motor lifetime prediction, using smart sensing and online data monitoring technologies, as well as the detection of possible degradation of critical components. To do this, we applied state-of-the-art artificial intelligence methods and identified critical parameters that have the greatest impact on the motor health to detect possible motor failure before it occurs. In this way, we captured the physical characteristics of motors even under non-ideal conditions, such as high measuring noise, concept drift due to accelerated aging, unknown failure modes, temporal correlation, and others. We also contributed to two book chapters on the application of artificial intelligence to reliability.

We successfully completed our participation in the ECSEL JU / Horizon 2020 project *InSecTT – Intelligent Secure Trustable Things* (https://www.insectt.eu/), which brought together 52 partners to synergize Artificial Intelligence (AI) algorithms with the Internet-of-Things (IoT) technologies. Within this project, our department actively participated in two distinct use cases. The first use case focused on implementing intelligent and adaptive solutions within the healthcare sector, particularly in smart hospitals. Our efforts focused on devising methods for detecting anomalies in patient biomedical signals using deep neural networks (DNNs). In 2023 we defined the final version of training and testing datasets to encompass approximately 85,000 annotated 12-lead ECG signals, each comprising 10-second segments sampled at 500 Hz, sourced from various public ECG databases. Following extensive exploration and evaluation of both supervised and unsupervised training methodologies, we honed in on optimizing the architecture of denoising auto-encoders, which proved highly suitable for processing the inherent noise in the ECG signals. We delved deeper into the latent space, where signals are initially encoded before being reconstructed back into the time domain. Through this process, we significantly reduced the dimensionality of the input data from 60,000 to 40, while maintaining comparable accuracy in anomaly recognition.

Moreover, we developed a live demonstration showing ECG anomaly detection via the FastAPI protocol, providing users with the probability of an anomalous ECG reading and a visual representation pinpointing the detected anomalies. This service seamlessly integrates into the broader architecture of our use case, along with complementary solutions from collaborating partners. The second use case revolved around enhancing emergency logistics services in healthcare, particularly concerning indoor localization and navigation, using smartphones without a network and satellite navigation support. The Android application to support rescue teams in critical scenarios such as mass casualty incidents was finalized and tested. This application enables precise navigation to user-defined destinations in multi-floor environments by using relevant information from QR codes at the entrances to the floors, including floor plans and navigation graphics. Using Dijkstra's navigation algorithm, in conjunction with Pedestrian Dead Reckoning, to track user movements between QR beacons, ensures reliable navigation accuracy. In the event of a mass-casualty incident, the application immediately transmits the user's current location, along with triage decisions, made by first responders, to a cloud-based repository that can be accessed by other stakeholders, such as other members of the rescue team caring for the injured. In the scenarios where the data communication networks are unavailable, the triage data are securely stored in a local JSON-based database, awaiting transmission once connectivity is restored. The work carried out as part of the project will be summarized in the chapters of a dedicated project book.

The Horizon Europe MSCA project *EXOWORLD – Understanding the evolution of EXOplanets and towards habitable WORLDs* (https://cordis.europa.eu/project/id/101086149) involves 12 organizations from 8 countries. The aim is to develop novel detection, characterization and statistical techniques for exoplanets. By funding the mobility of researchers, the project utilizes interdisciplinary and international expertise to investigate the diversity of extrasolar planetary systems with regard to their evolution and find out which conditions lead to habitable worlds. Our department leads the advanced computational tools work package, which aims to introduce the state-of-the-art machine learning and optimization methods into the existing computational pipelines of exoplanetary science. We are involved in several research activities, including optimizing planet detection algorithms and candidate vetting processes, exploring the potential of machine learning for exoplanet characterization, patterning mining for population studies, and identifying stellar activity. Two journal articles are currently in preparation, one on exoplanet population statistics and one on the use of deep learning for exoplanet detection using the TESS telescope data.

The PRIMA project *WEFE4MED – Towards a Mediterranean WEFE Nexus Community of Practice* (https://wefe4med.eu/) aims to ensure a resilient, circular and green economy and achieve the Sustainable Development Goals in the areas of water, energy, food and ecosystems. Together with the Knowledge Technologies Department and the Center for Smart Cities, we will contribute our knowledge on data analytics and decision support, where our data analytics, optimization, and machine learning solutions will help to achieve the overall goals and put the solutions into practice. This will be reached through a Nexus Community of Practice (NCoP) that brings together practitioners, academics, policy makers, and other stakeholders. In the initial phase we collaborated in collecting best practices and promoting their application among the stakeholders in the Balkan region.

The COST Action *PerMediK – Personalized medicine in chronic kidney disease: improved outcome based on Big Data* (https://www.cost.eu/actions/CA21165/) aims to advance personalized medicine in chronic kidney disease (CKD) using multidimensional -omics data (Big Data). Despite mature developments in molecular data and therapeutic targets, clinical implementation is hindered by communication gaps and isolated activities. This action is an important multidisciplinary platform bringing together European experts in nephrology, -omics, bioinformatics and other fields. By leveraging previous initiatives, resources will be maximized to address critical aspects of personalized medicine in CKD. Impacts include accelerating technology adoption, directing future research, fostering innovation, and training the next generation of precision medicine scientists. PerMediK promotes an integrative approach by disseminating expertise and tools, thus contributing to the progress of European research.

Data management and visualization

As part of the national project *OPKP – Open Platform for Clinical Nutrition* (http://www.opkp.si), the Slovenian Food Composition Database was reviewed and updated. In 2023 NutriBase (a data- and knowledge-based management system) was further upgraded. Data for around 20,000 branded foods were imported into the tool. NutriBase now serves as a tool collecting crowd-sourced data about branded foods. In addition, Slovenian food producers can now register in NutriBase, and add to and edit their products in the system. The unified system allows sharing the data with the consumers.

In the European project *FishEUTrust – European integration of new technologies and social-economic solutions for increasing consumer trust and engagement in seafood products* (https://www.fisheutrust.org/), we are leading a work package dealing with data activities. In collaboration with partners, we are developing a platform through which stakeholders can access data on fish quality and traceability. At the same time, we are designing a new data model for **semantic data integration**. We are supporting the *University of Florence* in processing data using machine learning methods. We published a paper in the journal *Scientific Reports.*

The mission of the Horizon 2020 project *COMFOCUS – Community on Food Consumer Science* (https://comfocus.eu) is to advance food consumer science beyond its current fragmentation that prevents it from becoming a data-rich scientific field that contributes to solving the societal problem of (un)healthy food choices. We are leading a work package on the development of data processing tools. In another work package, we are working on the development of a new ontology for semantic description of data on consumer dietary habits. We are using the ontology to develop a knowledge graph that will be used to support the advanced data analysis using representational learning. We published several papers in journals *Scientific Reports*, *Artificial Intelligence in Medicine*, *Appetite*, and *Nutrients,* and presented our findings at conferences *KDD Student Symposium 2023* and *European Nutrition Conference FENS 2023*.

In European projects *AGROSERV*, *INPROFF* and *PROMEDLIFE*, we are supporting the Environmental Sciences Unit in the development of a methodology for advanced processing of food isotopic composition data. We represented the IJS at the PROMEDLIFE annual meeting in Tunisia. The web-based tool IsoFoodTrack (http://isofoodtrack.ijs.si/) is continually updated and upgraded with new data. We presented papers at ISO-FOOD symposium *From Food Source to Health* and *Jožef Stefan International Postgraduate School Students' Conference*. Within the ESFRI project *MetroFood PP,* we completed its preparatory phase and started the early-phase implementation (EPI). In this project, we support IJS colleagues in the processing and management of food data.

The Horizon 2020 project *FNS-Cloud – Food Nutrition Security Cloud* (http://www.fns-cloud.eu) was successfully completed in 2023. We led a work package dedicated to developing methodologies and services for **semantic integration**, **analysis and visualization** of food and nutrition data. With colleagues from the *Knowledge Technologies Department* and the *University*

Figure 3: Prototype of the FPGA-based object-recognition system of an AGV

of Florence, we successfully developed and published the *FNS-Harmony* ontology and ran a workshop training domain experts to work with the ontology. In collaboration with the *Quadram Institute* in the UK, we developed and applied a methodology for advanced processing of the data collected in a study on the impact of diet on the microbiome of healthy adults. We presented a paper at the *KDD Student Symposium 2023*.

In August 2023, Eva Valenčič successfully completed her double doctorate at the *IPS* and the *University of Newcastle*, Australia, with the dissertation *Using information and communication technologies, data and knowledge to increase the impact of digital environments on food choices*. The dissertation focuses on designing supportive digital environments for consumers using promotional strategies and providing relevant and accurate food-composition data and knowledge to professionals planning and designing (digital) environments.

In the area of **efficient interaction systems**, we focused on the web tools and mobile apps for nutrition and food informatics. We deeply investigated and designed visual representations for various projects, applications, and web pages. In collaboration with partners and end-users, we analyzed user needs, defined appropriate user experiences and designed corresponding interfaces for several tools related to nutrition.

The project from the Interreg program called *SI4Care – Social Innovation for integrated health CARE of aging population in ADRION Regions* (https://si4care.adrioninterreg.eu) deals with social innovation in the field of long-term care and aims to create a joint transnational strategy and action plans for each of the countries involved in the project from the Adriatic-Ionian region. We have advanced our work on IoT solutions for specific areas. Our work on a smartboard platform with edge processing for sensorimotor training with balance boards

was published in the journal *IEEE Access*. Also, as part of the SI4Care project, we organized a local consultation focused on the use of technology for rehabilitation and training of the elderly, which was attended by all relevant stakeholders in the region. The main findings of the focus groups organized during the event were published in the journal *Frontiers in Public Health*. In the final year, we organized various events to disseminate the project results among stakeholders and joined the *MRRC UL SI-AHA – multidisciplinary research and development center for social innovations for active and healthy ageing*, where we will further contribute our technical expertise on this topic. In order to make better use of the project results, we have developed a web tool for chat interaction with the various documents produced during the project, e.g., deliverables, pilot reports, research papers, and the transnational strategy along with its national action plans.

In the second year of the ARIS research project in historical sciences *Historical Thopography of Posavinje and Posotelje Regions* (https://piir.zrc-sazu.si/sl/programi-in-projekti/historicna-topografija-posavinja-in-posotelja), in cooperation with the Slovenian Academy of Sciences and Arts, our efforts focused primarily on the gathering of pertinent historical data, **automation of processing**, and verification of the accuracy of the collected information. We also focused on efficient storing of the collected data. This research project represents the third phase of a long-term initiative, concentrating on the historical topography of the Posavinje and Posotelje regions. So far, about 3000 toponyms have undergone initial processing, sourced from scanned documents with OCR and various other archives. However, there is still a considerable amount of data to be collected, particularly with respect to resolving the majority of unresolved locations. These steps are crucial as they form the basis for further research and integration into the existing Slovenian Historical Topography database.

Adaptive computing platforms

To support and accelerate our algorithms, we have researched and developed various approaches at the hardware and computational structure level, including the use and online reconfiguration of FPGAs, customized embedded systems and sensors. We are building a high-performance **FPGA acceleration** infrastructure based on Xilinx ALVEO acceleration boards. We have investigated the hardware implementations of artificial neural networks on FPGA devices. The use of the high-performance ALVEO FPGA accelerator board has been investigated for fixed-point array multiplication that can be used in an ANN. The research also focuses on the adaptive quality of the computations delivered, i.e., the **approximate computing** approach.

In collaboration with the *Indian Institute of Technology Indore*, we developed an efficient hardware implementation of the Softmax (SF) unit. It is based on a CORDIC-based pipeline architecture with adjustable exponential unit (ExU) and division unit (DiU). The solution was tested on an FPGA device. The trade-offs between bit precision, pipeline depth, speed, and SF accuracy were investigated. The article describing the evaluation of the developed unit was published in the journal *IEEE Access*.

We continued the ECSEL JU / Horizon 2020 project *DAIS – Distributed Artificial Intelligent Systems* (https://dais-project.eu/) in collaboration with 47 partners from 11 countries. Together we research and deploy distributed and secure artificial intelligent systems. We aim to solve the problems that arise when running the existing algorithms on these widely distributed edge devices. Our department is collaborating with *CosyLab* and *TPV* to develop a smart automated guided vehicle (AGV) that will be used in an industrial environment. The ongoing work, which includes a configurable mixed-precision convolution processing unit generator and highly **quantized neural networks on FPGA**, was presented at *the 26th International Symposium on Design and Diagnostics of Electronic Circuits and Systems* and at the *26th Euromicro Conference on Digital System Design (DSD)*.

We continued research within the ARRS project *CODA – Context-aware on-device approximate computing* (https://www.fri.uni-lj.si/en/projects/1719) in collaboration with the *Faculty of Computer and Information Sciences* at the *University of Ljubljana*. The project aims to drastically reduce resource demands in mobile computing by **adapting the computational complexity** to the requirements imposed by the context of use. Our task in the project is to investigate use cases where the algorithms developed in the project would be most useful. After exploring, at the beginning of the project, the issue of mountain safety in winter, when the risk of avalanches is at its highest, we looked for new areas. Healthcare and the use of various sensors for continuous monitoring of chronic diseases or gamification of exercising are two fields that benefit from the context awareness and approximate computing with its promise of reducing energy consumption. A monitoring device for cervical dystonia consisting of a 9DOF sensor with mobile application was developed and tested in collaboration with the *Automation, Biocybernetics and Robotics Department* and the *University Medical Center* in Ljubljana.

The *Athena* project (https://www.athenaequality.eu/) supported the JSI and other project partners in the implementation of a Gender Equality Plan (GEP). Our department is actively involved at all levels of preparation, implementation and monitoring of the GEP. The formal adoption of the GEP at the JSI is a milestone on the road to gender equality. The 2023 monitoring report highlights progress in all GEP areas, including changes to the criteria

for academic promotion and the introduction of gender-sensitive language. In 2023 the JSI promoted gender equality through seminars, workshops and measures to prevent gender-based violence.

Some outstanding publications in the past year

1. Petelin, Gašper, Cenikj, Gjorgjina, Eftimov, Tome. Towards understanding the importance of time-series features in automated algorithm performance prediction. *Expert Systems with Applications*. 2023, vol. 213, pp. 1–20. ISSN 0957-4174. DOI: 10.1016/j.eswa.2022.119023.

2. Cenikj, Gjorgjina, Eftimov, Tome, Koroušić-Seljak, Barbara. FooDis: a food-disease relation mining pipeline. *Artificial Intelligence in Medicine*. 2023, vol. 142, pp. 1–13, ISSN 1873-2860. DOI: 10.1016/j.artmed.2023.102586.

3. Petelin, Gašper, Hribar, Rok, Papa, Gregor. Models for forecasting the traffic flow within the city of Ljubljana. *European Transport Research Review*. 2023, vol. 15, pp. 1–20, ISSN 1866-8887. DOI: 10.1186/s12544-023-00600-6.

4. Petelin, Gašper, Antoniou, Margarita, Papa, Gregor. Multi-objective approaches to ground station scheduling for optimization of communication with satellites. *Optimization and Engineering*. 2023, vol. 24, pp. 147–184, ISSN 1389-4420. DOI: 10.1007/s11081-021-09617-z.

5. Cenikj, Gjorgjina, Strojnik, Lidija, Angelski, Risto, Ogrinc, Nives, Koroušić-Seljak, Barbara, Eftimov, Tome. From language models to large-scale food and biomedical knowledge graphs. *Scientific Reports*. 2023, vol. 13, pp. 1–14. ISSN 2045-2322. DOI: 0.1038/s41598-023-34981-4.

6. Valenčič, Eva, Beckett, Emma, Collins, Clare Elizabeth, Koroušić-Seljak, Barbara, Bucher, Tamara. SnackTrack: an app-based tool to assess the influence of digital and physical environments on snack choice. *Nutrients*. 2023, vol. 15, pp. 1–13, ISSN 2072-6643. https://www.mdpi.com/2072-6643/15/2/349, DOI: 10.3390/nu15020349.

7. Kostovska, Ana, Vermetten, Diederick, Doerr, Carola, Džeroski, Sašo, Panov, Panče, Eftimov, Tome. OPTION: OPTImization algorithm benchmarking ONtology. *IEEE Transactions on Evolutionary Computation*. 2023, vol. 27, pp. 1618–1632, ISSN 1941-0026. DOI: 10.1109/TEVC.2022.3232844.

8. Mehra, Sumiran, Raut, Gopal, Das, Ribhu, Vishvakarma, Santosh Kumar, Biasizzo, Anton. An empirical evaluation of enhanced performance softmax function in deep learning. *IEEE Access*. 2023, vol. 11, pp. 34912–34924, ISSN 2169-3536. https://ieeexplore.ieee.org/document/10093848, DOI: 10.1109/ACCESS.2023.3265327.

9. Abina, Andreja, Cestnik, Bojan, Kovačič Lukman, Rebeka, Zavernik, Sara, Ogrinc, Matevž, Zidanšek, Aleksander. Transformation of the RESPO decision support system to higher education for monitoring sustainability-related competencies. *Sustainability*. 2023, vol. 15, pp. 1–18, ISSN 2071-1050. DOI: 10.3390/su15043477.

10. Fragkiadaki, Stella, Kontaxopolou, Dionysia, ***Šemrov***, Darja, Colnar, Simon, Luštrek, Mitja, Blažica, Bojan, Dimovski, Vlado, Papageorgiou, Sokratis G., et al. How well did the healthcare system respond to the healthcare needs of older people with and without dementia during the COVID-19 pandemic: the perception of healthcare providers and older people from the SI4CARE Project in the ADRION Region. *Geriatrics*. 2023, vol. 8, pp. 1–13, ISSN 2308-3417, DOI: 10.3390/geriatrics8010021.

INTERNATIONAL PROJECTS

1. ArcelorMittal Scholarship for Ana Nikolikj; ArcelorMittal - JSI Memorandum of Cooperation and Internship Agreement
Asst. Prof. Tome Eftimov
Arcelormittal Innovación Investigación

2. H2020 - FNS-Cloud; Food Nutrition Security Cloud
Barbara Koroušić Seljak
European Commission

3. H2020 - iRel40; Intelligent Reliability 4.0
Prof. Gregor Papa
European Commission

4. H2020 - InSecTT; Intelligent Secure Trustable Things
Dr. Drago Torkar
European Commission

5. H2020 - ATHENA; Implementing Gender Equality Plans to Unlock Research Potential of RPOs and RFOs in Europe
Dr. Vida Vukašinović
European Commission

6. H2020 - COMFOCUS; Communities on Food Consumer Science
Barbara Koroušić Seljak
European Commission

7. H2020 - DAIS; Distributed Artificial Intelligent Systems
Prof. Gregor Papa
European Commission

8. H2020 - FoodTraNet; Advanced Research and Training Network in Food Quality, Safety and Security
Barbara Koroušić Seljak
European Commission

9. Automated Configuration, Selection, and Design of Iterative Optimization Heuristics
Asst. Prof. Tome Eftimov
Slovenian Research Agency

10. Fair Benchmarking for Dynamic Algorithm Configuration
Asst. Prof. Tome Eftimov
Slovenian Research Agency

11. HE - AgroServ; Integrated SERvices supporting a sustainable AGROecological transition
Barbara Koroušić Seljak
European Commission

12. HE - CONDUCTOR; Fleet and Traffic Management Systems for Conducting Future Cooperative Mobility
Prof. Gregor Papa
European Commission

13. HE - BENCHMARKS; Building a European Network for the Characterisation and Harmonisation of Monitoring Approaches for Research and Knowledge on Soils
Dr. Bojan Blažica
European Commission

14. HE - WASTELESS; Waste Quantification Solutions to Limit Environmental Stress
Barbara Koroušić Seljak
European Commission
15. HE - EXOWORLD; Understanding the evolution of EXOplanets and towards habitable WORLDS
Rok Hribar, B. Sc.
European Commission
16. EIT Climate-KIC; UP SCALE - Urban Pioneers - Systemic Change Amid Livable Environments
Prof. Gregor Papa
Cinea - European Climate, Infrastructure
17. HE - FishEUTrust; European Integration of New Technologies and Social-Economic Solutions for Increasing Consumer Trust and Engagement in Seafood Products
Barbara Koroušić Seljak
European Commission
18. PRIMA; PROMEDLIFE - Novel food products for the PROmotion of MEDiterranean LIFEstyle and healthy diet
Barbara Koroušić Seljak
Prima Foundation - Partnership For Research And
19. PRIMA; WEFE4MED - Towards a Mediterranean WEFE Nexus Community of Practice
Prof. Gregor Papa
Prima Foundation - Partnership For Research And
20. EFSA; EU FCDB - Creation of an Open Access EU Food Composition Database
Barbara Koroušić Seljak
Eurofir Aisbl- European Food Information
21. WBL GRANT; Work-Based Learning Grant
Asst. Prof. Tome Eftimov
The University Of Wales Trinity Saint David
22. COST CA22137; ROAR-NET - Randomised Optimisation Algorithms Research Network
Dr. Vida Vukašinović
COST Association Aisbl
23. COST CA21165; PerMediK - Personalized Medicine in Chronic Kidney Disease: Improved Outcome based on Big Data
Asst. Prof. Tome Eftimov
COST Association Aisbl

RESEARCH PROGRAMME

1. Computer Structures and Systems
Prof. Gregor Papa

R&D GRANTS AND CONTRACTS

1. Context - aware on-device approximate computing
Dr. Bojan Blažica

2. Quality, Safety and Authenticity of INsect PROtein-Based Food and Feed Products
Barbara Koroušić Seljak
3. Personalized Fingerprints for Black-Box Optimization
Asst. Prof. Tome Eftimov
4. Auto-OPT: Automated selection and configuration of single-objective continuous optimization algorithms
Prof. Peter Korošec
5. Political and social systems, structures and processes
Prof. Peter Korošec
6. METROFOOD
Barbara Koroušić Seljak
7. Social Innovation for Integrated health CARE of ageing population in ADRION Regions-SI4CARE
Dr. Bojan Blažica
The Emillia-Romagna Region
8. Do you know what you're drinking? Empowering residents to reduce alcohol use
Barbara Koroušić Seljak
Ministry of Health
9. You know what you eat and ensuring it works Innovative solutions for informed decisions
Barbara Koroušić Seljak
Ministry of Health
10. ZaUpam -support to commercial companies for proactively improving the composition of food and promoting healthy choices
Barbara Koroušić Seljak
Slovenian Chamber of Commerce
11. PISKR - Implementation program of the Guidelines for healthy eating in educational institutions to strengthen the supply of healthy school meals.
Barbara Koroušić Seljak
National Institute of Public Health
12. Digital solutions and increasing the competence of using Information Technologies to promote healthy choices and health promotion (DoIT)
Barbara Koroušić Seljak
Slovene Consumers' Association
13. Consolidation and Integration of Whole Genome Sequencing (WGS) into Routine Surveillance in Slovenia
Dr. Drago Torkar
National Laboratory of Health, Environment and Food
14. CROSSING - Crossing Borders and Scales - An Interdisciplinary Approach
Prof. Gregor Papa
Helmholtz-Zentrum Dresden-Rossendorf E.V.

NEW CONTRACT

1. Simulation-based optimization of cogging torque in electric motor design
Prof. Peter Korošec
Mahle Electric Drives Slovenija d. o. o.

VISITORS FROM ABROAD

1. Luisa Maria Serrano, Universita degli Studi di Torino, Italy, 27 March to 27 April 2023
2. Jan Kincl, Tomas Bata University, Faculty of Applied Informatics, Zlin, Czech Republic, 1 April to 31 July 2023
3. Dr Anja Jankovic, Sorbonne University, Paris, France, 15–24 May 2023
4. Carolin Benjamins, prof. dr Marius Lindauer, Aditya Mohan, Leibniz University, Hannover, Germany, 24–28 July 2023

STAFF

Researchers
1. Asst. Prof. Anton Biasizzo
2. Dr. Bojan Blažica*
3. *Dr. Bojan Blažica, left 01.07.23*
4. Asst. Prof. Tome Eftimov
5. Prof. Peter Korošec
6. Prof. Barbara Koroušić Seljak
7. **Prof. Gregor Papa, Head**
8. Prof. Veljko Pejović*
9. Dr. Drago Torkar
10. Dr. Vida Vukašinović
Postdoctoral associates
11. Dr. Gordana Ispirova
12. *Dr. Marko Pavlin*, left 01.12.23*
13. Dr. Urban Škvorc
14. Dr. Eva Valenčič
Postgraduates
15. Margarita Antoniou, M. Sc.

16. Gjorgjina Cenikj, B. Sc.
17. Rok Hribar, B. Sc.
18. Ana Nikolikj, B. Sc.
19. Gašper Petelin, B. Sc.
20. Jure Vreča, B. Sc.
Technical officers
21. Robert Modic, B. Sc.
22. Matevž Ogrinc, B. Sc.
23. Andraž Simčič, B. Sc.
Technical and administrative staff
24. Jolanda Jakofčič
25. Tina Kondić
26. Andreja Vlašič, B. Sc.

Note:
* part-time JSI member

DEPARTMENT OF KNOWLEDGE TECHNOLOGIES E-8

At the Department of Knowledge Technologies we develop artificial intelligence methods and other advanced information technologies that support the acquisition, management, modelling and use of knowledge and data, thus enabling a knowledge-based society. Our research covers many areas of artificial intelligence, such as machine learning and natural language processing, as well as related fields, such as decision support. Our research has five pillars: machine learning, decision support and artificial intelligence, artificial intelligence and science, natural language processing and digital humanities, and knowledge technologies for society. We use the developed knowledge technologies in various fields, from sustainable agriculture to personalized medicine and health, through media, education and the arts, to various industrial sectors such as energy, transport and space research.

Head:
Prof. Sašo Džeroski

In 2023 we were involved in two national research programs (on knowledge technologies and quantum technologies), twenty national projects, and thirteen EU projects. We also participated in two infrastructure projects, one applied project, and five other international projects. Finally, we had three young-researcher projects, through which we hosted junior researchers working towards their PhDs.

Machine Learning. In this area we presented CLUS$_{PLUS}$ – an open-source machine-learning framework based on decision trees specialized for complex predictive modeling tasks, supporting multi-target prediction, i.e., the simultaneous prediction of multiple continuous values, multiple discrete values, and hierarchically organized discrete values. Furthermore, CLUS$_{PLUS}$ enables state-of-the-art predictive performance via ensemble learning, exploitation of unlabeled data via semi-supervised learning, and data understanding via feature importance and building interpretable models.

In the area of *representation learning* we developed a multimodal AutoML approach via representation evolution, which was published in the *Machine learning and knowledge extraction* journal. Nada Lavrač had two invited talks in this area: *Learning representations for relational learning and literature-based discovery: keynote speech at 21st International Conference on Artificial Intelligence in Medicine, AIME 2023 Portorož, Slovenia, June 12–15, 2023* and *Machine learning from relational and text data*, presented jointly with M. Robnik-Šikonja at *31. Dnevi Jožefa Stefana at JSI, 23. 3. 2023 in Ljubljana, Slovenija*.

> **Nada Lavrač gave an invited lecture Learning representations for relational learning and literature-based discovery at the 21st International Conference on Artificial Intelligence in Medicine, AIME 2023, Portorož, Slovenia, on June 14, 2023.**

Decision Support and Artificial Intelligence. In the field of decision support, we develop decision-modeling methods and decision-support software. We completely renovated our software tools for qualitative multi-criteria modeling according to the DEX method and offered them under the name *DEXi Suite* for free use on the website https://dex.ijs.si/. Together with the University of Belgrade, Faculty of Organizational Sciences, we developed a new method DIDEX for the machine learning of DEX models from data. We carried out a preliminary study of the stability and consistency of the decision rules acquired by the DEX method.

The applications took place mainly within the SmartMOVE project (*Smart mobility measures for sustainable mobility in Slovenia*, https://kt.ijs.si/project/smartmove/). We evaluated the effects of the dynamic group transportation of employees to workplaces and prepared a methodology for awarding certificates to organizations that particularly excel in the field of sustainable mobility. DEX and MAUT methods are also applied in the evaluation of pilot studies in the scope of the UP-SCALE project (Urban Pioneers – Systematic Change Amid Livable Environments). With a delay and a publication date of 2022, an article was published with a description of the decision support system *Severa*, aimed at decision support during severe accidents in nuclear power plants.

In the area of *explainable artificial intelligence,* we developed and evaluated methods for variable importance estimation and feature ranking in several contexts. This includes novel methods for feature ranking in the context of semi-supervised learning based on predictive clustering tree ensembles and the Relief family of algorithms. The feature rankings are learned in the context of classification and regression, as well as in the context of structured output prediction (multi-label classification, MLC, hierarchical multi-label classification, HMLC and multi-target regression, MTR) tasks.

Figure 1: Nada Lavrač and Marko Robnik-Šikonja presented their achievements as part of the invited lecture Machine Learning from Relational and Text Data at the 31st Jožef Stefan Days at the JSI on March 23, 2023.

Language Technologies and Digital Humanities. In these areas we address the fields of natural language processing and understanding, text and network analytics, open-access language resources, and digital humanities. In the field of natural language processing and understanding, we successfully completed the national project CANDAS (Computer-assisted multilingual news discourse analysis with contextual embeddings) and started the project EMMA (Embeddings-based techniques for Media Monitoring Applications) co-financed by the media monitoring company Kliping d.o.o. We analysed cross-lingual transfer for named entity recognition, focusing on South Slavic languages. Our work compared the performance of multilingual models and the influence of including linguistically related training data and showed that for less-resourced languages, including data from related languages, could enhance model performance in specific contexts. We proposed novel document representation methods based on graphs. Our team also developed an innovative method employing auto-encoder neural networks to assist journalists in the task of identifying relevant news articles for translation and localization. We also investigated how news articles around meat evolved through time.

We successfully completed the RobaCOFI project (Robust and adaptable comment filtering, funded by Horizon Europe via the project AI4Media), providing a range of software tools for automatic content moderation, using transfer learning to achieve good performance with little or no annotated training data. This has linked to a range of work on related phenomena such as hate speech, misogyny, and sexism in text: building lexicons via explainable methods, improving classifiers via novel activation functions for soft and hard label prediction. We continued our work on the SOVRAG project (Hate speech in contemporary conceptualizations of nationalism, racism, gender and migration) in collaboration with the Peace institute. We investigated social biases in large language models across languages, analysed political leanings in the Slovenian parliamentary debates on migrations, using explainable computational linguistics methods – the paper received best student paper award in LTC 2023 conference in Poznan– and presented our methods for analysing LGBTIQ+ and migration-related texts.

We continued work on two Slovenian basic research projects, both led by ZRC SAZU, the Scientific Research Center of the Slovenian Academy of Sciences and Arts, namely, "Formant Combinatorics in Slovenian" where we researched the automation of morphological segmentation and the analysis of word-formation in Slovenian and "Traditional Paremiological Units in Dialogue with Contemporary Use" where we published a new version of the Collection of Slovenian paremiological units. We successfully finished our task on terminology extraction in the scope of the project Development of Slovene in a Digital Environment, contributing to the development of the Slovene terminological portal (https://terminoloski.slovenscina.eu/) including automated term extraction module. We also evaluated several methods for definition extraction and proposed a novel dataset for their evaluation.

We developed and improved general natural language processing models, at a range of scales and levels of granularity. At the sentence level, we developed fine-grained models of semantic interpretation for text-to-SQL database query interfaces. For larger, noisier datasets we developed coarser-grained models for segmentation and querying, tested on podcasts and radio broadcasts: we developed new neural encoders for topic segmentation across domains, investigated how to fairly compare and evaluate segmentation models, and showed that the methods could be extended to audio-only data and multimodal audio/text data. This large-scale work was also applied to organizational communication in large email archives, leading to models of distributed organizational decision-making and findings about how people manage feedback and error reporting in large organizations. This work also looked at cognitive aspects, analyzing how the linguistic features of email communication relate to the author's influence in the organization and investigations of how users perceive interactive robots' social identity.

We also developed novel word-sense induction methods for low-resourced settings, and evaluated them on Buddhist Sanskrit literature and contributed to the corpus of textbooks for teaching Slovenian as a foreign and second language and the CEFR (Common European Framework of Reference for Languages) level proficiency labeled core vocabulary for Slovene. We were involved in two bilateral projects. In the scope of the PROTEUS project with University La Rochelle, we worked on terminology extraction, while in the scope of the bilateral project with Johns

Hopkins University, we analyse the working memory in large language models. We also started the work in the project Linguistic Accessibility of Social Assistance Rights in Slovenia led by the Faculty of Law.

We organised the 9th Workshop on Slavic Natural Language Processing 2023 and the 10th VarDial Workshop on Natural Language Processing for Varieties and Dialects in the scope of the 17th Conference of the European Chapter of the Association for Computational Linguistics. We enriched our ClowdFlows online tool with some new use cases from the field of digital humanities and continued to promote it in this research domain.

In the scope of the EU project MaCoCu (Massive Collection and Curation of Monolingual and Bilingual Data: Focus on Under-resourced Languages) we have published the second data release of monolingual crawls of Slovenian, Croatian, Macedonian, Bulgarian, Turkish, Maltese, Icelandic, and extended the list of languages with Bosnian, Montenegrin, Albanian and Catalan. Most of these represent the largest published text collections of the corresponding languages, and are of great use for training large language models. We have also expanded the list of large language models, most of which represent the state-of-the-art, on some natural language understanding tasks (https://huggingface.co/MaCoCu). Along with the monolingual collections, parallel data collections were updated or published as well, for the following language pairs: Slovenian-English, Croatian-English, Macedonian-English, Bulgarian-English, Turkish-English, Maltese-English, Icelandic-English, Bosnian-English, Montenegrin-English, Albanian-English and Catalan-English. Along with the work on enriching these text collections, we have performed a survey on web-based genre identification, performed experiments on automating genre identification via large language models and published a benchmark on closely related language identification.

Figure 2: Nada Lavrač gave a keynote talk Learning representations for relational learning and literature-based discovery at the 21st International Conference on Artificial Intelligence in Medicine, AIME 2023 in Portorož, Slovenija, 12–15.6. 2023, attended by 210 registered participants.

We concluded our work in the project Quantitative and qualitative analysis of the unregulated corporate financial reporting led by School of Economics and Business, University of Ljubljana, where we investigated various multi-task learning methods for financial text classification with the focus on financial sentiment, objectivity, forward-looking sentence prediction and ESG-content detection and analysed the contextual differences of terms in annual reports given the performance of the company.

In the field of *open-access language resources* we lead CLARIN.SI, the Slovenian national node of the European CLARIN ERIC research infrastructure, which provides easy publication and sustainable access to digital language data for scholars in the humanities and social sciences and other disciplines that use or produce language resources. CLARIN.SI maintains the CTS-certified CLARIN.SI repository, concordancers and other Web services, and supports the creation of language resources and the promotion of digital linguistics.

CLARIN.SI is organized as a consortium of partner institutions that unites all Slovenian universities (UL, UM, UNG, UP), four research institutes (ZRC SAZU, JSI, INZ, ZRS Koper), two companies (Amebis, Alpineon) and the Slovenian Association for Language Technologies. In 2023, Trojina, the Institute for Applied Slovene Studies, left the consortium, while NUK, the National and University Library of Slovenia joined it. In 2023, the Management Board of the consortium approved the CLARIN.SI Strategy for the period 2024-2030.

In 2023 the CLARIN.SI repository saw 69 new language resources (40 for Slovenian) submitted, reviewed and published; at the end of the year the repository contained 589 entries, of these 256 for Slovenian. The CLARIN.SI concordancers were upgraded to the latest released versions, and an additional 85 corpora were made available; at the end of the year the concordancers offered 238 corpora. CLARIN.SI also has a virtual organization on the GitHub platform, where 2023 saw the creation of 20 new repositories, and gathered 113 repositories at the end of 2023. Three new web applications were included in the infrastructure. The first two are the result of the project SLOKIT "Upgrading CLARIN.SI: A corpus informer and a text analyser", are the SENTA sentence simplification and analysis tools and the KORPUSNIK basic overview of word use tool, while the third one is the result of the project "Development of Slovenian in the digital context" and the CLASSLA K-centre, and is the CLASSLA tool for text annotation.

CLARIN.SI, together with the Institute for the Croatian Language at the Croatian Academy of Sciences and the Bulgarian CLARIN center, manages the CLARIN certified Knowledge Centre (K-Centre) CLASSLA for assistance in computational processing of South Slavic languages. In 2023, CLASSLA-web corpora were created for all South Slavic languages (7 languages, 11 billion words), where texts are tagged with genres, and linguistic annotation is performed with the latest version of CLASSLA-Stanza. The tool was trained on the upgraded hand-annotated datasets for Croatian, Serbian and Macedonian.

CLASSLA also participated in the ParlaMint project of creating corpora of parliamentary debates, where it contributed the Croatian, Bosnian and Serbian corpora. A shared task for benchmarking large language models for several dialects (Cerkno, Chakavian, Torlak) has also been co-organised. The FAQs have been updated with information about accessible language resources and technologies for Slovenian, Croatian, Serbian, Macedonian and Bulgarian languages.

Starting in 2018, CLARIN.SI annually publishes tenders for projects to create or upgrade resources and services that contribute to the mission of CLARIN. In 2023, six projects were accepted for funding, all of which were successfully completed.

CLARIN.SI participated in several projects in 2023. Within the framework of the project RSDO "Development of Slovenian in the Digital Environment", we managed work group 6, where we reviewed and converted the produced project language resources for depositing in the CLARIN.SI repository and for inclusion in the concordancers. In 2023 the project was successfully completed, with the final corpora published. CLARIN.SI also participated in the successfully completed CLARIN ERIC ParlaMint II project, where we managed several work groups, e.g. for the project infrastructure, for corpus collection in for adding metadata to the corpora. In 2023, we published "Multilingual comparable corpora of parliamentary debates ParlaMint 4.0", a collection of 29 corpora with more than a billion words. The corpora were also machine translated into English. These resources were deposited in the CLARIN.SI repository and integrated into the concordancers. The corpora have already been used in various research, and were also the basis for one of the tasks at the Digital Humanities Hackathon 2023 in Helsinki. We also indirectly cooperated with European projects that submitted their results to our repository, e.g. MaCoCu, INTAVIA, EMBEDDIA, as well as Slovenian projects, e.g. MEZZANINE (Development of speech resources and technologies for Slovenian) and PoVeJMo (Flexible processing of natural language with the help of large language models).

> **Department members contributed to the public debate on artificial intelligence with an online contribution Let's focus on AI's tangible risks rather than speculating about its potential to pose an existential threat, at a meeting of the ELLIS board.**

CLARIN.SI supported several events in Slovenia that are related to its mission, the main one being the 34th EUROPEAN SUMMER SCHOOL IN LOGIC, LANGUAGE AND INFORMATION (University of Ljubljana, Faculty of Computer Science and Informatics. July 31 - August 11, 2023) and four lectures JOTA (Language technology seminar series). We also edited a special issue of the journal Slovenščina 2.0, which collects the expanded papers of the best contributions to the Conference on Language Technologies and Digital Humanities, which took place in 2022 in Ljubljana.

We made several presentations related to the operation of CLARIN.SI, i.e., at the Linguistic Circle of the Faculty of Arts in Ljubljana, at the Days of Open Science 2023, at the Digital Humanities Conference in Graz, and gave a course at ZRC SAZU and NUK (tutorial for librarians). Part of the promotion of the operation of the infrastructure was also the creation of CLARIN.SI accounts on the Discord platforms (now over 80 members) and on LinkedIn. We continue to publish news on the CLARIN.SI account of the X platform (formerly Twitter).

We participated intensively in the work of CLARIN ERIC. Tomaž Erjavec, the national coordinator of CLARIN.SI, participated in the meetings of the National Coordinators and of the CLARIN Strategy and Management Board, to which he was elected in 2022. Since he was the chairman of the program committee of the CLARIN Annual Conference in 2022, he was, in 2023, the co-editor of the Selected papers from the CLARIN Annual Conference 2022. At the CLARIN 2023 conference (Leuven), Slovenian researchers were (co)authors of 10 papers or presentations. Slovenian researchers participated in CLARIN ERIC working groups, namely in the group for the development of language resource recording standards, for Legal issues, for User Involvement and for Technical Centers.

Knowledge Technologies and Society. This part of our work concerned the use of knowledge technologies for solving practically relevant problems from many different areas, ranging from agriculture and industry, medicine and healthcare, to media and education. In agriculture, environment and sustainability, we were involved in several projects, where we used data mining and decision modelling methods to develop predictive and decision models to support sustainable agricultural and food system development.

As part of the Horizon 2020 IPM Decisions (Increasing the Impact of Decision Support Systems for Integrated Pest Management) project, we published a scientific article on the barriers perceived by users of decision support systems in integrated pest management and agriculture. The main reasons given were lack of trust in DSS, lack of computer knowledge of users and insufficient access to information on available DSS. We have incorporated the published results into the final development of the IPM Adviser web application (https://ipmadviser.ijs.si/) to address most of the identified barriers. The main objective of the IPM Adviser application is to allow users to easily search and compare 80 decision support systems in integrated pest management. We have actively integrated the application into the IPM Decisions platform (https://www.platform.ipmdecisions.net/). We aim for the IPM Adviser to become the most important platform for DSS in crop protection in Europe.

As part of the Horizon 2020 project COCOREADO (Balancing Links between Producers and Consumers through Education Ambassadors), we collected and structured existing decision support systems for small and innovative

companies and farms. We then developed a typology on the basis of which we evaluated 134 collected DSS. We selected the six most suitable DSS and presented them to potential users. In the area of developing decision support systems for public procurement, we further developed the concept in co-operation with the Municipality of Laško and the Local Action Group for Rural Development. Through workshops and working meetings, we have harmonised the main user functions of the DSS and at the same time acquired the necessary theoretical knowledge about public procurement and the necessary administrative procedures as part of a master's thesis entitled "Public Procurement as a Lever for the Development of Local Communities". The DSS will help to initiate synergy effects of public financial investments in the development of sustainable food production and utilisation at local and regional level.

As part of the Horizon RADIANT project (Introduction of Dynamic Value Chains for Neglected Crop Production), we continued the development of a new methodological approach to analyse dynamic supply chains for neglected crops. We conducted workshops with seven representatives of selected companies and farms and prepared business briefs for them, which will later be incorporated into their business models. We validated individual modules of the decision support system for the search for market channels and prepared them for integration into the DSS.

As part of the COST project EUdaphobase (European Soil Biology Database Warehouse for Soil Protection), we have carried out a comprehensive survey of the status of data, existing research infrastructure and research activities in 15 Balkan countries. The results will be published in the journal Applied Soil Ecology and in a master's thesis entitled "Soil Biodiversity of the Balkan Peninsula: Data Availability and Accessibility". We have also conducted a comprehensive analysis of data users' requirements for the Edaphobase database at European level. The results will also be published in the journal Applied Soil Ecology.

As part of the Horizon BENCHMARKS project (Building a European Network for the Characterization and Harmonization of Monitoring Approaches for Research and Knowledge on Soils), we carried out various text analyses to gain the necessary knowledge for the development of a soil health assessment system. For the analysis of the survey of stakeholders' objectives and contexts we developed relational databases to store tabular data and applied various machine learning methods including phrase extraction, similarity computation, topic modelling, dimensionality reduction, ranking comparison and LLM analysis. Visualisation techniques such as tables, heatmaps, scatterplots and word clouds were used and the selected results were automatically compiled into structured reports. Finally, a user interface was designed and developed for comparing data and results between the workshops and for querying the results and data using LLMs. For the Catalogue of Management Practises, we worked on the development of a pipeline that guides a Language Learning Model (LLM) in the extraction of reusable knowledge from the scientific literature. Our focus was on capturing the documented impacts of land management practises on soil biota. The pipeline is currently being evaluated, but the initial results are promising.

Members of the department participated in organization of The First European Summer School on Artificial Intelligence (ESSAI) and The 20th Advanced Course on AI (ACAI) in Ljubljana, 24-28 July 2023.

Figure 3: Sašo Džeroski was programme co-chair of the First European Summer School on Artificial Intelligence (ESSAI), as well as the 20th Advanced Course on AI (ACAI), devoted to the topic of Artificial Intelligence for Science. The joint event took place under the honorary patronage of the President of Slovenia and was attended by more than 500 participants from over 40 countries.

We also performed some work on applying natural language processing in the context of well-being and mental health, which includes development of approaches for automated detection of depression from social media content. We tested several global and transformer-based models, as various ensembling techniques; further cognitive NLP work included new models for longitudinal dementia tracking. By employing graph neural network analysis, we provide a new perspective on interpreting the sophisticated large-scale dynamics of brain activity on a synthetic EEG dataset that we crafted to explore the complex interactions of brain oscillations.

2023 also marked the start of the DIGITOP project whose goal is the introduction of advanced digital technologies, such as robotics, artificial intelligence, information and communication technologies (ICT) into manufacturing companies for the automation and optimization of production processes. Our two focuses in the project will be forecasting and managing the energy consumption of industrial processes and capture, formalization and digitalization of process operator knowledge.

In the area of *knowledge technologies for education,* we continued our collaboration with the University of Nova Gorica and published the results of investigations that focused on the questions of following, encouraging and enhancing active learning with data analytics. During the observed learning process, students interacted on a social network Mastodon. Their posts and interactions were extracted and analysed to understand student engagement over time, opening up new avenues for dialogue between students and professors. The results were presented in a chapter of a book published by Springer.

We also applied knowledge technologies to problems from industry, with a focus on the *space sector*, especially the use of machine learning for spacecraft operations and Earth observation. In the context of spacecraft operations, we address the task of predicting the thermal power consumption of the MarsExpress spacecraft on all of its 33 thermal power lines, learning predictive models from the stream of its telemetry data, which is a task of multi-target regression on data streams. We investigate the performance of local and global models, the influence of the time resolution of the measurements, and the success of the methods in detecting and adapting to change. In the context of Earth Observation, we executed an experimental analysis of methods for multi-label classification of remote sensing imagery by comparing several popular deep learning methods based on two modes of operation, where they are used as feature extractors in a combination with tree ensemble methods such as random forests and extra trees, and used as end-to-end approaches to directly address the MLC task. Next, we proposed AiTLAS—an open-source, state-of-the-art toolbox for exploratory and predictive analysis of satellite imagery. It implements a range of deep-learning architectures and models tailored for a variety of EO tasks, including image scene classification, semantic image segmentation, object detection, and crop type prediction. Furthermore, we presented AiTLAS: Benchmark Arena – an open-source benchmark suite for evaluating state-of-the-art deep learning approaches for image classification in Earth Observation (EO). To this end, we present a comprehensive comparative analysis of more than 500 models derived from ten different state-of-the-art architectures and compare them to a variety of multi-class and multi-label classification tasks from 22 datasets with different sizes and properties. Finally, we investigated the utility of in-domain self-supervised pre-training of vision models in the analysis of remote sensing imagery by executing a comprehensive study of different self-supervised pre-training strategies and evaluating their effect across 14 downstream datasets with diverse properties. Our results demonstrate that leveraging large in-domain datasets for self-supervised pre-training consistently leads to improved predictive downstream performance, compared to the standard approaches found in practice.

Some outstanding publications in the past year

1. Ana Kostovska, Diederick Vermetten, Carola Doerr, Sašo Džeroski, Pance Panov, Tome Eftimov, "OPTION : OPTImization algorithm benchmarking ONtology", IEEE transactions on evolutionary computation, Dec. 2023, vol. 27, iss. 6, str. 1618-1632, ilustr., ISSN 1941-0026, DOI: 10.1109/TEVC.2022.3232844.

2. Jure Brence, Sašo Džeroski, Ljupčo Todorovski, "Dimensionally-consistent equation discovery through probabilistic attribute grammars", Information sciences, Jun. 2023, vol. 632, str. 742-756, ilustr., ISSN 1872-6291, https://www.sciencedirect.com/science/article/pii/S0020025523003705?via%3Dihub#bl0010, DOI: 10.1016/j.ins.2023.03.073.

3. Sandro Radovanović, Marko Bohanec, Boris Delibašić, "Extracting decision models for ski injury prediction from data", International transactions in operational research, [Online ed.], Nov. 2023, vol. 30, iss. 6, str. 3429-3454, ilustr., ISSN 1475-3995, DOI: 10.1111/itor.13246.

4. Ivica Dimitrovski, Ivan Kitanovski, Dragi Kocev, Nikola Simidjievski, "Current trends in deep learning for Earth observation : an open-source benchmark arena for image classification", ISPRS journal of photogrammetry and remote sensing, Mar. 2023, vol. 197, str. 18-35, ilustr., ISSN 1872-8235, DOI: 10.1016/j.isprsjprs.2023.01.014.

5. Tomaž Erjavec, Maciej Ogrodniczuk, Petja Osenova, Nikola Ljubešić, Kiril Simov, Andrej Pančur, Michał Rudolf, Matyáš Kopp, Darja Fišer, et al., "The ParlaMint corpora of parliamentary proceedings", Language resources and evaluation, [Online ed.], 2023, vol. 57, str. 415–448, ISSN 1574-0218, https://link.springer.com/article/10.1007/s10579-021-09574-0, DOI: 10.1007/s10579-021-09574-0.

6. Nikola Ljubešić, Igor Mozetič, Petra Kralj Novak, "Quantifying the impact of context on the quality of manual hate speech annotation", Natural language engineering, 2023, vol. 29, no. 6, str. 1481-1494, ISSN 1351-3249, DOI: 10.1017/S1351324922000353.

7. Žiga Kokalj, Sašo Džeroski, Ivan Šprajc, Jasmina Štajdohar, Andrej Draksler, Maja Somrak, "Machine learning-ready remote sensing data for Maya archaeology", Scientific data, 2023, vol. 10, article no.558, 13 str., ilustr., graf. prikazi, zvd., ISSN 2052-4463, https://www.nature.com/articles/s41597-023-02455-x, DOI: 10.1038/s41597-023-02455-x.

8. Škrlj, Blaž, Bevec, Matej, Lavrač, Nada. Multimodal AutoML via representation evolution. Machine learning and knowledge extraction. Mar. 2023, iss. 1, vol. 5, str. 1-13, ilustr. ISSN 2504-4990. DOI: 10.3390/make5010001.

9. Kuzman Pungeršek, Taja, Ljubešić, Nikola, Mozetič, Igor. Automatic genre identification for robust enrichment of massive text collections : investigation of classification methods in the era of large language models. Machine learning and knowledge extraction. Sep. 2023, vol. 5, iss. 3, str. 1149-1175, ilustr. ISSN 2504-4990. DOI: 10.3390/make5030059.

10. Petković, Matej, Džeroski, Sašo, Kocev, Dragi. Feature ranking for semi-supervised learning observations. Machine learning. Nov. 2023, vol. 112, iss. 11, str. 4379–4408, tabele, graf. prikazi. ISSN 1573-0565. DOI: 10.1007/s10994-022-06181-0.

11. Mežnar, Sebastian, Džeroski, Sašo, Todorovski, Ljupčo. Efficient generator of mathematical expressions for symbolic regression. Machine learning. Nov. 2023, vol. 112, iss. 11, str. 4563-4596, ilustr. ISSN 1573-0565. DOI: 10.1007/s10994-023-06400-2.

12. Brence, Jure, Mihailović, Dragan, Kabanov, Viktor V., Todorovski, Ljupčo, Džeroski, Sašo, Vodeb, Jaka. Boosting the performance of quantum annealers using machine learning. Quantum machine intelligence. Jun. 2023, vol. 5, iss. 1, article no. 4, str. 1-11, ilustr. ISSN 2524-4914. DOI: 10.1007/s42484-022-00092-y.

Awards and Appointments

1. Marko Bohanec won the best paper award at the conference CECIIS 2023 for the paper Inter- and intra-personal differences, and consistency of decision rules, in multi-criteria modelling method DEX: a preliminary study.

2. Boshko Koloski, Perdih Stepišnik, Timen Robnik, Marko Šikonja, Senja Pollak, Blaž Škrlj: Excellence in Science 2023 (field of linguistics), awarded by ARIS for "Knowledge graph informed fake news classification via heterogeneous representation ensembles." Neurocomputing, ISSN 0925-2312. Jul. 2022, vol. 496, pp. 208–226.

3. Bojan Evkoski received the Best Student Paper award for his paper 'XAI in Computational Linguistics: Understanding Political Orientations in the Slovenian Parliament' at LTC23 in Poznan, Poland, which is based on the ParlaMint corpus.

4. Bojan Evkoski: "XAI and Computational Linguistics: Understanding Political Orientations and the Slovenian Parliament" co–authored with Senja Pollak, award for best student paper at the conference LTC'23–10th Language & Technology Conference: Human Language Technologies as a Challenge for Computer Science and Linguistics, 21.–23. 4. 2023, Poznań, Poland

Organization of Conferences, Congresses and Meetings

1. Symposium on AAAI 2023 Spring Symposium Series. Palo Alto, California, 27.–29. 3. 2023

2. 1st European Summer School on Artificial Intelligence–ESSAI 2023 & 20th Advanced Course on Artificial Intelligence–ACAI 2023. Ljubljana, Slovenia, 24.–28. 7. 2023

3. Dagstuhl Seminar: Space and Artificial Intelligence Dagstuhl. Schloss Dagstuhl, Germany, 12–17. 11. 2023.

4. 15th International Conference Jožef Stefan Postgraduate School Students. Kamnik, Slovenia, 31.–2. 6. 2023

5. Workshop on Open AI, leaded by CrowdMT 2023, on 24th Annual Conference of The European Association for Machine Learning (EAMT 2023, Tampere, Finland, 15. 6. 2023

6. SiNAPSA Conference on Neuroscience '23, Ljubljana, 28.–30. 9. 2023

7. 9th Workshop on Slavic Natural Language Processing 2023 (SlavicNLP), collocated with EACL (The 17th Conference of the European Chapter of the Association for Computational Linguistics), Dubrovnik, Croatia, 6. 5. 2023

INTERNATIONAL PROJECTS

1. INEA/CEF - MaCoCu; Massive Collection and Curation of Monolingual and Bilingual Data: Focus on Under-Resourced Languages
   Dr. Nikola Ljubešić
   Innovation And Networks Executive Agency (inea)

2. ParlaMint II - Towards Comparable Parliamentary Corpora
   Prof. Tomaž Erjavec
   Clarin Eric

3. COST CA18237; EUdaphobase - European Soil-Biology Data Warehouse for Soil Protection
   Prof. Marko Debeljak
   COST Association Aisbl

4. H2020 - FNS-Cloud; Food Nutrition Security Cloud
   Prof. Nada Lavrač
   European Commission

5. H2020 - HECAT; Disruptive Technologies Supporting Labour Market Decision Making
   Prof. Biljana Mileva Boshkoska
   European Commission

6. H2020 - TAILOR; Foundations of Trustworthy AI - Integrating Reasoning, Learning and Optimization
   Prof. Sašo Džeroski
   European Commission

7. H2020 - COCOREADO; Connecting COnsumers and producers to REbalance farmers
   Prof. Marko Debeljak
   European Commission

8. H2020 - RADIANT; ReAlising DynamIc vAlue chaiNs for underuTilised crops
   Prof. Marko Debeljak
   European Commission

9. RobaCOFI; H2020 - AI4Media; Robust and Adaptable Comment Filtering
   Matthew Richard John Purver
   European Commission

10. Working Memory Based Assessment of Large Language Models
    Asst. Prof. Senja Pollak
    Slovenian Research Agency

11. Cross-Lingual and Cross-Domain Methods for Terminology Extraction and Alignment
    Asst. Prof. Senja Pollak
    Slovenian Research Agency

12. HE - PARC; Partnership for the Assessment of Risks from Chemicals
    Prof. Sašo Džeroski
    European Commission

13. HE - INQUIRE; Identification of Chemical and Biological Determinants, Their Sources, and Strategies to promote Healthier Homes in Europe

Prof. Sašo Džeroski
European Commission
14. HE - ASSAS; Artificial Intelligence for the Simulation of Severe AccidentS
Prof. Sašo Džeroski
European Commission
15. HE - BENCHMARKS; Building a European Network for the Characterisation and Harmonisation of Monitoring Approaches for Research and Knowledge on Soils
Prof. Marko Debeljak
European Commission
16. HE - OppAttune; Countering Oppositional Political Extremism Through Attuned Dialogue: Track, Attune, Limit
Prof. Biljana Mileva Boshkoska
European Commission
17. HE - TRUSTroke; Trustworthy AI for Improvement of Stroke Outcomes
Dr. Dragi Kocev
European Commission
18. HE - ELIAS; European Lighthouse of AI for Sustainability
Prof. Sašo Džeroski
European Commission
19. EIT Climate-KIC; UP SCALE - Urban Pioneers - Systemic Change Amid Livable Environments
Asst. Prof. Martin Žnidaršič
Cinea - European Climate, Infrastructure
20. HE - SMASH; Machine Learning for Sciences and Humanities
Prof. Sašo Džeroski
European Commission
21. PRIMA; WEFE4MED - Towards a Mediterranean WEFE Nexus Community of Practice
Prof. Marko Debeljak
Prima Foundation - Partnership For Research And
22. COST CA18237; COST CA18237 - E-COST-GRANT-CA18237-f1232c5c - Soil Biodiversity of the Balkan Peninsula: Data Availability and Accessibility through Edaphobase Data Warehouse
Prof. Marko Debeljak
COST Association Aisbl
23. COST CA22154; DAEMON - Data-driven Applications towards the Engineering of functional Materials: an Open Network
Prof. Sašo Džeroski
COST Association Aisbl

RESEARCH PROGRAMMES

1. Knowledge Technologies
Prof. Sašo Džeroski
2. Physics of quantum technologies
Dr. Jure Brence

R&D GRANTS AND CONTRACTS

1. The linguistic landscape of hate speech on social media
Prof. Tomaž Erjavec
2. Quantitative and qualitative analysis of the unregulated corporate financial reporting
Asst. Prof. Senja Pollak
3. Tradition and Innovation: Traditional Paremiological Units inDialogue with Contemporary Use
Prof. Tomaž Erjavec
4. CRISPR/CAS9-mediated targeted mutagenesis for resistance of grapevine and potatoagainst phytoplasmas
Prof. Nada Lavrač
5. Determining the origin of lever metastases from liquid biopsy
Prof. Sašo Džeroski
6. Application of single cell sequencing and machine learning in mammary gland biology
Prof. Sašo Džeroski
7. Hate speech in contemporary conceptualizations of nationalism, racism, gender and migration
Asst. Prof. Senja Pollak
8. Formant Combinatorics in Slovenian
Asst. Prof. Senja Pollak

9. Corporate investment as the key to building a sustainable company: building a theoretical model and multimethod empirical analysis
Prof. Biljana Mileva Boshkoska
10. Fundamental understanding of the hydrogen formation reaction for a new generation of nickel-based electrocatalysts in alkaline and chloralkali electrolysis
Prof. Sašo Džeroski
11. Basic Research for the Development of Spoken Language Resources and Speech Technologies for the Slovenian Language
Dr. Nikola Ljubešić
12. Linguistic Accessibility of Social Assistance Rights in Slovenia
Asst. Prof. Senja Pollak
13. Predictive clustering on data streams
Prof. Sašo Džeroski
14. Computer-assisted multilingual news discourse analysis with contextual embeddings
Asst. Prof. Senja Pollak
15. Innovative isotopic techniques for identification of sources and biogeochemical cycling of mercury in contaminated sites – IsoCont
Prof. Sašo Džeroski
16. Intelligent inference system for biological discoveries and its application to cancer research
Prof. Sašo Džeroski
17. Auto-OPT: Automated selection and configuration of single-objective continuous optimization algorithms
Prof. Sašo Džeroski
18. Exploring the biofilm phenotype and surfactome of Listeria monocytogenes to predict its persistence and pathogenicity potential using machine learning
Asst. Prof. Blaž Škrlj
19. 4D STEM of energy related materials down to quantum level
Prof. Sašo Džeroski
20. Probabilistic and explainable data-driven modelling of Solid-oxide fuel cells
Prof. Sašo Džeroski
21. Embeddings-based techniques for Media Monitoring Applications (EMMA)
Prof. Nada Lavrač
22. Development of Slovene in the digital environment
Prof. Tomaž Erjavec
Ministry of Culture
23. Smart mobility measures for sustainable mobility in Slovenia – SmarMOVE
Prof. Marko Bohanec
Institute for Spatial Policies
24. Co-funding of the Project HE - SMASH; Machine Learning for Sciences and Humanities
Prof. Sašo Džeroski
Ministry of Higher Education, Science and Innovation
25. SLOKIT: Upgrade of CLARIN.SI: Corpus informer and text analyzer
Dr. Nikola Ljubešić
Ministry of Culture
26. NOO-DIGITOP; Digital transformation of robot-supported factories of the future
Dr. Aljaž Osojnik
Slovenian Research And Innovation Agency
27. Physics of quantum technologies
Dr. Jure Brence
Slovenian Research And Innovation Agency
28. Establishing an ecosystem of AI cloud services to support open science AI4SI, connected to ecosystems for supporting AI at EU level and beyond
Prof. Sašo Džeroski
Slovenian Research And Innovation Agency
29. The First European Summer School on Artificial Intelligence (ESSAI) and the 20th Advanced Course on Artificial Intelligence (ACAI), 2023, Ljubljana, Slovenia, 24 - 28 July 2023
Prof. Sašo Džeroski
Lancaster University
30. Clarin
Prof. Tomaž Erjavec
Institut Jožef Stefan

NEW CONTRACT

1. Embeddings-Basad techniques for Media Monitoring Application
Prof. Nada Lavrač
Kliping d. o. o.

VISITORS FROM ABROAD

1. prof. dr. Tomislav Stankovski, Faculty of Medicine, University of Skopje, Macedonia, 25. 1.–1. 2. 2023
2. dr. Gabriel Reder, Chalmers University, Gothenburg, Sweden, 5. 4. 2023
3. dr. Thomas Dietterich, University of Oregon, Sweden, from 21.–29. 6. 2023
4. prof. dr. Antoine Doucet, Carlos Gonzalez Gallardo, Hanh Tran Thi Gong and Julien Delaunay, Laboratory L3i from the La Rochelle University, La Rochelle, France,11.–15. 9. 2023

5. dr. Marko Šoštar, Institut Rudjer Bošković, Division of Molecular Biology, Zagreb, Croatia, 27. 10. 2023
6. Damar Hoogland, Newcastle University, Newcastle upon Tyne, Great Britain, 10. 7.–10. 11. 2023
7. Larisa Soldatova, Goldsmiths University of London, Great Britain, 31. 7.–11. 8., 1.–8. 12. 2023

STAFF

Researchers
1. Prof. Marko Bohanec
2. Dr. Michelangelo Ceci
3. Prof. Bojan Cestnik*
4. Prof. Marko Debeljak
5. **Prof. Sašo Džeroski, Head**
6. Prof. Tomaž Erjavec
7. Dr. Dragi Kocev
8. Asst. Prof. Petra Kralj Novak
9. Prof. Nada Lavrač
10. Prof. Zoran Levnajić*
11. Dr. Nikola Ljubešić
12. Prof. Biljana Mileva Boshkoska
13. Prof. Igor Mozetič
14. Asst. Prof. Panče Panov
15. Dr. Vid Podpečan
16. Asst. Prof. Senja Pollak
17. Dr. Matthew Richard John Purver
18. Prof. Ljupčo Todorovski*
19. Asst. Prof. Ana Zwitter Vitez*
20. Asst. Prof. Bernard Ženko
21. Asst. Prof. Martin Žnidaršič

Postdoctoral associates
22. *Dr. Martin Breskvar, left 01.11.23*
23. *Dr. Jurica Levatić, left 01.04.23*
24. Dr. Aljaž Osojnik
25. *Dr. Matej Petković*, left 01.10.23*
26. Dr. Nikola Simidjievski
27. Dr. Blaž Škrlj*
28. Dr. Jovan Tanevski
29. *Dr. Anita Valmarska*, left 01.09.23*

Postgraduates
30. Jure Brence, B. Sc.
31. Tanja Dergan, B. Sc.
32. Boštjan Gec, B. Sc.
33. Boshko Koloski, B. Sc.
34. Ana Kostovska, B. Sc.
35. Taja Kuzman, B. Sc.
36. Marijan Manoilov*, M. Sc.
37. Jurij Marinko, B. Sc.
38. Martin Marzidovšek*, M. Sc.
39. Katja Meden, B. Sc.
40. Sebastian Mežnar, B. Sc.
41. Nina Omejc, M. Sc.
42. Andraž Pelicon, B. Sc.
43. Marko Pranjić, M. Sc.
44. Andraž Repar*, B. Sc.
45. Sintija Stevanoska, M. Sc.
46. Marjan Stoimchev, B. Sc.

Technical officers
47. Živa Antauer, B. Sc.
48. Peter Rupnik, B. Sc.
49. *Luka Terčon, B. Sc., left 01.10.23*

Technical and administrative staff
50. Milica Bauer, B. Sc.
51. Lenka Trdina, B. Sc.

Note:
* part-time JSI member

DEPARTMENT OF INTELLIGENT SYSTEMS

<div style="text-align: right;">

E-9

</div>

The Department of Intelligent Systems researches and develops advanced methods and techniques to create intelligent computer systems with real-world applications. The research areas include artificial intelligence, ambient intelligence, agent and multi-agent systems, computational intelligence, language and speech technologies, e-health and m-health systems, smart cities, cognitive intelligence, and superintelligence. In collaboration with the Faculty of Computer and Information Science at the University of Ljubljana, the department is part of a joint research program called "Artificial Intelligence and Intelligent Systems". With over 50 years of experience in the AI field and 20 in superintelligence, we are dedicated to exploring the latest advances in AI and intelligent systems.

In 2023 the department initiated a national effort to address concerns surrounding AI, generative AI in particular, promoting responsible use and accelerating its adoption. M. Gams conducted public presentations attended by approximately 2000 participants, media appearances, and a prominent interview on national television, reaching a broad audience of several hundred thousand individuals. Additionally, M. Luštrek attained the title of full professor, adding to the department's academic excellence.

Head:
Prof. Matjaž Gams

The department collaborates closely with industry partners to integrate intelligent systems into various products and services. These systems aim to replicate human behavior and intelligence through sophisticated mechanisms and digital platforms, facilitating a seamless interaction of users. It is important to acknowledge that the field of intelligent systems extends beyond AI and is experiencing rapid global expansion, contributing to the advancement of the information society.

Ambient intelligence is a research field aiming to introduce technology into our everyday environment in a friendly way that is undemanding for the user. The main area where the department applies methods of ambient intelligence is health. We concluded the H2020 project **WideHealth**, concerned with training and networking activities on pervasive health and related topics. Particularly interesting was the thematic school on trustworthy AI – an increasingly important topic for our department – organized by the project. We also finished the H2020 project **COVIRNA**, where we developed a diagnostic test that can predict the outcome of COVID-19 patients from the expression of long non-coding RNAs in their blood. In 2023 we started three new projects. The first is a Horizon Europe project, **SmartCHANGE**, which we coordinate and whose objective is long-term risk prediction of chronic diseases for children and youth using trustworthy AI methods. The second is a Weave project with Switzerland **TRUST-ME**, concerned with monitoring well-being and productivity in a workplace using contact-free sensing. Since such monitoring is problematic from the privacy perspective, the project will use federated learning, which enables building models without removing data from the user's computer. The third new project is **WASTELESS**, which again belongs to Horizon Europe and whose topic is food loss and waste measurement. We are finishing **doctoral research** on contact-free sensing of physiological signals and states, particularly multi-wavelength analysis of photoplethysmogram (optical reading of blood volume in the skin). Close to the finish are two other studies: a study of methods to select questions in nutrition questionnaires to obtain the most information with the fewest questions and a study of stress detection from sensor and smartphone data. In the final doctoral study, we are detecting empathy from physiological readings during virtual reality sessions.

> We launched a national initiative to address concerns surrounding artificial intelligence (AI), generative AI in particular, and promote its widespread adoption. One of our team members led this effort by conducting public presentations, reaching an audience of 2000 individuals, and engaging with various media outlets, including a prominent interview on the national television. As a result, valuable information was shared with hundreds of thousands of people. Additionally, another department member was granted the title of full professor, adding to the department's academic excellence.

Figure 1: We are trying to detect empathy from physiological readings during virtual reality sessions in which people are faced with different scenarios.
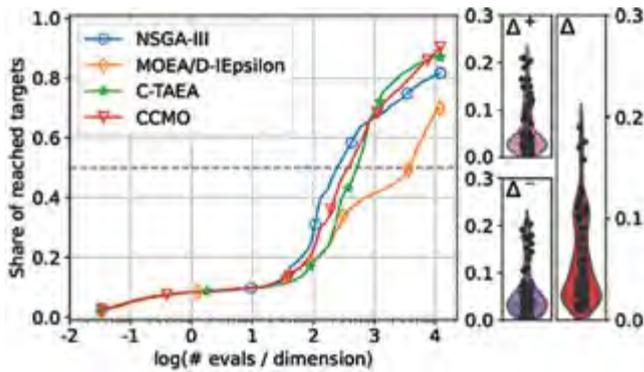
Figure 2: We developed two measures useful for constrained multi-objective optimization. The first measures the algorithm performance in solving constrained multi-objective problems, and the second assesses the ability of a problem to differentiate among algorithms.

We started a Horizon Europe project, SmartCHANGE, which we coordinate. The project involves 13 partners. The project concerns long-term risk prediction of chronic diseases of children and youth using trustworthy AI methods. The final goal is to develop tools to select appropriate preventive health interventions for young people.

Figure 3: At the IRT 2023 Industrial Forum, the Jožef Stefan Institute and the company MAHLE Electric Drives Slovenija, d. o. o., received the TARAS award for successful cooperation in the development of an electric motor for the automotive industry with an innovative simulation-optimization procedure.

We completed the Urbanite project and developed a platform and tools for smart cities for four major European cities. Our main contribution was the development of traffic simulations and a user-friendly interface for creating new simulations easily. Based on simulation results, we developed a decision support system and a recommendation system to improve citizens' quality of life.

In the field of **agents and multi-agent systems**, the main research areas focus on developing intelligent autonomous systems for the management of smart cities and intelligent support systems in healthcare. In the **AI Bee System** project, we developed a prototype of an intelligent system for monitoring bees in their home environment with a Slovenian company. We started the **Wellbeeing** project, where, together with our Slovenian partners, we are continuing the development of an intelligent system for monitoring bees, focusing on the impact of the environment on bee stress and the resulting honey production. The **DIGITOP** project was started, aiming at the digital transformation and robotization of production, especially in Slovenia. In the H2020 **Urbanite** Intelligent Cities project, we developed a system that simulates traffic and identifies and delivers the best mobility policies and enhancements. Four European cities are included in the project: Amsterdam, Helsinki, Bilbao, and Messina. In the **Cestel** project, based on the sensor signals from the bridges, we predict the number of axles, the distances between the axles, and the weight of the vehicles crossing the bridge. We completed the **Valence** project, where we collaborated with international partners to modernize computer science learning, emphasizing learning modern artificial intelligence methods in secondary schools. We are happy to track, teach, and participate in developing general, generative, and super-intelligence programs like ChatGPT. In the project **Personalized Treatment with Stem Cell Transplantation in Hearts with Heart Failure**, we explore novel treatment methods adapted to the patient.

Computational intelligence is the study of randomized search, optimization, and learning methods inspired by biological and physical systems. Research in this area at the Department of Intelligent Systems focuses on evolutionary computation and optimization. We study evolutionary algorithms for multiobjective optimization, constraint handling techniques, problem characterization through problem landscape analysis, algorithm performance prediction, visualization of optimization results, methodology of algorithm benchmarking, and their applicability in science and engineering. In collaboration with the Technical University of Ostrava, Czech Republic, we are carrying out the research project **Constrained Multiobjective Optimization Based on Problem Landscape Analysis**, co-funded by the Slovenian Research and Innovation Agency and the Czech Science Foundation under the Weave research scheme. This research aims to contribute to the theoretical foundations of constrained multiobjective optimization and provide a new generation of evolutionary metaheuristics for this type of problems. We focus on problem landscape analysis, feature-based problem characterization, algorithm performance prediction, and algorithm selection and configuration. We joined the COST Action **CA22137 Randomized Optimization Algorithms Research Network (ROAR-NET)**, the purpose of which is to stimulate research and development of random optimization algorithms, make them competitive in solving real-world problems, and achieve their widespread adoption in practice. In collaboration with the Computer Systems Department, we carried out **Simulation-Based Optimization of Cogging Torque in Electric Motor Design** for MAHLE Electric Drives Slovenia. This project aimed to determine the geometric and material characteristics of the selected electric motor for the automotive industry so that numerous technical requirements for its operation are met and the manufacturing costs are minimal. Because of the high computational complexity of the simulation-based optimization, the emphasis was on developing a procedure that finds the most favorable solution with as few solution evaluations as possible. Using this procedure, we reduced the cost of the electric motor components by 10% compared to its initial version. For this achievement, the Jožef Stefan Institute and MAHLE Electric Drives Slovenija received the TARAS award at the IRT 2023 Industrial Forum in Portorož. The award recognizes a successful cooperation between industry and research institutions in the fields of innovation, development, and technology. In

the project **Intelligent and Environmentally Friendly Scheduling of Field Work (MF-Scheduler)** we assisted the Comland company in their design of a computer system for scheduling workers to field tasks. We evaluated the system on real-world problems.

In **speech and language technologies**, we work on speech synthesis, semantic analysis of text, question-answering and LLMs. Together with the companies Alpineon and Amebis, we developed a new, high-quality speech synthesizer, **eBralec** (https://ebralec.si/). The software package has more than a thousand subscribers and is an indispensable tool for blind and visually-impaired users (it is the "official" speech synthesizer of the Slovenian Association for the Blind and Visually Impaired) and people with reading impairments (the Bravo association). For these users, eBralec is free of charge and can be ordered at the Library for the Blind and Visually Impaired (https://www.kss-ess.si/ebralec-sintetizator-govora-slovenskega-jezika/). eBralec is also an integral part of the DarsTraffic+ application, which provides traffic information, while its server version has been used by the National and University Library since 2017. In addition, it has been reading news on the renewed Delo (national daily newspaper) website. Furthermore, we successfully completed the **AudiBook** project: "Education accessibility through a digital audio library for the blind and visually impaired".

The **26th International Multiconference Information Society, IS 2023** (https://is.ijs.si), was held at the Jožef Stefan Institute from 9 to 13 October 2023, comprising 12 separate conferences, where participants presented more than 100 papers. The Michie-Turing Award for outstanding lifetime contribution to the development and promotion of the Information Society was awarded to Prof. Andrej Brodnik. The Achievement of the Year Award went to Benjamin Bajd. The Information Lemon for the least appropriate information move was received by the incompatibility of healthcare systems in Slovenia. The Information Strawberry for the best information move was awarded to RTV portal dostopno.si.

Some outstanding publications in the past year

1. Janko, V., Reščič, N., Vodopija, A., Susič, D., De Masi, C., Tušar, T., Gradišek, A., Vandepitte, S., De Smedt, D., Javornik, J. S., Gams, M., Luštrek, M. Optimizing non-pharmaceutical intervention strategies against COVID-19 using artificial intelligence. Frontiers in Public Health, 2023, 11, 1073581

2. Mlakar, M., Gradišek, A., Luštrek, M., Jurak, G., Sorić, M., Leskošek, B., Starc, G. Adult height prediction using the growth curve comparison method. PLOS One, 2023, 18 (2), e0281960, 1–13

3. Shulajkovska, M., Smerkol, M., Dovgan, E., Gams, M. A machine-learning approach to a mobility policy proposal. Heliyon, 2023, 9 (10), e20393

4. Susič, D., Syed-Abbdul, S., Dovgan, E., Jonnagaddala, J., Gradišek, A. Artificial intelligence based personalized predictive survival among colorectal cancer patients. Computer Methods and Programs in Biomedicine, 2023, 231, 107435, 1–9

5. Volz, V., Naujoks, B., Kerschke, P., Tušar, T. Tools for landscape analysis of optimisation problems in procedural content generation for games. Applied Soft Computing, 2023, 136, 110121, 1-14

Awards and appointments

1. Andrejaana Andova, Tobias Benecke, Harald Ludwig, Tea Tušar: Best poster award at EvoStar 2023, Brno, Czech Republic, 12–14 April 2023, paper "Towards constructing a suite of multi-objective optimization problems with diverse landscapes"

2. Bogdan Filipič, Tea Tušar, Aljoša Vodopija, Jordan Cork, Peter Korošec and the company MAHLE Electric Drives Slovenija, d. o. o.: The TARAS award for successful collaboration between the business enterprise and research and development sector in the field of innovation, development and technology, Industrial Forum IRT 2023, Portorož, 12–13 June 2023, project "Development of an electric motor for the automotive industry with an innovative simulation-based optimization procedure"

We developed an innovative optimization procedure based on computationally demanding numerical simulations, also ensuring the robustness of the solutions. Using it, we managed to reduce the component costs of a selected electric motor for automotive power steering systems by 10%.
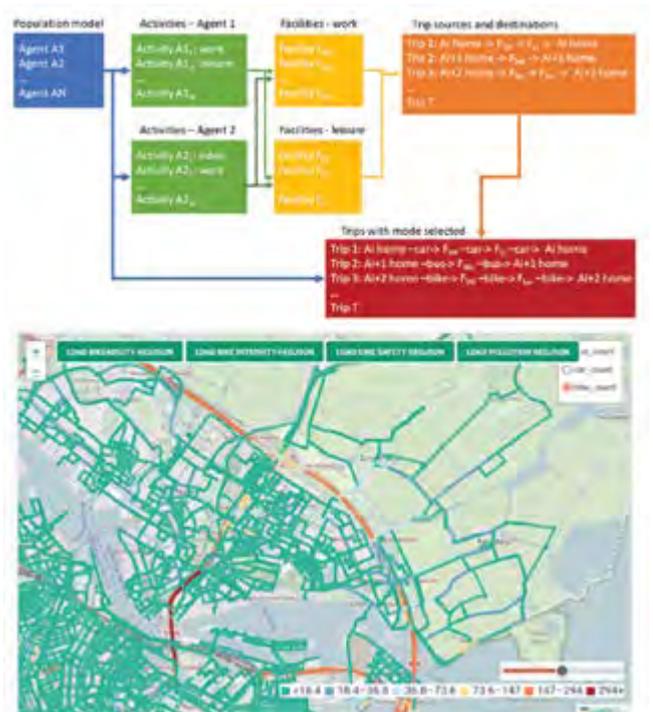

Figure 4: In the H2020 project URBANITE, we developed a new system for smart cities based on artificial intelligence. We successfully tested the prototype in four major cities: Amsterdam, Bilbao, Helsinki, and Messina. The image shows an analysis of bicycle traffic in Amsterdam.

Figure 5: The department initiated a national effort to address concerns surrounding artificial intelligence, promoting responsible use and accelerating its adoption. M. Gams conducted public presentations attended by approximately 2000 participants, media appearances, and a prominent interview on the national television, reaching a broad audience of several hundred thousand individuals. Another important event was also the traditional Information Society conference. The main award winner was Prof. Andrej Brodnik.

3. Bogdan Filipič: Best paper award at the International Technology Transfer Conference, 26th International Multiconference Information Society, IS 2023, Ljubljana, 9–13 October 2023, paper "Randomized optimization: from algorithmic studies to industrial applications"
4. Tea Tušar, Peter Korošec, Bogdan Filipič: Best paper award at the Slovenian Conference on Artificial Intelligence, 26th International Multiconference Information Society, IS 2023, Ljubljana, 9–13 October 2023, paper "A multi-step evaluation process in electric motor design"

Organization of conferences, congresses and meetings

1. WideHealth Winter School on Trustworthy AI, Potsdam, Germany, 14–17 March 2023
2. Organization of the Project Kick-Off Meeting for SmartChange, Ljubljana, 23–24 May 2023
3. International Workshop on Computer Vision for Physiological Measurement, CVPM 2023, Vancouver, Canada, 18 June 2023
4. 19th International Conference on Intelligent Environments, Flic-en-Flac, Mauritius, 27–30 June 2023
5. 12th International Workshop on Intelligent Environments Supporting Healthcare and Well-Being, WISHWell 2023, Flic-en-Flac, Mauritius, 28 June 2023 (online)
6. Blackbox Optimization Benchmarking Workshop, BBOB 2023, GECCO Job Market, and the Session on Evolutionary Computation in Practice, ECiP, at the Genetic and Evolutionary Computation Conference, GECCO 2023, Lisbon, Portugal, 15–19 July 2023
7. 26th International Multiconference on Information Society, IS 2023, Ljubljana, 9–13 October 2023
   - Data Mining and Data Warehouse – SIKDD, 9 October 2023
   - Demographic and Family Analysis, 9 October 2023
   - Legends of Computing and Informatics, 10 October 2023
   - Healthy Longevity Conference, 10 October 2023
   - Myths and Truths about Environmental Protection, 11 October 2023
   - International Conference on Technology Transfer, 11 October 2023
   - Digital Inclusion in the Information Society – DIGIN 2023, 11 October 2023
   - Slovenian Conference on Artificial Intelligence, 12 October 2023
   - Cognitive Science, 12 October 2023
   - Education and Training in the Information Society, 13 October 2023
8. 41st Slovenian Workshop on Nature-Inspired Algorithms, Ljubljana, 24 November 2023

INTERNATIONAL PROJECTS

1. ERASMUS+; VALENCE - Advancing Machine Learning in Vocational Education
   Prof. Matjaž Gams
   European Commission
2. H2020 - URBANITE; Supporting the decision-making in URBAN transformation with the use of dIsruptive Technologies
   Prof. Matjaž Gams
   European Commission
3. H2020 - COVIRNA; A Diagnostic Test to improve Surveillance and Care of COVID-19 Patients
   Prof. Mitja Luštrek
   European Commission
4. H2020 - WideHealth; Widening Research on Pervasive and eHealth – WideHealth
   Prof. Mitja Luštrek
   European Commission
5. HE - WASTELESS; Waste Quantification Solutions to Limit Environmental Stress
   Prof. Mitja Luštrek
   European Commission
6. HE - SmartCHANGE; AI-Based Long-Term Health Risk Evaluation for Driving Behaviour Change Strategies in Children and Youth
   Prof. Mitja Luštrek
   European Commission
7. ERASMUS+; TSAAI - Transversal Skills in Applied Artificial Intelligence
   Asst. Prof. Anton Gradišek
   European Commission
8. DIGITAL EU; DIGI-SI - Digital Emergency Responce for Slovenia
   Asst. Prof. Anton Gradišek
   European Commission
9. AIBeeSystem; AI-Powered Bee Monitoring System
   Asst. Prof. Anton Gradišek
   Politecnico Di Milano
10. COST CA22137; ROAR-NET - Randomised Optimisation Algorithms Research Network
    Prof. Bogdan Filipič
    COST Association Aisbl
11. COST CA22129: InsectAI - Using Image-based AI for Monitoring & Conservation
    Asst. Prof. Anton Gradišek
    COST Association Aisbl

RESEARCH PROGRAMME

1. Artificial Intelligence and Intelligent Systems
   Prof. Mitja Luštrek

R&D GRANTS AND CONTRACTS

1. Precision Medicine Approach to Cell Therapy in Heart Failure
   Asst. Prof. Anton Gradišek
2. Constrained multiobjective optimization based on problem landscape analysis
   Prof. Bogdan Filipič
3. TRUST-ME:TRUstworthy enhancment of job SaTisfaction and productivity using Micro-sensing in wor...
   Prof. Mitja Luštrek
4. WellBEEing: IoT monitoring of bee colonies in the presence of external stressors
   Asst. Prof. Anton Gradišek
5. Social Innovation for Integrated health CARE of ageing population in ADRION Regions-SI4CARE
   Prof. Mitja Luštrek
   The Emillia-Romagna Region
6. EDIH DIGI-SI Project - Co-founding by Ministry for Digital Transformation
   Asst. Prof. Anton Gradišek
   Ministry of Digital Transformation
7. NOO-DIGITOP; Digital transformation of robot-supported factories of the future
   Prof. Matjaž Gams
   Slovenian Research And Innovation Agency

8. 26th International Multiconference Information Society 2023, IS 2023, Ljubljana, Slovenia, 09 October 2023 - 13 October 2023
   Prof. Matjaž Gams
9. 20th International Conference Intelligent Environments 2024, Ljubljana, Slovenia, 17 June 2024 - 20 June 2024
   Prof. Mitja Luštrek

NEW CONTRACTS

1. Intelligent and environmentally friendly scheduling of field work - MF-Scheduler
   Prof. Bogdan Filipič
   Comland d. o. o.
2. Simulation-based optimization of cogging torque in electric motor design
   Prof. Bogdan Filipič
   Mahle Electric Drives Slovenija d. o. o.
3. Measurements of physical activity
   Prof. Mitja Luštrek
   ZŠ RS Planica
4. Software designed based on AI for predicting number and load on axes
   Prof. Matjaž Gams
   Cestel d. o. o.
5. Development of a mobile system for weighing vehicles while driving using artificial intelligence methods
   Prof. Matjaž Gams
   Cestel d. o. o.

VISITORS FROM ABROAD

1. Mathis Jeroncic, Thomas Velard, Paris-Saclay University, Paris, France, 24 April to 30 June 2023
2. Kawai Kitoshi, University of Tokyo, Japan, 15 June to 22 September 2023

STAFF

Researchers
1. Prof. Bogdan Filipič
2. **Prof. Matjaž Gams, Head**
3. Asst. Prof. Anton Gradišek
4. Prof. Mitja Luštrek
5. Dr. Tomaž Šef
6. Asst. Prof. Tea Tušar

Postdoctoral associates
7. *Dr. Carlo Maria De Masi*, left 01.07.23*
8. *Dr. Vito Janko*, left 01.05.23*
9. *Dr. Aleš Tavčar*, left 01.04.23*

Postgraduates
10. Andrejaana Andova, B. Sc.
11. *Emilija Kizhevska, M. Sc., left 03.04.23*
12. Dr. Jana Krivec*
13. Junoš Lukan, M. Sc.
14. Gašper Slapničar, B. Sc.
15. David Susič, B. Sc.
16. Aljoša Vodopija*, B. Sc.

Technical officers
17. Zoja Anžur, B. Sc.
18. *Ana Arnež, B. Sc., left 16.01.23*

19. Jordan Nicholas Cork
20. *Jure Grabnar, B. Sc., left 09.07.23*
21. Marko Jordan, B. Sc.
22. Primož Kocuvan, B. Sc.
23. Žiga Kolar, B. Sc.
24. Sebastjan Kramar, B. Sc.
25. Maj Smerkol, B. Sc.
26. *Jakob Valič, B. Sc., left 01.05.23*
27. *Zdenko Vuk, B. Sc., left 01.02.23*

Technical and administrative staff
28. Vesna Koricki, B. Sc.
29. Mitja Lasič
30. Liljana Lasič
31. Blaž Mahnič, B. Sc.
32. *Marcel Franse Martinšek, left 06.09.23*
33. Mateja Mavrič, B. Sc.
34. Nina Reščič, B. Sc.
35. Lana Zemljak

Note:
* part-time JSI member

DEPARTMENT OF REACTOR ENGINEERING R-4

The Department of Reactor Engineering is involved in basic and applied research in the fields of nuclear engineering and safety. Topics include theoretical and experimental research of basic thermal-hydrodynamic phenomena, thermal-hydraulic safety analyses of fission and fusion reactors, and structural safety analyses. Most research activities are part of international cooperation programmes. Research results are incorporated into projects for the industry and for the regulatory authority, as well as in undergraduate and doctoral studies programmes.

Head:
Prof. Leon Cizelj

Modelling of basic thermal-hydrodynamic phenomena

In the field of two-phase gas-liquid flow we continued simulations of Taylor bubbles (bullet-shaped bubbles that extend over almost the entire tube cross-section) in the counter-current flow regime using the OpenFoam open-source Computational Fluid Dynamics (CFD) code. The Large Eddy Simulation (LES) was used with a volume-of-fluid (VOF) and an improved geometric Piecewise Linear Interface Capturing (PLIC) method, which allow a high-fidelity reproduction of the flow. Results were validated using measurements obtained in the department's THELMA laboratory. These simulations improved the predictions of bubble decay rate for laminar flow conditions, whereas they still overestimate the decay rate for turbulent flow. To resolve this problem, a new model was proposed, in which the surface tension depends on the curvature of the gas-liquid interface. The model was implemented and tested in two-dimensional simulations, demonstrating its capability to effectively inhibit the formation of small bubbles trailing downstream of the Taylor bubbles.

Within the framework of the CROSSING bilateral project, we cooperated with HZDR (Rossendorf, Germany) on the development of advanced methods for simulating multiphase flows. We focus on advancing the hybrid two-fluid modelling approach and on the development of momentum-, heat- and mass-transfer models that can adapt to the local interface morphology, depending on the resolution of the computational mesh. Such an approach should offer a good trade-off between accuracy and computational cost and is intended for practical simulations of industrial applications.

In the modelling of convective subcooled boiling, we analysed the population balance model for bubble sizes used in CFD simulations of boiling in a vertical pipe of the DEBORA experiment (CEA, France). We studied the influence of bubble coalescence and breakup models on the distribution of vapour in the pipe. Simulation results were most affected by the coalescence model, especially the contribution of collisions between bubbles due to turbulence.

Basic phenomena of vapour explosion and debris bed coolability, which might occur during a severe accident in a nuclear power plant (NPP) if the hot reactor-core melt comes into contact with the coolant, were further investigated. Among studies of explosions in stratified melt-coolant configurations, reactor conditions were further simulated, using the developed model of the premixed layer formation, implemented in our patch of the MC3D code (IRSN, France). Based on previous analyses of vapour explosions in a stratified configuration that indicated a potential contribution to melt-coolant mixing also from fragmentation of the melt jet, we continued to study fuel-coolant interaction in the combined stratified and melt jet configurations. Next, to improve the understanding of heat transfer during the explosion phase, CFD simulations were performed applying the developed dynamic vaporization modelling. Finally, we continued with an investigation of debris bed coolability in top flooding conditions, within which several experiments performed in the FLOAT facility (IKE, Stuttgart, Germany) were simulated with the MC3D code.

Experimental investigations in THELMA laboratory

In the department Thermal-Hydraulics Experimental Laboratory for Multiphase Applications (THELMA), we continued flow boiling experiments in a test section that represents part of a single rod in a light-water nuclear reactor fuel assembly. For the first time since 2018, this experimental loop was dismantled to replace the test section with a new one, capable of facilitating heat flows at least twice as high. We measured and characterized the surface roughness on the old and new test sections. Additional modifications were also completed, which now makes it possible to select different directions of the primary or secondary fluid flows in the co-flow or counter-flow regime. Along with quality improvements of the boiling images captured with a high-speed camera, we improved the method of analysing images with neural networks in cooperation with HZDR. The bubble-size distributions obtained in this way are used to develop bubble-population balance models in CFD.

The study of Taylor bubbles in laminar and turbulent flows was carried on in cooperation with CEA. The liquid velocity field was measured using Particle Image Velocimetry (PIV) with Laser Induced Fluorescence. To mitigate the optical reflections at the gas-liquid interface and enhance the accuracy of the measurements, we introduced a novel technique that integrates data from both optical and PIV images. Namely, optical images underwent post-processing with an in-house interface recognition algorithm, enabling the extraction of bubble shapes and motion at each time step. Subsequently, this data was utilized to generate dynamic masking for the Taylor bubbles in the PIV images. Through testing on Taylor bubbles within laminar flows, the effectiveness of the method was demonstrated, displaying its ability to identify subtle secondary vortices previously undetectable by existing methodologies. These findings serve to validate the simulations of Taylor bubbles in the counter-current turbulent flow regime. The partner CEA reproduced the current regime with an accurate front tracking method that directly solves the Navier-Stokes equations and simultaneously tracks the interface. The simulation results correctly predict the shape of the bubble and the velocity field, although minor discrepancies subsist in predicting the existence of secondary flows inside Taylor bubbles. We also investigated the hydraulic jump, which is always visible in the obtained high-speed camera images of the Taylor bubble but, so far, numerical simulations failed to predict it.

The new upgraded test section for a convective boiling experiment now enables the study of flow boiling at heat fluxes twice as high as previously achieved.
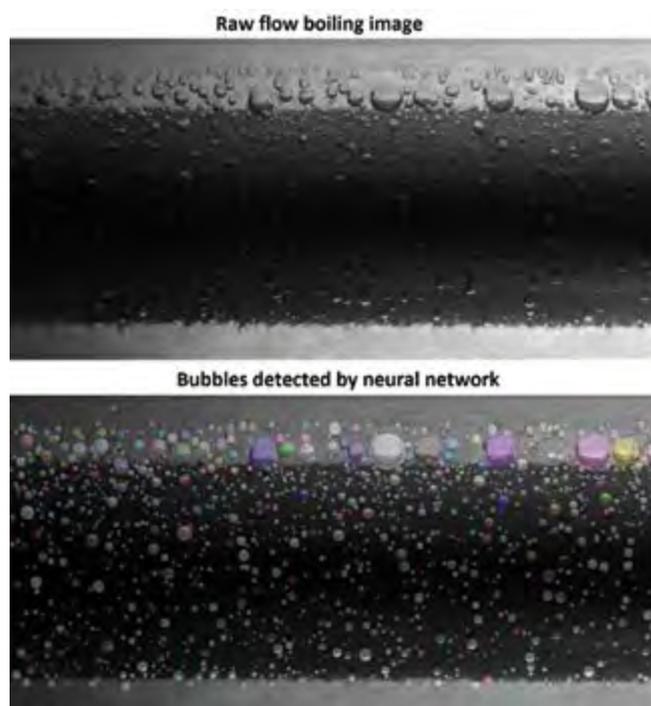

Figure 1: Convective boiling inside annular channel in horizontal position. Top: image captured by high-speed camera. Bottom: bubbles detected using neural network algorithm.

Thermal-hydraulic safety analyses of fission and fusion reactors

The SEAKNOT European project considers severe accidents in light-water reactors, with the following purposes: identification of phenomena during severe accidents, for which further research is essential; establishment of a directory of experimental databases; development of a network of experimental infrastructures; dissemination of existing and novel knowledge. In 2023, initial identification of phenomena and compilation of experiments were performed, with JSI leading the tasks related to NPP containment phenomena.

The purpose of the ASSAS European project is the use of Artificial Intelligence methods to simulate severe accidents. As, due to the complexity of some phenomena, simulations based on physical principles are too long for an adequate severe-accident simulator to be developed, the basic idea is to replace some of the models with so-called "surrogate models" that are not based on physical principles but are able to calculate comparable results in a shorter time. In 2023, in cooperation with the JSI Department of knowledge technologies, a general methodology for the development of surrogate models based on machine learning was defined. The following issues were considered: 1) to develop global or time-stepping models? 2) to consider individual physical phenomena or individual NPP systems? Possible quantitative metrics for the validation of surrogate models were also identified: least-squares method, method based on fast Fourier transform, and Wasserstein metric.

In the frame of the CAMP (US Nuclear Regulatory Commission) research program, the RELAP5 thermal-hydraulic system code was used to perform an uncertainty and sensitivity analysis of a small-break loss-of-coolant accident in the hot leg of a two-loop Pressurized Water Reactor (PWR); this represents an overcooling scenario that can cause high-pressure thermal shock in the reactor pressure vessel. More than 200 runs were performed, with the uncertainty and sensitivity analysis performed with the SUSA (Software for Uncertainty and Sensitivity Analyses) code. In the sensitivity study, one uncertain input parameter at a time was varied among the 15 selected ones.

An analysis was performed of the efficiency optimization of the design of the cooling channel for the stellarator W7-X, using local instantaneous description.

The European project AMHYCO deals with the prevention of hydrogen and carbon monoxide combustion in an NPP containment during a severe accident. With the system code ASTEC (IRSN), we performed simulations of the distribution of these combustible gases in a generic containment model, but without mitigation using safety systems. The final purpose of the project is an improvement to the severe-accident management guidelines.

In the frame of the European nuclear fusion project WPDES, the assessment of the thermal loading in the DEMO fusion reactor breeding blanket during an ex-vessel loss-of-coolant accident was continued. For an assessment of the thermal loading due to decay heat generated inside the activated components, a transient CFD model was developed. It was shown that with the design of two loops for the cooling system, the occurring peak temperatures in affected in-vessel components are lower and faster thermalization of the system is achieved. The work was performed

in close cooperation with the EUROfusion Programme Management Unit (Garching, Germany).

A water-cooled divertor element for the stellarator W7-X in Greifswald (Germany) is being developed within the European fusion project DIV-W7X. A CFD analysis was performed on the efficiency optimization of the meander-type design of the cooling channel with three U-turns, with and without a twisted tape insert. The results showed that the optimisation of the U-turn shape does not significantly increase the heat transfer but increases the pressure drop. The effects of twisted tape extension and orientation can also be considered as negligible. Instead, a new, more efficient, cooling concept consisting of 12 smaller parallel pipes was proposed and analysed, demonstrating enhancement of the heat transfer and a reduction of the pressure drop.

For the DEMO fusion reactor, the loss of cryostat vacuum due to large ingress of helium was further analysed with the MELCOR for Fusion code. A parametric study on break size was performed to determine the number of the pressure-relief rupture disks in order to maintain the pressure below the cryostat's designed pressure limit. The work was performed in the frame of the European nuclear fusion project WPSAE.

Figure 2: Calculated temperature distribution on the cooling channel walls of the new W7-X divertor cooling element.

Structural safety analyses

The research was focused on the process of inter-granular stress-corrosion cracking, in particular on the micro-mechanical aspects of its initiation stage. The idea is to decouple the effect of a local stress state from that of the environment by assigning grain boundaries to distinct types, based on their associated strengths, and then studying the distribution of intergranular normal stresses of each type. These distributions can then be used for the probabilistic modelling of grain-boundary-damage initiation.

A novel approach was proposed for predicting the intergranular normal stress distributions using symmetries of linear-elastic polycrystalline materials such as macroscopic mechanical isotropy of a polycrystal and linear material behaviour of grains.

A strain gradient crystal plasticity theory was formulated and integrated into the in-house solver for simulating strain localization phenomena in irradiated polycrystalline materials.

The previously proposed buffer-grain model for predicting the induced grain-boundary stresses in linear-elastic polycrystalline materials under uniform external loading was upgraded to the bicrystal model. The main improvement consists of a consideration of a complete set of boundary conditions on the microscale, resulting in a more realistic description of the stress field within the aggregate. Bicrystal model predictions were verified through finite element simulations, showing good agreement for cubic crystal lattices.

An in-house solver based on the fast-Fourier-transform homogenization method was developed for simulating the mechanical response of irradiated austenitic stainless steel at varying irradiation doses. The results were successfully validated against the commercial finite-element software Abaqus.

A strain gradient crystal plasticity theory was formulated and integrated into our in-house solver. This development addresses and mitigates numerical instabilities, allowing for more robust computational analyses. The method was employed to accurately simulate strain localization phenomena in polycrystalline materials with softening-grain behaviour resulting from irradiation effects.

In the topic of thermal fatigue due to fluid mixing, a thermally stratified flow past a pipe elbow was studied using CFD, thermo-mechanical and fatigue analyses, in cooperation with North China Electric Power University. The tangential oscillation and mixing enhancement phenomena of thermal stratification were studied for different elbow radii together with their impact on fatigue damage risk.

Within the European project APAL, our contribution to deterministic benchmarks was completed where advanced methods for pressurized thermal shock assessment were developed and verified. Safety margins for the long-term operation of NPPs were evaluated with consideration of thermal-hydraulic uncertainties in subsequent deterministic structural integrity analyses.

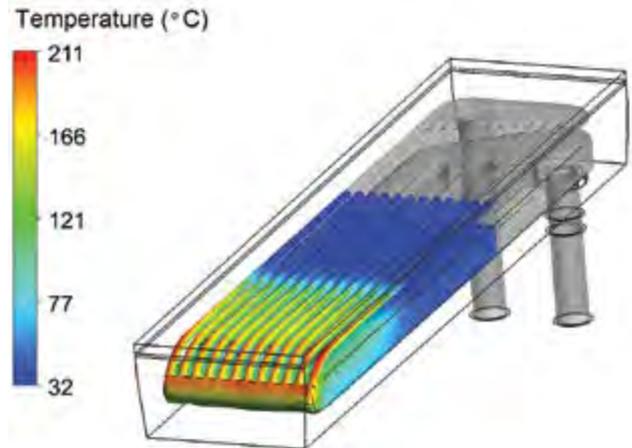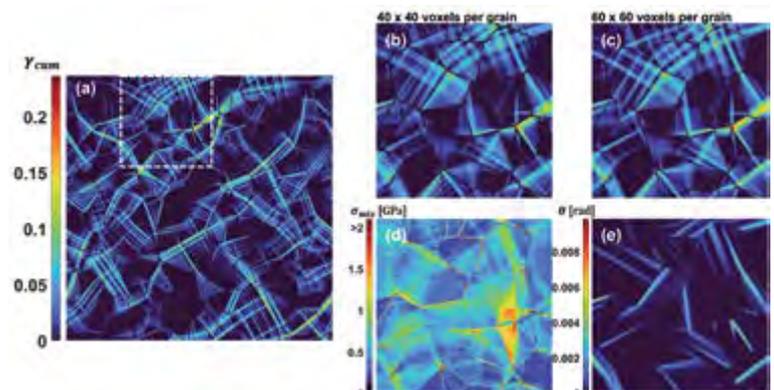Figure 3: Results of strain gradient crystal plasticity simulation: (a) distribution of cumulative shear strain in 2D polycrystalline aggregate; (b) and (c) same quantity at two different grid resolutions; (d) and (e) von-Mises stress and lattice rotation angle.

Fusion-related activities focused on the thermo-mechanical and structural integrity analyses of the plasma facing units of the Divertor Tokamak Test facility. The analyses considered the thermal loads from CFD simulations for three plasma scenarios, as well as electromagnetic loads for the single-null configuration.

Technical cooperation, consulting services and education

In 2023 the department cooperated in projects for industry and the state administration as well. As an authorized institution for radiation and nuclear safety, we prepared an independent evaluation on outage and refueling activities in the Krško NPP. For the Slovenian Nuclear Safety Administration, we used the MELCOR code to perform an uncertainty analysis of a selected severe accident scenario.

Following a leak of a safety injection pipe in the Krško NPP in autumn 2023, the department allocated a significant workforce (seven researchers) for the root-cause analysis of the pipe damage. One group of researchers was focused on CFD analyses of thermal phenomena in the pipe dead end during normal operation. Analyses have pointed to thermal fatigue as a possible cause for the pipe corrosion. The second group was focused on structural analyses of phenomena in the pipe walls, which elucidated stresses and strains in the affected section.

Researchers of the department represent the core staff of the Chair for Nuclear Engineering at the Faculty of Mathematics and Physics at the University of Ljubljana, and are involved in nuclear engineering undergraduate, master and doctoral studies. The programmes are associated with the European Nuclear Education Network (ENEN). In the autumn of 2023, the fourth generation of students of the international MSc program in nuclear engineering SARENA, in which the department is actively involved, was admitted to the faculty. In 2023, the EU approved the extension of the program, which will continue in a similar form from 2024 to 2029.

Some outstanding publications in the past year

1. Leon Cizelj, Ivo Kljenak, Iztok Tiselj, "Know-why? and know-how? in the development of nuclear talents: An analysis of recent nuclear engineering Ph.D. research", *Nuclear Engineering and Design*, 2023, **415**, 112734.
2. Jan Kren, Boštjan Zajec, Iztok Tiselj, Samir El Shawish, Žiga Perne, Matej Tekavčič, Blaž Mikuž, "Dynamics of Taylor bubble interface in vertical turbulent counter-current flow", *International Journal of Multiphase Flow*, 2023, **165**, 104482.
3. Rok Krpan, Iztok Tiselj, Ivo Kljenak, "Atmosphere homogenization induced by vertical jets in large enclosures", *Annals of Nuclear Energy*, 2023, **180**, 109476.
4. Janez Kokalj, Mitja Uršič, Matjaž Leskovar, Renaud Meignen, "Modelling and simulating of premixed layer in stratified fuel coolant configuration", *Annals of Nuclear Energy*, 2023, **185**, 109740.
5. Samir El Shawish, Timon Mede, "Grain boundary stresses in elastic materials", *European Journal of Mechanics - A/Solids*, 2023, **99**, 104940.

Awards and Appointments

1. Khaled Al-Athel, Abdulaziz Alyamani, Mohanad Alzahrani, Jan Kren, Blaž Mikuž, Afaque Shams: Best poster award (3rd prize) for „Experimental investigation of heating a turbulent flow in a square duct using a heated foil", International Conference on Nuclear Power Engineering-SCOPE, Dhahran, Saudi Arabia.
2. Mihael Boštjan Končar, Matej Tekavčič, Mitja Uršič: Prešeren award for MSc thesis „Modelling of severe accidents in sodium-cooled fast nuclear reactors", University of Ljubljana, Slovenia.
3. Iztok Tiselj, Jan Kren, Blaž Mikuž: Best paper award for „Experimental study of isothermal vertical slug flow", International Conference on Nuclear Power Engineering-SCOPE, Dhahran, Saudi Arabia.

Organization of conferences, congresses and meetings

1. 14th Meeting „European MELCOR and MACCS User Group (EMUG)", Ljubljana, Slovenia, 12-14 April 2023
2. Advanced workshop and workpackage meetings of APAL project, Ljubljana, Slovenia, 9-12 May 2023
3. Workshop on safety of small modular, advanced and fusion reactors and progress meeting of HARMONISE project, Celje, Slovenia, 20-22 June 2023
4. Short course on nuclear engineering experiments, Ljubljana, Slovenia, 3-14 July 2023

INTERNATIONAL PROJECTS

1. H2020 - EURAD; European Joint Programme on Radioactive Waste Management
   Prof. Leon Cizelj
   European Commission
2. H2020 - ECC-SMART; Joint European Canadian Chinese Development of Small Modular Reactor Technology
   Prof. Leon Cizelj
   European Commission
3. H2020 - AMHYCO; Towards an Enhanced Accident Management of the Hydrogen/CO Combustion Risk
   Asst. Prof. Ivo Kljenak
   European Commission
4. H2020 - APAL; Advanced PTS Analysis for LTO
   Dr. Oriol Costa Garrido
   European Commission
5. HE - EUROfusion; WP12: DIV-IDTT, DIV-W7X, DIV-DEMO_HE-FU
   Dr. Oriol Costa Garrido
   European Commission
6. HE - EUROfusion; WP08: DES-1,2_HE-FU
   Dr. Martin Draksler
   European Commission
7. HE - EUROfusion; WP19: SAE-1_HE-FU
   Asst. Prof. Mitja Uršič
   European Commission
8. HE - EUROfusion; WP25: PMU_HE-FU, RU-Mgmt-1_HE-FU
   Asst. Prof. Boštjan Končar
   European Commission
9. HE - EUROfusion; WP24: TRED_HE-FU, EDU_HE-FU
   Asst. Prof. Boštjan Končar
   European Commission
10. HE - HARMONISE; Towards Harmonisation in Licensing of Future Nuclear Power Technologies in Europe
    Prof. Leon Cizelj
    European Commission
11. HE - SEAKNOT; Severe Accident Research and Knowledge Management for LWRS
    Asst. Prof. Ivo Kljenak
    European Commission
12. HE - ENEN2plus; Building European Nuclear Competence Through Continuous Advanced and Structured Education and Training
    Prof. Leon Cizelj
    European Commission
13. HE - OFFERR; eurOpean platForm For accEssing nucleaR R&d facilities
    Prof. Leon Cizelj
    European Commission
14. HE - ASSAS; Artificial Intelligence for the Simulation of Severe AccidentS
    Asst. Prof. Ivo Kljenak
    European Commission

RESEARCH PROGRAMMES

1. Reactor engineering
   Prof. Leon Cizelj
2. Fusion technologies
   Asst. Prof. Boštjan Končar

R&D GRANTS AND CONTRACTS

1. Experimental and numerical studies of vertical slug flows
   Prof. Iztok Tiselj
2. Simulation of selected design extension conditions without core melt
   Asst. Prof. Boštjan Končar
3. Understanding stratified steam explosions in reactor conditions
   Dr. Matjaž Leskovar
4. Uncertainties in advanced safety analyses of nuclear facilities
   Dr. Andrej Prošek
5. Fuel-coolant interactions in combined stratified and melt jet configurations
   Dr. Janez Kokalj
6. The development and maintenance of independent expertise and tools for predicting and analyzing the progression of severe accidents in nuclear facilities
   Asst. Prof. Mitja Uršič
7. Uncertainty analysis of selected severe accident scenario in Krško NPP
   Dr. Matjaž Leskovar
   Ministry of the Environment and Spatial Planning
8. Fusion technologies
   Asst. Prof. Boštjan Končar
   Slovenian Research Agency
9. The development and maintenance of independent expertise and tools for predicting and analyzing the progression of severe accidents in nuclear facilities
   Asst. Prof. Mitja Uršič
   Ministry of the Environment and Spatial Planning
10. CROSSING - Crossing Borders and Scales - An Interdisciplinary Approach
    Dr. Matej Tekavčič
    Helmholtz-Zentrum Dresden-Rossendorf E.V.
11. Summer School on Experimental Nuclear Engineering for Students of King Fahd University of Petroleum & Minerals, Ljubljana, Slovenia, From 03 July 2023 to 14 July 202
    Prof. Iztok Tiselj
    King Fahd University of Petroleum & Minerals

NEW CONTRACTS

1. Joint Expert Assessment of the Outage Activities, Interventions and Tests during a shutdown and refueling outage 2022
   Asst. Prof. Mitja Uršič
   Elektroinštitut Milan Vidmar
2. Uncertainties in advanced safety analyses of nuclear facilities
   Dr. Andrej Prošek
   Krško Nuclear Power Plant
3. Fuel-coolant interactions in combined stratified and melt jet configurations
   Dr. Janez Kokalj
   Krško Nuclear Power Plant
4. Supporting studies following the on-power leak in line SI-53: Thermal fatigue: Contribution to the preliminary root cause analysis of the 2023 Krško SI-53 line leak (Scope 1)
   Dr. Martin Draksler
   Krško Nuclear Power Plant
5. Independed expert assessment of overhaul, interventions and performed rests during the Krško nuclear power plant 2023 extraordinary outage
   Asst. Prof. Mitja Uršič
   Elektroinštitut Milan Vidmar
6. Uncertainty analysis of selected severe accident scenario in Krško NPP
   Dr. Matjaž Leskovar
   Ministry of Natural Resources and Spatial Planning

VISITORS FROM ABROAD

1. Ms Florence Levy, Embassy of France in Slovenia, 2 March 2023
2. Mr Frédéric Mazallon, EDF, France, 2 March 2023
3. Mr Alexandre Freu, Embassy of France in Slovenia, 2 March 2023
4. Prof. Yassin A. Hassan, Texas A&M University, Texas, USA, 4-9 June 2023
5. Mr Hirofumi Takinami, House of Councilors, Tokyo, Japan, 17 July 2023
6. Prof. Niro Nagai, University of Fukui, Japan, 17 July 2023
7. Mr Tetsuji Shindo, Honorary Consul of Slovenia, Fukui, Japan, 17 July 2023
8. Dr Igor Kirillov, National Research Center Kurchatov Institute, Moscow, Russia, 9 August 2023
9. Dr Cédric Flageul, University of Poitiers, France, 14-16 August 2023
10. Mr Ted Jones, Nuclear Energy Institute, Washington, USA, 12 October 2023
11. Mr Marcus Nichol, Nuclear Energy Institute, Washington, USA, 12 October 2023
12. Dr Mariano Tarantino, Italian National Agency for New Technologies, Energy and Sustainable Economic Development ENEA, Bologna, Italy, 27-28 November 2023
13. Mr Pietro Cioli Puviani, Italian National Agency for New Technologies, Energy and Sustainable Economic Development ENEA, Bologna, Italy, 27-28 November 2023
14. Mr Tommaso Del Moro, Italian National Agency for New Technologies, Energy and Sustainable Economic Development ENEA, Bologna, Italy, 27-28 November 2023
15. Mr Alessandro Bellomo, Italian National Agency for New Technologies, Energy and Sustainable Economic Development ENEA, Bologna, Italy, 27-28 November 2023
16. Mr Richard Meller, Helmholtz-Zentrum Dresden-Rossendorf, Germany, 13 December 2023
17. Mr Fabian Schlegel, Helmholtz-Zentrum Dresden-Rossendorf, Germany, 13 December 2023

STAFF

Researchers
1. **Prof. Leon Cizelj, Head**
2. Dr. Oriol Costa Garrido
3. Dr. Martin Draksler
4. Dr. Samir El Shawish
5. Asst. Prof. Ivo Kljenak
6. Asst. Prof. Boštjan Končar
7. Dr. Matjaž Leskovar
8. Dr. Blaž Mikuž
9. Dr. Andrej Prošek
10. Prof. Iztok Tiselj
11. Dr. Mitja Uršič

Postdoctoral associates
12. Dr. Janez Kokalj
13. Dr. Rok Krpan
14. Dr. Timon Mede

15. Dr. Matej Tekavčič
16. Dr. Boštjan Zajec

Postgraduates
17. Aljoša Gajšek, B. Sc.
18. Jan Kren, B. Sc.
19. Amirhossein Lame Jouybari, M. Sc.
20. Patrik Tarfila, B. Sc.

Technical officers
21. Nejc Kromar, B. Sc.
22. Žiga Perne, B. Sc.
23. Andrej Sušnik, B. Sc.

Technical and administrative staff
24. Tanja Klopčič
25. Zoran Petrič, B. Sc.
26. Nina Rehar, B. Sc.

REACTOR INFRASTRUCTURE CENTRE
RIC

The Reactor Infrastructure Centre (RIC) incorporates a TRIGA Mark II research reactor and a Hot Cells Facility. The reactor, operating since 1966, is used for neutron research, education and training, as well as radioactive isotope production. A detailed technical description of the reactor is available at ric.ijs.si/en/. The Hot Cells Facility is used for the treatment and handling of radioactive materials and radioactive waste in research, developmental and applicative programs, and projects. In addition, it is used for performing regular radiological control measurements of the reactor. The Reactor Infrastructure Centre staff operate and maintain the reactor and the Hot Cells Facility. They also participate in other activities, requiring specialists, skilled in working with sources of radiation and in reactor technology, such as the servicing of industrial radioactive sources, surveillance of fuel management in NPP Krško, and characterization, processing, and preparation of radioactive waste.

Head:
Prof. Borut Smodiš

In 2023 the reactor operated for 572 hours and produced 92.1 MWh of heat in 140 days. Altogether, 35 pulses were carried out and 579 samples were irradiated in the irradiation channels.

The reactor operators supported users by performing operations and services for which the researchers were not qualified and authorized, such as operating the reactor, performing irradiations and experiments, and handling irradiated samples.

In 2023 the TRIGA Mark II reactor was mainly used as a neutron source for research in different areas, such as radiation-hardness studies, neutron-activation analysis, education, and training. For educational purposes, it was mostly used by the Reactor Physics Department (F8), while the Nuclear Training Centre (ICJT) used it for training purposes, and the Department of Environmental Sciences (O2) and the Department of Experimental Particles Physics (F9) both used it for sample irradiation. Lastly, the reactor was also used for experiments in reactor physics by the Reactor Physics Department (F8). The shutdown reactor, being a powerful source of gamma radiation, was used for testing the radiation hardness of electronic components and other materials. In the Hot Cells Facility, the activities were mostly performed by the Department of Environmental Sciences (O2), the Radiation Protection Unit (SVPIS) and the Slovenian Agency for Radioactive Waste Management (ARAO) – processing and preparation of radioactive waste for storage.

Figure 1: A training course for students of the University Aix-Marseille, Marseille, France, 26 June 2023 – 6 July 2023.

The reactor was used for the following research activities:
– Reactor physics and neutronics.
– Activation analyses.
– Research on radiation damage of semiconductors.
– Neutron dosimetry and spectrometry.
– Activation of materials, research on nuclear waste, and decommissioning.
– Radiation-hardness studies.
– Irradiation of materials for fusion reactors.
– Irradiation of electronic components.
– Irradiation of medical components.
– Development and testing of new detectors.
– Development of new methods for measuring power profiles, neutron spectra, etc.
– Verification and validation of methods for calculating the transport of neutrons, photons, and electrons.
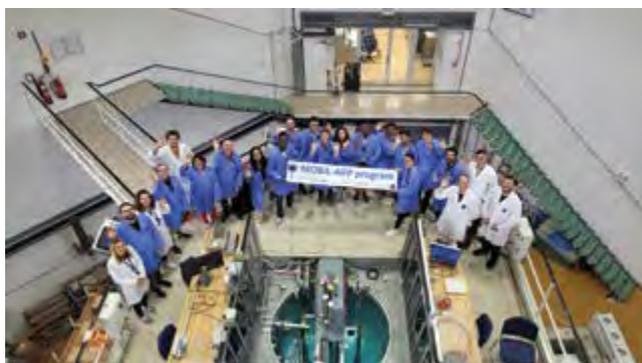– Development of educational tools in reactor physics.

Last year, silicon detectors for large accelerators were irradiated as a part of the EURO-LABS *(EUROpean Laboratories for Accelerator Based Science)* project, which falls under the Horizon EU programme - research infrastructure services to support health research, accelerate the green and digital transformation, and advance frontier knowledge. For the greater part, sample components for CERN *(Conseil européen pour la Recherche*

Figure 2: Training course for students of the King Fahd University of Petroleum and Minerals, Saudi Arabia, 3 – 14 July 2023.

Figure 3: Training course for EERRI (Eastern European Research Reactor Initiative), 16 – 20 October 2023.

Figure 4: New pipes of the secondary cooling system.

nucléaire or the European Organization for Nuclear Research) were irradiated on an almost weekly basis. The duration of the EURO-LABS project is 4 years, ending in August 2026.

In 2023 a major installation project of new experimental equipment in the horizontal channel no. 1 was carried out – Irradiation device with activated water – KATANA. The idea was to use demineralised, activated water as a source of high-energy gamma rays. In May, the channel was inspected and roughly cleaned. In November, it was completely cleaned, and the internal part of water activation loop was installed. By the end of the year, first preliminary results were obtained on the device, followed by small-scale upgrades that additionally improved its capacity.

In January, a course for the Aix-Marseille University was carried out remotely.

In February, the reactor did not operate for the majority of the month due to the maintenance of the reactor's cooling system. The NUMIP workers changed the pipes of the secondary cooling system, together with all the corresponding valves and sensors. They replaced the old heat exchanger with a new, flatter type that takes up much less space. In March, several detector irradiations were performed in collaboration with CEA (*Commissariat à l'énergie atomique et aux énergies alternatives* or the French Alternative Energies and Atomic Energy Commission) and Instrumentation Technologies Ltd.

In March, weekly practical classes began at our facilities for the Faculty of Mathematics and Physics (University of Ljubljana) students that lasted until May.

In June, CEA researchers were hosted at the reactor for calorimeters' testing. Towards the end of the month, two courses were organised: firstly, for the CDT – UKRI (*Centres for Doctoral Training – UK Research and Innovation*), and secondly, for the Aix-Marseille University – this time in person, and not remotely.

In July, students from the King Fahd University in Saudi Arabia were hosted at our facilities for the very first time.

In September, students from the Uppsala University in Sweden were hosted at the reactor, as they had been for many years.

In October, the EERRI (*East European Research Reactor Initiative*) training course participants were hosted by our staff for a 2-week course. Due to the NPP Krško emergency shutdown, our reactor was used for the start-up testing equipment calibration by our colleagues from the F8 department.

Simultaneously, regular weekly practical classes for students of the Faculty of Mathematics and Physics began. The course was carried out together with the international masters' program students under the SARENA project *(MSc in SAfe and REliable Nuclear Applications)*, and lasted until the end of the year.

In November, the CEA researchers visited our facilities once more to irradiate the passive gamma-ray and neutron detectors. Afterwards, practical classes for the NPP Technology course began, organised by ICJT for future NPP Krško operators. The classes took place four times a week until the end of the year. A yearly pulsed-operation exercise was performed for the Politecnico di Milano students from Italy.

In December, on top of everything else, an international ENEEP (*European Nuclear Experimental Education Platform*) course was held for young professionals at the beginning of their careers in the nuclear industry.

The reactor facilities hosted several groups on short visits, altogether accumulating around 1950 visitors. Among them were Slovenian and neighbouring countries' primary- and secondary-school students, university students, courses participants, around 500 Open Day and 250 European Researchers' Night visitors, foreign researchers, etc.

INTERNATIONAL PROJECTS

1. Irradiation Services for the Rolls-Royce Civil Nuclear SAS Company
   Dr. Anže Jazbec
   Rolls-Royce Civil Nuclear Sas
2. HE - EURO-LABS; EUROpean Laboratories for Accelerator Based Science
   Dr. Anže Jazbec
   European Commission
3. HE - DETMED; Novel Detector Concept for Medical Gamma Probe
   Dr. Anže Jazbec
   European Commission
4. Training Costs for IAEA"s Fellows Mr. Diya Mahmoud Ismail Al Kisieh and Mr. Essa Al Khalaylah (SV-JOR9019-2202817), 04 September 2023 - 08 September 2023
   Prof. Borut Smodiš
   IAEA - International Atomic Energy Agency

R&D GRANTS AND CONTRACTS

1. Hot Cell Facility Usage
   Dr. Anže Jazbec
   ARAO - Agency for Radioactive Waste Management
2. Irradiations on the TRIGA Reactor
   Dr. Anže Jazbec
3. Irradiations of FT-TIMS Capsule on the TRIGA Reactor for Years 2020-2023
   Prof. Borut Smodiš
   CEA-commissariat A L' Energie Atomique Et Aux
4. Refubrished Lazy Susan
   Prof. Borut Smodiš
   University of Pavia
5. Experimental Testing of the MONACO Acquisition System at the JSI TRIGA Reactor
   Prof. Borut Smodiš
   CEA Saclay
6. Testing of SiC Neutron Detectors at JSI TRIGA Reactor
   Prof. Borut Smodiš
   CEA Saclay
7. Development of Electronic Systems for Ex-Core Nuclear Instrumentation
   Prof. Borut Smodiš
   CEA Saclay

VISITORS FROM ABROAD

1. Loïc Barbot, Gregoire de Izarra, Commissariat à l'énergie atomique et aux énergies alternatives (CEA) Cadarache, Saint-Paul-lez-Durance, France, and Anže Uršič, Instrumentation Technologies d.o.o., Solkan, Slovenia, 6–9 March 2023.
2. Oliver Llido, Commissariat à l'énergie atomique et aux énergies alternatives (CEA) Cadarache, Saint-Paul-lez-Durance, France, 22–24 March 2023.
3. Philibert Herve, Domergue Christophe, Commissariat à l'énergie atomique et aux énergies alternatives (CEA) Cadarache, Saint-Paul-lez-Durance, France, 5–9 June 2023.
4. Euan Allatt, Thomas Ashton Key, Harrison Brown, Daniel Cogbill, Jamie Edwards, Martin Gillet, Alfred Hewetson, Siobhan Kingsley, Parth Kulkarni, Jason Lee Yung Sing, Alexandre Lhoest, Alexandre Little, Fernandes Luis, Marat Margulis, Eleni Mowery, Ben Sargeant, Bryan Tan Yi Chuen, Jonathan Tate, William Thomas, William Watson, Ewan Woodbridge, *Experimental Educational Course "Experimental reactor and radiation physics"*, UK centres for doctoral training (CDTs), United Kingdom 19–23 June 2023.
5. Fezane Ada Angwe, Eric Asra, Yorick Barou, Lisa Box, Michel Carette, Axel Caron, Donatien Djerabe, Romain Guibaud, Alexia Hernandes, Adrien Hodee, Noemie Jouglard, Miloud Kandoussi, Abdallah Lyoussi, Christelle Reynard Carette, Leopold Thevenot, Adrien Volte, University Aix-Marseille, Marseille, France, 26 June 2023 – 6 July 2023.
6. Abdulaziz Alsaleh, Khaled Al-Athel, Yazeed Alsehaibani, Abdulaziz Alyamani, Afaque Shams, Akbar Alnasser, Ali Alkhalefa, Anas Alnewirah, Mogbil Alrushaid, Mohammed Bushafia, Mohanad Alzahrani, Musaad Altanam, Seraj Albahrani, Sufyan Alrubayyi, Turki Hakami, training course for the King Fahd University of Petroleum and Minerals, Saudi Arabia, 3–14 July 2023.
7. Dzemil Adrovic, Caleb Barnes, Can Demirci, Sven Ekman, Mika Ekros, Liam Ilkilic, Martin Kassar, Isak Lundell, Gustav Robertson, Haydar Said, Karl Skjolderand, Andreas Solders, Jeffrey Tare, Uppsala University, Uppsala, Sweden, 27–29 September 2023.
8. Ali Emhemed Khalifa Ahbika, Bilasan Alshomrani, Anselm Niwemuhwezi, Dolphine Queenter Osoro, Mohammadhadi Porhemmat, Josue Shema, Siriporn Teparos, training course EERRI *(East European Research Reactor Initiative)*, 16–20 October 2023.
9. Loic Barbot, Gregoire De Izarra, Mathieu Trocme, Husson Wilfrid, Commissariat à l'énergie atomique et aux énergies alternatives (CEA) Cadarache, Saint-Paul-lez-Durance, France, 13–17 November 2023.
10. Anna Abramuk, Anna Anchini, Federico Di Croce, Matej Kleštinec, Luis Leitao, Jakub Luley, Juan Antonio Monleon De la Lluvia, Quentin Potiron, Marc Pouradier Duteil, Saverio Quaanta, Rafal Stoga, Mika Vaanamen, training course ENEEP (*European Nuclear Experimental Education Platform*), 4–7 December 2023.

STAFF

Researcher
1. **Prof. Borut Smodiš, Head**
Postdoctoral associate
2. Dr. Anže Jazbec
Technical and administrative staff
3. Andrej Gyergyek, B. Sc.
4. Marko Rosman
5. Sebastjan Rupnik, B. Sc.
6. Nina Udir, B. Sc.
7. Andraž Verdir, B. Sc.

NETWORKING INFRASTRUCTURE CENTRE
NIC

The Networking Infrastructure Centre (NIC) is responsible for managing the Jožef Stefan Institute's core network, ICT services and computing infrastructure. The NIC also supports the development of computing, communication, data and security infrastructure for the Institute's research departments, centres and support units, and participates in national and international collaborations related to networking, network services and ICT infrastructure for science.

The centre manages computing networks, services and equipment to provide the Jožef Stefan Institute with its core information and communication infrastructure. The centre is active in a number of different areas, both nationally and internationally. It provides connectivity and integration with local and international communication networks and infrastructures. The centre also delivers ICT support for research activities at the Jožef Stefan Institute, including the development, management and administration of the ICT infrastructure, computing facilities and services. The NIC delivers this through our efforts in four main areas under our responsibility: networking infrastructure, network security, network services, and distributed network supercomputing. Our work is organised within the bounds of regular activities, the activities of the JSI Infrastructure Centre (where our unit is responsible for the Network Infrastructure Centre and the Centre for Intensive Computing Support, CICS), and a number of national and international projects.

Head:
Dr. Jan Jona Javoršek

Networking Infrastructure. The Networking Infrastructure Centre is responsible for maintaining and developing the Institute's network backbone, departmental networks, wireless networks, and dedicated networks for services, projects, and activities. These include dedicated links to external centres, secure links to the Reactor Infrastructure Centre in Podgorica, and connections to high-bandwidth scientific VPN networks maintained by Arnes and GÉANT.

Physical Network: In 2023, we continued to extend the capabilities of the physical network, updating and upgrading our active equipment in the process. This included installing additional wireless access points and upgrading core backbone components, such as backbone network routers. We carried out a step-by-step refurbishment of the network hubs to accommodate changes resulting from the relocation of central services and repurposing of office spaces. This also included replacing network equipment that had reached end of life. The most noticeable changes were the complete refurbishment of the network hubs on the ground floor of Building A, in the Department of Condensed Matter Physics in the basement of Building A, and on the first floor of Building C. The network hub that used to serve the management offices on the second floor of Building C was replaced with a smaller, newer hub. This allowed for much better utilisation of the floor that has now been dedicated to research activities. We set up a new IT room for management equipment in Building J, and upgraded the network switches in several locations, including the ground and second floors of Building C, the reconstructed workshops, Technical Services, the new garage offices, the renovated cafeteria spaces on Jadranska Street, and the Thin Films and Surfaces Department in Domžale. We also replaced missing components at the management offices at Tržaška 134. In addition, many departmental networks were reorganised during this upgrade to introduce local IPv4 networks with automated host configuration for workstations and supporting equipment. Based on our analysis of the Reactor Infrastructure Centre network in Podgorica, we have prepared a plan to renovate the network and introduce additional security measures.

Backbone network with multiple 10 Gbit/s connections, modern protocol stacks, a flexible ICT infrastructure supporting numerous fixed and wireless clients and fast external connection with a100-Gbit/s links, has been expanded with first dedicated optical links for quantum communication.

Figure 1: Networking racks are being systematically rewired so that old, messy cables are replaced with new ones.

We introduced additional virtual network links for dispersed internal departments and laboratories, as well as for (super)computing clusters and virtual machine farms. This included remote VPN access and device support access for outside contractors.

We continued to provide external connectivity to support experiments requiring high throughput within international collaborations such as EuroHPC, EOSC and WLCG (the Worldwide LHC Computing Grid) for ATLAS,

Figure 2: *Renovation of cabling under the raised floor ended the time of one of the oldest existing network cables in the Southern Annexe.*

Figure 3: *Uninterrupted power supply system Socomec1X200KVA is delivering safe uninterrupted power to the central services in the Southern Annexe computer centre.*

as well as Belle2 and other projects using the EGI and PRACE infrastructures. We also provided access to specific GÉANT networks and dedicated scientific VPNs such as LH-CONE and PRACE, as well as access to the national dedicated backbone network connecting supercomputing and data centres. To support projects in the field of quantum communications, we have set up several optical links pairs between laboratories in Building C and the Quantum Optics Laboratory at the Faculty of Mathematics and Physics. We have also prepared a plan for similar connectivity towards the Ultracool laboratory at the Reactor Infrastructure Centre in Podgorica. The links are dedicated to connecting sources of entangled photons, which are the building blocks of quantum networks. They also support the development of a quantum network technology demonstrator that can support various quantum-based techniques, such as quantum key exchange and quantum communication.

Monitoring and Observability: In line with the expansion of network infrastructure, monitoring and observability capabilities must be enhanced to enable responses to network events, tracking of traffic and service availability, monitoring of infrastructure, and integration of sensors that track physical conditions in areas where our infrastructure is deployed. Our monitoring systems allow us to capture, monitor, report on and react to fluctuations in usage and events relating to our services, security policies, firewalls, authentication and authorisation systems, network time systems and email delivery, as well as the analysis, processing and security systems themselves. We also integrate sensory, environmental data and power-line data from physical rooms and machines. In light of new security standards and forthcoming legal requirements, we have introduced additional oversight and new security mechanisms. These include an asset and security control catalogue management system, which has been initially implemented for the Reactor Infrastructure Centre network in Podgorica. The Icinga service monitoring system has been upgraded and updated.

Wireless network: The first phase of the overhaul of the wireless network at the Jamova and Teslova campuses has been completed. This included a coverage measurement, which was used to plan the introduction of new access points. These replaced old systems, introduced new standards and better monitoring, and allowed us to implement a denser layout and improve coverage. The renewed networks now cover over half of the Jamova campus and the fourth floor of Teslova, as well as improving the density of several areas of the Reactor Infrastructure Centre.

Network Security. The NIC is responsible for managing security measures and policies at the external network border, within the internal network, and in relation to the services and software deployments managed for users. External network security is implemented using active security devices, firewall systems and secure-first configurations, as well as passive measures such as configuration, filtering and supervision. In 2023, the main firewall system was replaced with a newer system and new software versions. Constant, dynamic supervision, traffic monitoring and event analysis are needed to ensure suitable security while adhering to complex constraints and requirements. Since the network is shared by research departments, which are expected to have an open academic network policy, and management units and laboratories, which require much higher levels of security and isolation, such as the nuclear reactor and hot cells facility, particle accelerators, internal laboratory and scientific instrument networks, as well as networks with very specific flexibility requirements (e.g., robotics), we improved the segmentation of

Internal development of e-mail security, dynamic network firewalling, encrypted connections, virtual networks, advanced analysis and monitoring ensure the security of an open academic network in the age of a precarious Internet.

the institute's networks, as well as our internal network filtering. We also took the opportunity to transfer many hosts to local networks and local address spaces. Based on the new cyber security policy introduced at the Reactor Infrastructure Centre, we have started to implement new security mechanisms. We have set up a system for managing asset and security control catalogues, created an initial asset list, and enrolled personnel in a programme of security-oriented training.

As the NIC is responsible for the security of the Institute's ICT infrastructure, we have set up an incident response team at the centre. However, we also participate in the activities of relevant institutions and groups, including the National Security Response Centre (SI-CERT), the Forum of Incident Response and Security Teams (FIRST) and the European Grid Initiative Distributed Computing Security Incident Response Team (EGI-CSIRT). We also participate in the response team established for the SLING national distributed computing network consortium, and we are involved in the security team for the HPC Vega system. SiGNET CA (Slovenian Grid Network Certification Authority), the national science certificate agency managed by the NIC, is a full member of the EU Grid Policy Management Authority (EU Grid PMA) and the Interoperable Global Trust Federation (IGTF). We participate in the work of the Slovenian Network Operators Group (SINOG), the EOSC EU Node Computing Security Incident Response Team (EEN CSIRT), and we contribute to the organisation of training and workshops in the field of cybersecurity, e.g., the CERN Summer School, training sessions run by the International Atomic Energy Agency (IAEA), and the activities of the Cybersecurity Group of Reactor Centres at JSI, as well as workshops organised by the Slovenian Nuclear Safety Administration.

E-Mail: In terms of email security and protection against unwanted or malicious messages, we have continued to develop email content filters and protective measures. This has enabled us to improve our solutions continuously and provide new, advanced features for handling and filtering email messages and protocols.

Cryptography and certificates: We support the automated verification of signatures using DNSSEC-signed internet domain names, as well as the DANE system (which integrates TLS certificates with the DNS system) for email transfers. We also publish SSHFP records via our DNS servers. We support the increased use of digital certificates for both external and internal services, prioritising TLS with public certificates. Besides the public certificates provided through a contract with Arnes/GEANT, we also see many 'Let's Encrypt' certificates. Our virtual private network (VPN) infrastructure is widely used. We provide an internal remote desktop management instance for technical support using ISL Online services, and we support the issuance of digital certificates for employees provided by the national trust provider, SIGEN CA.

Figure 4: Southern Annexe computer centre hosts many department systems, central services and disks of the CEPH distributed filesystem.

Central ICT services. The NIC develops, provisions and maintains a number of core ICT services. The most important of these are email services (email routing and delivery, inbox management, directory management and webmail services), and World Wide Web support (the main Institute web server, web hosting for users, departments and projects, and a web directory). Secondary ICT services are provided to support certain core or specific activities at the Institute, such as web presentations, a conference management system, supervision and monitoring, etc. Some of these services involve the NIC directly investing in software or infrastructure development, such as network time services, email filtering and security. Others simply involve administration and maintenance.

The third NIC service category comprises services that support our users. The most popular services are NextCloud (which offers calendaring, event management, directories, file sharing and collaborative editing) and GitLab (which offers code repositories, integration and verification). However, the category also includes a web questionnaire service, online voting, licence management, mobile platform software development and integration and shipping for the Apple App Store and Google Play.

We also provide physical server hosting and management, primarily for larger projects and systems. Our services include directory administration for personal computing, user management (such as departmental single sign-on and directory services) and administration of mission-critical workstations and components. At the NIC computing centre on Jamova, where highly reliable cooling, network connectivity and an uninterrupted power supply are provided for critical services, we accepted additional systems into hosting. We currently host over 140 distinct websites on modern hardware in a highly secure network environment.
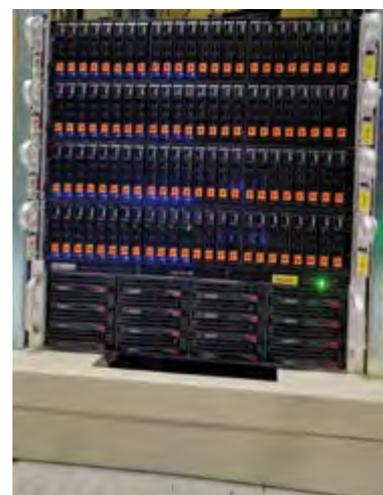

Figure 5: Our Proxmox cluster is equipped with fast disks in a CEPH distributed filesystem, providing a safe environment for virtual machines and containers.

We have updated our Single Sign-On (SSO) service and integrated it with the national AAI federation at Arnes and the European eduGAIN federation. This gives our users easier access to numerous national and international services using their institutional credentials. This feature also simplifies user and authentication management for organisations and software developers working on internal projects and services.

Network super-computing. Since its inception as the National Supercomputing Center, the NIC has remained active in the field of supercomputing technologies. We organized our work within the framework of the JSI Computing Centre on Teslova and the Centre for High Performance Computing Support, which is part of the JSI infrastructure group. HPC Vega started operating in April 2021 and became the first system to accept European users through the initiative, setting new trends and attracting considerable attention. The Jožef Stefan Instiute created a task force

Repositories for software development, file sharing and data storage as well as support for collaborative work and development have become essential for modern scientific collaborations. Because large data storage and access to the best systems, including the new EuroHPC Vega and other new European HPC systems, have become a basic necessity for many researchers, we are continuously adding disk arrays and expanding high-speed networks.
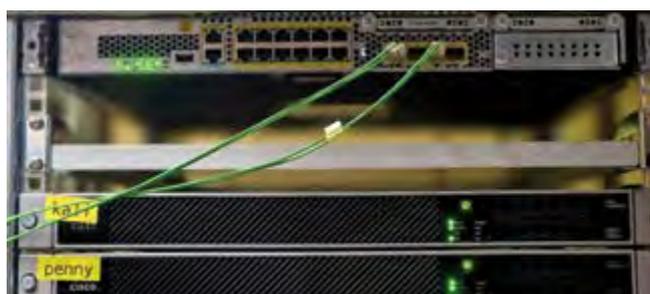

Figure 6: The Institute is equpped with a new firewall unit, here shown with units that provide virtual private network services.

Figure 7: CMI is providing many services, including web hosting, web mail, NextCloud (calendars, tasks, directories, file sharing, collaborative editing) OpenProject for project management, mailing lists, Indico for event organization and room booking, GitLab (software development, continuous integration) and even booking of internal institute shuttle.

Figure 8: Within the SLING consortium, we contribute to the organization of the Austria-Slovenia HPC conference.

that profited from the long tradition and technical expertise at the NIC and the Experimental Particle Physics Department F9 that participated in the design, architecture, procurement, installation and operations of the new system that has been established at the IZUM data centre in Maribor. In the year 2023 we also provided operational oversight, system administration support, user support and high-level support and guidance for the new system within the Slovenian National Supercomputing Network SLING consortium, as Vega is still the busiest system in EU due to high visibility of the EuroHPC intiative. Some of its technical innovations, such as large bandwidth and on-site storage, have been very successful and well accepted. We have also participated in the EuroCC project's training and support efforts with our expertise in high throughput computing, high performance computing, network and grid middleware, vectorisation, software containers, virtualisation and ICT as a service (cloud). The NIC also maintains the Slovenian certification agency SIGNET CA for science, research and grid computing, takes part in the maintenance and support of the core national supercomputing grid network services and coordinates work with international infrastructure projects and collaborations.

In 2023, we again recorded an increase in the number of users, including many international users, at the New System Cluster (NSC). The high-performance computing infrastructure that we have been establishing at the Computer Center on Teslova since 2015, is operating at the capacity of the current electrical infrastructure, and users are constantly replacing older pieces of equipment with newer ones. Additionally, the new Arnes HPC system, hosted in the same location since 2020, which was the largest publicly available HPC cluster in Slovenia before Vega became operational, has seen extensive utilisation. Besides supporting users of JSI clusters, we also worked on the integration of clusters with the national supercomputing network SLING and Vega using the NorduGrid ARC Grid Middleware to enable users to use all the resources in the network with the same interfaces and to use software containers to facilitate portability of user software.

In the domain of network supercomputing we have been most involved with the Slovenian National Supercomputing Network (SLING) and EuroHPC, but we also worked within the European Grid Initiative EGI, PRACE (Partnership for Advanced Computing in Europe), the EuroHPC initiative, notably the EuroHPC Leonardo hosting entity consortium (operations started in 2022), the NorduGrid ARC collaboration and a number of international projects (ATLAS – dedicated link, Belle2 – computing support, CLARIN – support for different services of the Slovenian national node, ELIXIR – participation in establishing the Slovenian national node and forming a European network). SLING has supported a number or research projects and applications, among others in high-energy physics, medical sensor and image analysis, theoretical physics, astrophysics, biochemistry, protein folding simulations, crystal analysis, knowledge technologies, artificial intelligence, statistical analysis and fluid dynamics, computational linguistics etc. In a number of cases, we have been involved as part of the SLING support group in the parallelization and preparation of computing tasks and administration of required run-time environments. In numerous projects, the SLING support group, whose members are CMI administrators, was involved in software parallelization, task preparation, and setting up the working environment for tasks.

Members of NIC have also contributed as advisers in EuroHPC and European Open Science Cloud, HPC RIVR consortium expert committee, training and set-up of the new national supercomputer HPC RIVR Maister at the University of Maribor and the operational opening of Slovenian EuroHPC petascale site at IZUM with HPC Vega. Additionally, we have been working within the MaX project, a center of excellence in the field of material modeling software, where we are responsible for providing access, testing, and installing software packages on EuroHPC

supercomputers. We joined the EPICURE project, which provides high-level user support on EuroHPC supercomputing systems, while NIC staff collaborated with EuroHPC as advisors on the management board and as experts in the EuroHPC advisory group for development and innovation. We also participated in the EuroHPC Container Forum and the HPC Container Advisory Council.

Figure 9: During a panel at the EuroHPC Summit conference, and at the EuroHPC Vega demonstration booth.

INTERNATIONAL PROJECTS

1. EACEA: B-AIR; Art Infinity Radio - Creating Sound Art for Babies, Toddlers and Vulnerable Groups
   Dr. Jan Jona Javoršek
   EACEA - European Education and Culture Executive Agency
2. H2020 - EGI-ACE; EGI Advanced Computing for EOSC
   Dr. Jan Jona Javoršek
   European Commission
3. EGI Foundation; Security Coordination and Security Tools
   Dr. Jan Jona Javoršek
   Egi Foundation
4. HE - MaX; MAterials design at the eXascale
   Dr. Jan Jona Javoršek
   European Commission

5. DIGITAL EU; SiQUID - Slovenian Quantum Communication Infrastructure Demonstration
   Dr. Jan Jona Javoršek
   European Commission

R & D GRANTS AND CONTRACTS

1. Co-financing of the Project B-AIR in the Year 2023: Art Infinity Radio - Creating Sound Art for Babies, Toddlers and Vulnerable Groups
   Dr. Jan Jona Javoršek
   Ministry of Culture
2. XRootD and FTS23: XRootD and FTS International Workshop, Ljubljana, Slovenia, from 27 March 2023 to 31 March 2023
   Dr. Jan Jona Javoršek

STAFF

Postdoctoral associate
1. Dr. Alja Prah

Technical officers
2. Jan Ivanjko, B. Sc.
3. **Dr. Jan Jona Javoršek, Head**
4. Dr. Florian Klauser
5. Barbara Krašovec, M. Sc.
6. Mark Martinec, B. Sc.

7. Sebastien Strban, B. Sc.

Technical and administrative staff
8. Andraž Filipčič
9. Ivan Ivanjko
10. Janez Jezeršek
11. *Matjaž Levstek, retired 01.04.23*
12. Janez Srakar
13. Matej Wedam

SCIENCE INFORMATION CENTRE

SIC

The Scientific Information Centre of the Jožef Stefan Institute (JSI) is one of the largest specialized libraries in Slovenia. It provides the JSI's staff with access to literature, manages their bibliographies in the SICRIS system, and offers support in fulfilling open-access requirements.

Scientific communication is based on the exchange of knowledge through peer-reviewed publications in scholarly journals. Regular monitoring of these publications is essential to ensure the competitiveness and relevance of research activities. The information age has fundamentally changed access to information, yet the majority of articles remain available only to subscribers. The inflation of publications and journals in recent years has led us to adopt consortial subscriptions to major publishers' journal packages. The Scientific Information Centre participates in the consortial acquisition of journal packages from Elsevier, Springer, Wiley, IEEE, RSC, and ACS, which are crucial for the success of research in Slovenia. This approach reduces costs while providing Slovenian researchers with access to over 4,000 scientific journals. Our online editions are complemented by our library collection, which comprises approximately 100,000 publications in physics, chemistry, biochemistry, electronics, computer science, artificial intelligence, nuclear technology, energy, and environmental sciences. Users also have access to the Reaxys database and the SciVal evaluation tool.

Head:
Dr. Luka Šušteršič

The Slovenian Research Information System, SICRIS, serves as the foundation for all calls and appointment procedures of the Slovenian Research Agency (ARRS). Data in the system are stored in the COBISS bibliographic database, which also records the creative work of the JSI since its establishment in 1949. Our cataloguers regularly update and maintain publication records for approximately 700 researchers; in 2023, more than 4700 records were added. These data are used in ARRS evaluation processes and in the appointments of JSI staff to research and professional positions. One of our tasks is also the preparation of publication assessments used in appointment procedures.

Increasingly, funders include open-access requirements in their contracts. Slovenia has adopted an open-access strategy, and ARRS, as a signatory of Plan S, already incorporates open-access requirements in its calls. One of the strategy's requirements is the deposition of the author's final version of articles in an internationally accessible repository. To this end, the Scientific Information Centre, at the authors' request, deposits articles in the DIRROS repository, which meets all the requirements of the European Commission and ARRS.

An important part of our work also involves collecting, verifying, and organizing the data included in this report, preparing contributions that present the JSI's work over the past year, and preparing the report for publication. The electronic archive of annual reports is available at https://www.ijs.si/ijsw/Informacije%20javnega%20zna%C4%8Daja.

R&D GRANTS AND CONTRACTS

1. NOO - GET TO KNOW; Support in Introducing the Principles of Open Science in Slovenia
   Helena Klančnik
   Ministry of Higher Education, Science and Innovation

STAFF

Technical officers
1. **Dr. Luka Šušteršič, Head**
2. Marjan Verč, M. Sc.

Technical and administrative staff
3. Anja Blažun, B. Sc.
4. Helena Klančnik, B. Sc.
5. Suzi Korošec, B. Sc.
6. Jasna Malalan
7. Irena Rebov, B. Sc.
8. Jože Škulj
9. Branka Štrancar
10. *Saša Žnidar, B. Sc., left 01.02.23*

ENERGY EFFICIENCY CENTRE
EEC

The basic activities of the Energy Efficiency Centre are in efficient energy use, long-term planning in energy and the reduction of greenhouse-gas (GHG) emissions and other air pollutants. The centre is a focal point for the collection and transfer of energy-efficiency technologies to energy users, the state, energy-service and equipment providers, and other interested agencies. At the same time it covers the environmental effects of energy use and conversion. The most significant part of the EEC's activities is thus cooperation with state institutions in the preparation of strategic documents and legislation in the field of efficient energy use, energy planning, distributed electricity production, GHG emissions and air pollutants. Nevertheless, it still remains strongly connected, by its consulting and training role in energy, with industrial companies and other institutions as well as also being deeply involved in European research projects.

Head:
Stane Merše, M. Sc.

Energy and the Environment

In 2023 the EEC, with its professional work, ensured high-quality support to ministries in the preparation of the strategic development documents and the transfer of EU legislation. Energy efficiency is a priority field to achieve global climate and energy goals. In accordance with the Directive on energy efficiency (2012/1791), Directive (2023/2413) on the promotion of the use of energy from renewable sources and the Regulation on the Governance of the Energy Union (2018/1999) the EEC prepared the first reporting on the implementation of the National Energy and Climate Plan (NECP) and report on the achievement of the national targets and implementation of the measures in 2020. The EEC was involved in the preparation of the Energy poverty mitigation action plan for Slovenia, approved by the Slovenian government in July 2024 and continued with the update process of the NECP, Long-term building renovation strategy and expert support for the new support scheme for electricity and heat production from renewable energy sources (RES).

Other EEC expert support of the new Ministry of environment, climate and energy focused on the development of the energy management system of the public sector and update and development of the Climate Action Mirror indicators. The EEC continued with activities of the LIFE IP CARE4CLIMATE - Boosting greenhouse-gas emissions reduction by 2020 with a view to 2030, where the EEC leads several actions on training, local energy planning and the development of advanced instruments for sustainable buildings' retrofit. Within the project, a new Laboratory for energy efficiency and RES was established, which has started an efficiency evaluation of several key household appliances of the IKEA sales program.

The EEC cooperates with the Statistical Office of the Republic of Slovenia, where it prepares an annual model calculation of fuels and energy use in households for the national energy. Also in 2023, the EEC continued with activities of the state referential centre for energy by preparing an expanded set of indicators for energy and the environment.

Promotion of Efficient Energy Use and Energy Consulting

In 2023 the EEC continued with its training activities where, as part of the LIFE IP CARE4CLIMATE project, it continued the comprehensive training programme in the field of energy management in industry and the public sector, as well as energy contracting. The EEC continued with the fifteenth cycle of energy managers training within the European programme EUREM. Due to a very positive reaction of the participants and their interest (in Slovenia there is already more than 290 energy managers with the EUREM licence), it is clear that there is a great need for such training. High-quality knowledge in this field is of key importance for the execution of efficient solutions in practice.
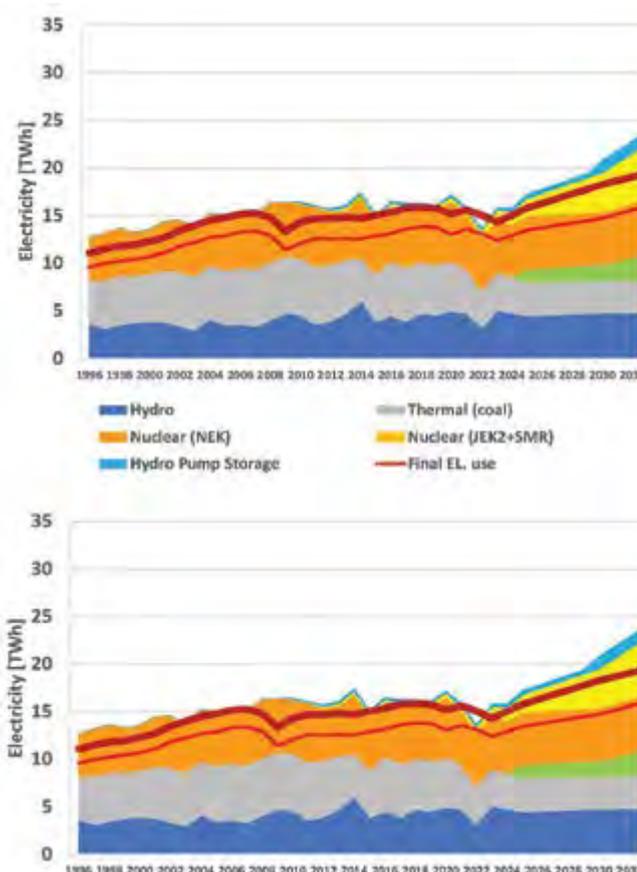

Figure 1: NECP electricity supply scenarios: Nuclear +RES (upper) and RES (lower)

The research and development work of the Energy Efficiency Centre is an important contribution to the preparation of key documents in Slovenia in the field of energy development, energy efficiency, renewables' exploitation and the transition of Slovenia to a carbon-neutral society, with training activities and support to industry it contributes to the an increase of in competitiveness and a successful green-technology transition.

Figure 2: Energy-poverty mitigation action plan preparation workshop.

Figure 3: Code of Conduct for Smart Readiness and Sustainability Rating developed by the Creators project.

In 2023, the EEC continued its intensive development work in the field of local energy planning with further development of the GIS tool for the spatial analysis of heat consumption in buildings ("heatmap"). The GIS tool was used for the preparation of the National heating and cooling strategy and upgrading the methodology for the preparation of local energy concepts.

EEC continued with a calculation of the carbon footprint for the NLB Group in South East Europe countries and the Slovenian sovereign holding portfolio, developed a strategy for decarbonizing NLB's business operations and successfully finished the environmental study and an energy climate plan of the company Luka Koper until 2030 with a view to 2050 and the implementation of energy audits in the companies Koto d.o.o. and Ljubljanske mlekarne. The EEC started preparing a methodology for calculating greenhouse-gas emissions and air pollutants for the users of the DARS motorway network in Slovenia.

The EEC prepared the programme for the 25th conference "Energy Managers Days", the annual meeting of energy managers with more than 200 participants, which confirms the quality and public profile of the EEC's professional work.

International Cooperation

In 2023 the EEC carried out 16 international projects, financed from the European Union resources in the framework of HORIZON 2020, LIFE, ERASMUS+, Interreg, EUKI program and European Climate Foundation. These projects cover activities in the fields of:

- Creating Community Energy Systems – (CREATORS);
- Towards Innovative Methods for Energy Performance Assessment and Certification of Buildings (TIMEPAC);
- Streamlining Energy Savings Calculations – (streamSAVE);
- Mainstreaming of Refinancing Schemes as Enhancer for the implementation of energy efficiency projects - (REFINE);
- Making heating and cooling for European consumers efficient, economically resilient, clean and climate friendly (REPLACE);
- Boosting greenhouse-gas emissions reduction by 2020 with a view to 2030, (LIFE IP CARE4CLIMATE);
- Monitoring the Energy Efficiency Pillar for Climate Neutrality (LIFE21-CET-POLICY-OdysseeMure fit-4-55);
- Evaluation, Quantification and Strengthening of the Implementation of the Policies and EM&V under Article 7 of the EED (LIFE21-CET-POLICY-ENSMOV Plus);
- Tuning EPC and SRI Instruments to deliver Full Potential (LIFE-2023-CET – tunES)
- Supporting Smart Financing Implementation for Energy Renovation of Existing Private and/or Public Buildings, Investments in SMEs and the Tertiary Sector (LIFE22-CET- SMAFIN Expanded);
- EU climate dialog – (EUKI, Climate Recon 2050);
- Energy Efficiency Experts, (EEE, ERASMUS+);
- Carrying out the EU directive on energy efficiency (CA – EED3),
- Smart Management and Green Financing for Sustainable and Climate Neutral Buildings in Central Europe (MESTRI-CE);
- Increase Clarity and Consistency of GHG Emissions Reduction Scenarios in Slovenia Using the Low Carbon Pathways Explorer Tool (ECF – MIRROR);
- Residents-Owned Heat Cooperatives to Push Urban Decarbonisation (HeatCOOP).

Projects include cooperation with research and development organisations from Europe with a strong emphasis on concrete applications and the promotion of energy efficiency. In the framework of each project the EEC staff took part in numerous foreign professional meetings and visits.
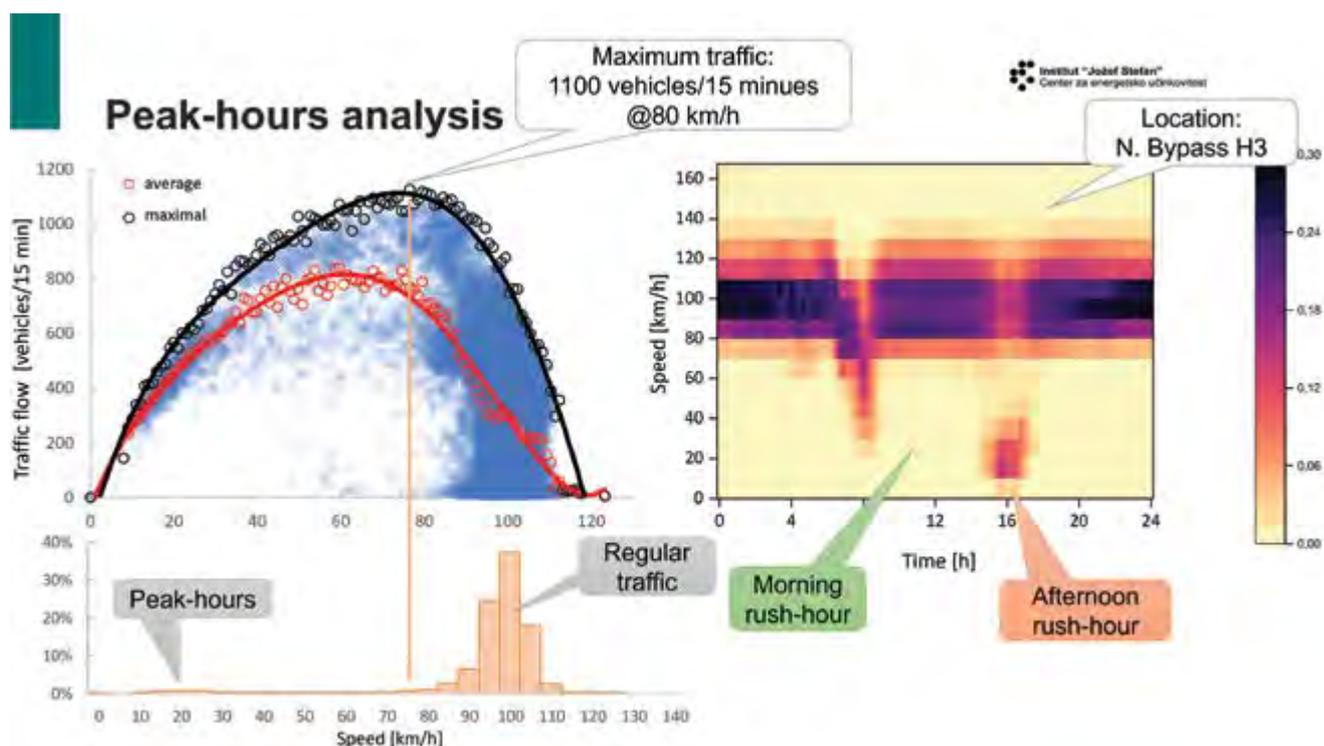
Figure 4: Analysis of peak-hours and speeds analysis on the DARS motorways for the calculation of greenhouse-gas emissions and air pollutants.

Some outstanding achievements in the past three years

1. Preparation of several key support documents for the government of the Republic of Slovenia in the field of energy and climate policy: National Energy and Climate Plan - NECP), Long-term climate strategy for Slovenia until 2050, Long-term renovation strategy to support the renovation of national building stock into a highly energy efficient and decarbonised building stock by 2050, etc., and establishment of a comprehensive monitoring system, implementation of the climate and energy policy (Climate Mirror, ARSO environmental indicators, etc.)

2. Establishment of energy managers' training in the framework of the European project EUREM and new comprehensive training program for the transition to a low-carbon society of the LIFE IP CARE4CLIMATE project.

3. Professional support to industry and other institutions for a successful green-technology transition: Strategy of energy and resource efficiency and renewable energy sources for the sustainable development of the company DARS d. d. until 2030, by carrying out energy audits and other consulting (Luka Koper, Ljubljanske mlekarne, BTC, AMZS, etc.). Preparation of the European code of Conduct for energy contracting and design of new financial instruments with ECO Fund.

Organization of conferences, congresses and meetings

1. Presentation of the project "Study and expert basis for the development of measures for reducing energy poverty" results, Ljubljana, 26/1/2023

2. What is the perspective of sustainable renovation and construction of buildings in Slovenia? First conference of the Hub of sustainable renovation and construction of buildings, Ljubljana, 3/4/2023

3. Expert consultations regarding the updating of the NECP, Consultation "Future of natural gas and alternatives", Ljubljana, 11/04/2023.

4. Expert consultations regarding the updating of the NECP, "Green transition in industry" consultation, Ljubljana, 11/04/2023.

5. Expert consultation regarding the updating of the NECP, Consultation "Reliability of energy supply and energy efficiency", Ljubljana, 11/04/2023.

6. Expert consultation regarding the updating of the NECP, Consultation "Sustainable transport and alternative fuels", Ljubljana, 17/04/2023.

7. Expert consultations regarding the updating of the NECP, Consultation "Development and possibilities of Slovenian electricity supply", Ljubljana, 17/04/2023.
8. Expert consultations regarding the modernization of NECP, Consultation "Heating and cooling strategy and integration of sectors", Ljubljana, 17/04/2023.
9. 25th Energy Managers Conference, Meeting of energy managers of Slovenia, Portorož, 18–19/4/2023
10. Climate Mirror Indicators – Where are we and how to proceed, Green economic growth, Ljubljana, 3/10/2023
11. Climate Mirror Indicators – Where are we and how to proceed, Agriculture and LULUCF, Ljubljana, 3/10/2023
12. Climate Mirror Indicators – Where are we and how to proceed, Buildings, Ljubljana, 10/10/2023
13. Climate Mirror Indicators – Where are we and how to proceed, Transport, Ljubljana, 10/10/2023
14. Event with lecture and round table: The impact of cars on our daily life and possible alternatives. ZRC SAZU. Ljubljana. 16 October 2023
15. 15th European Energy Managers training EUREM XV

INTERNATIONAL PROJECTS

1. Environmental Analysis of the Investment Portfolio of NLB d.d. in the Countries of SE Europe
   Tomaž Fatur, M. Sc.
   NLB Banka d. d., Sarajevo
2. 2nd National Round Table in Slovenia, Ljubljana, May 2023
   Damir Staničić, M. Sc.
   Pracsis S.r.l.
3. Life IP Care4Climate - Boosting greenhouse gas emissions reduction by 2020 with a view to 2030
   Stane Merše, M. Sc.
   European Commission
4. ERASMUS+; EEE - Energy Efficiency Expert
   Dr. Boris Sučić
   INAPP - Istituto Nazionale Per L'analisi
5. H2020 - REPLACE; Making Heating and Cooling for European Consumers Efficient, Economically Resilient, Clean and Climate-Friendly
   Dr. Gašper Stegnar
   European Commission
6. H2020 - REFINE; Mainstreaming of Refinancing Schemes as Enhancer for the Implementation of Energy Efficiency Service Projects
   Damir Staničić, M. Sc.
   European Commission
7. H2020 - streamSAVE; Streamlining Energy Savings Calculation
   Dr. Matevž Pušnik
   European Commission
8. H2020 - CREATORS; Creating Community Energy Systems
   Dr. Boris Sučić
   European Commission
9. H2020 - TIMEPAC; Towards Innovative Methods for Energy Performance Assessment and Certification of Buildings
   Dr. Boris Sučić
   European Commission
10. LIFE21-CET-POLICY-OdysseeMure fit-4-55; Odyssee-MURE - Monitoring the Energy Efficiency Pillar for Climate Neutrality
    Dr. Fouad Al-Mansour
    CINEA - European Climate, Infrastructure
11. LIFE21-CET-POLICY-ENSMOV Plus; Evaluation, Quantification and Strengthening of the Implementation of the Policies and EM&V under Article 7 of the EED
    Dr. Matevž Pušnik
    CINEA - European Climate, Infrastructure
12. LIFE-2022-CET - tunES; Tuning EPC and SRI Instruments to deliver Full Potential
    Dr. Boris Sučić
    CINEA - European Climate, Infrastructure
13. LIFE22-CET- SMAFIN Expanded; Supporting Smart Financing Implementation for Energy Renovation of Existing Private and/or Public Buildings, Investments in SMEs and the Tertiary Sector
    Damir Staničić, M. Sc.
    European Commission
14. ECF - MIRROR; Increase Clarity and Consistency of GHG Emissions Reduction Scenarios in Slovenia Using the Low Carbon Pathways Explorer Tool
    Marko Đorić, B. Sc.
    ECF - European Climate Foundation
15. Cofinancing of the Project LIFE17 IPC7SI/000007 - LIFE IP CARE4CLIMATE
    Stane Merše, M. Sc.
    Ministrstvo za Okolje in Prostor

RESEARCH PROGRAMME

1. Modelling and environmental impact assessment of processes and energy technologies
   Dr. Fouad Al-Mansour

R&D GRANTS AND CONTRACTS

1. Eco innovation and circular economy - a path toward a more sustainable and inclusive future: the role of demographic changes and digitalization
   Dr. Boris Sučić
2. Residemts Owned Heat Cooperatives to Push Urban Decarbonisation
   Dr. Gašper Stegnar
3. GeoCOOL FOOD- Cold food storage using shallow geothermal energy
   Dr. Gašper Stegnar
4. Methodology for the Placement of Photovoltaic Devices on Cultural Heritage Buildings and in Settlement Heritage Areas, and the Update of Guidelines for the Energy Renovation of Cultural Heritage Buildings
   Dr. Gašper Stegnar
5. Evaluation of factors for effective reduction of greenhouse gas emissions.
   Dr. Matevž Pušnik
6. The establishment and development of model infrastructure fort the economic evaluation of the effects of climate and energy measures on the economy and society
   Dr. Matevž Pušnik
7. Efficient Energy Management in the Public Sector
   Dr. Gašper Stegnar
8. MESTRI-CE: Smart Management and Green Financing for Sustainable and Climate Neutral Buildings in Central Europe
   Dr. Gašper Stegnar
   City of Vienna
9. Preparation of expert documents, design of a database and development of a vehicle simulation model for calculation of the energy and environmental footprint with an aim to optimize implementation of the public transport service
   Dr. Marko Kovač
   Ministry of Infrastructure
10. Refreshment of the environment-energy indicators 2021-2023
    Matjaž Česen, B. Sc.
    Ministry of the Environment and Spatial Planning
11. Study and technical basis for the development of measures to combat energy poverty
    Barbara Petelin Visočnik, M. Sc.
    Ministry of Infrastructure
12. Preparation of technical bases regarding the support scheme and implementation of other technical tasks and measures in the field of energy efficiency and renewable energy sources
    Stane Merše, M. Sc.
    Ministry of Infrastructure
13. Professional and technical support in the Comprehensive National Reporting on progress in implementing the National Energy and Climate Plan and preparing its update
    Stane Merše, M. Sc.
    Ministry of Infrastructure
14. Update of Climate Mirror Indicators
    Barbara Petelin Visočnik, M. Sc.
    Ministry of the Environment, Climate and Energy
15. EUREM XV - European Energy Manager, 15. Group
    Dr. Boris Sučić

NEW CONTRACTS

1. OctaGen_Lek
   Asst. Prof. Marko Matkovič
   M4M Invest d. o. o.
2. Environmental analysis of the investment portofolio of NLB d.d. in the countries of SE Europe
   Tomaž Fatur, M. Sc.
   NLB d. d.
3. NLB Operationa Emissions Net Zero Strategy
   Tomaž Fatur, M. Sc.
   NLB d. d.
4. Methodology and calculation of greenhouse gases and air pollutants emissions from motorway system users in Slovenia
   Dr. Marko Kovač
   DARS d.d.

STAFF

Researchers
1. Dr. Fouad Al-Mansour
2. Asst. Prof. Marko Matkovič
3. **Stane Merše, M. Sc., Head**
4. Damir Staničić, M. Sc.
5. Dr. Gašper Stegnar
6. Dr. Boris Sučić
7. Andreja Urbančič, M. Sc.

Postdoctoral associates
8. Dr. Matevž Pušnik

Postgraduate
9. Ana Marija Udovič, M. Sc.

Technical officers
10. Matjaž Česen, B. Sc.

11. Jure Čižman, M. Sc.
12. Marko Đorić, B. Sc.
13. Tomaž Fatur, M. Sc.
14. Tadeja Janša, B. Sc.
15. Edvard Košnjek, M. Sc.
16. Dr. Marko Kovač
17. Goran Matešić, M. Sc.
18. Marko Pečkaj, B. Sc.
19. Barbara Petelin Visočnik, M. Sc.
20. Luka Tavčar, B. Sc.
21. Katarina Trstenjak, B. Sc.

Technical and administrative staff
22. Marija Kavčič, B. Sc.
23. Igor Ribič

CENTRE FOR ELECTRON MICROSCOPY AND MICROANALYSIS   CEMM

The Centre for Electron Microscopy and Microanalysis (CEMM) is an instrumental centre at the JSI that comprises analytical equipment for electron microscopy and microanalysis. Access to the research equipment within the CEMM is available for the JSI departments as well as for other research institutions, universities and industrial partners. The equipment in the CEMM is used by researchers who are interested in the morphology and structural and chemical characterization of materials at the micrometre and atom level. In 2023, the CEMM comprised three scanning electron microscopes (JSM-7600F, Verios G4 HP and Quanta 650), two transmission electron microscopes (JEM-2100 (CO NiN), Spectra 300) and the equipment for the TEM and SEM sample preparation. Additionally, the IJS is a co-owner (20%) of the JEM-ARM200CF at the Chemical Institute. The CEMM and the JSI members will also have future access to a Talos 200 kV scanning transmission electron microscope, a new Focused Ion Beam (FIB) from Thermo Fisher and an Apreo scanning electron microscope, also from Thermo Fisher, which will be in operation in 2024. During 2023 extensive adaptation work was also performed at the TEM premises of the CEMM where Spectra 300 and Talos transmission electron microscopes are installed.

Head:
Prof. Miran Čeh

The Verios G4 HP from Thermo Fisher Scientific, a high-resolution scanning electron microscope, is unique in this part of Europe and provides extremely high imaging resolution at low accelerating voltages. It also features automatic sample insertion and the ability to observe non-conductive specimens with exceptional Z-contrast, even at low voltages. In addition to a highly sensitive EDXS detector, the microscope is equipped with a transmission detector (STEM) as well.

The Quanta 650 scanning electron microscope from Thermo Fisher Scientific is operational in three vacuum ranges that are achieved through differential pumping. This allows us to investigate a wide range of materials, both conductive and non-conductive.

The Spectra 300 scanning transmission electron microscope from Thermo Fisher Scientific is the most modern research equipment of the last generation of transmission electron microscopes, allowing comprehensive structural and chemical characterization of materials at the atomic and subatomic level. The microscope has an FEG electron source, a spherical aberration corrector and a monochromator, enabling the following scanning electron microscopy techniques to be performed: observation with a parallel electron beam (TEM, HRTEM), electron diffraction (SAED, CBED, PED), 4D STEM, qualitative and quantitative chemical analysis (EDXS, EELS), all with the ultimate imaging and analysis resolution at the atomic and subatomic level.

Figure 1: JSM-7600F scanning electron microscope

Figure 2: Verios 4G HP scanning electron microscope

Figure 3: Spectra 300 scanning transmission electron microscope

Figure 4: ESEM Quanta 650 scanning electron microscope

The research carried out using the equipment in the CEMM is diverse due to many different research topics of the JSI departments:

- Scanning electron microscopy is employed to observe the morphology and the structure of surfaces and for the microstructural investigation and determination of the chemical composition of investigated materials. Samples that are most frequently investigated include ceramics (polycrystalline oxide and non-oxide compositions), nanostructured materials, metallic magnetic materials, metals, alloy glass, etc.
- Transmission electron microscopy (TEM) provides an insight into the structure of a material at the nanoscale (atomic level). Transmission electron microscopy enables structural and chemical analyses of nanostructured phenomena, such as grain boundaries, precipitates, planar defects, dislocations, etc. Materials that are investigated include thin films on different substrates, alloys, metallic magnetic materials, dielectric materials, ferroelectrics, etc.
- The CEMM also manages the necessary equipment for the SEM and TEM sample preparation.

The operation of the centre is managed by the CEMM personnel. Besides the maintenance of the equipment, other CEMM activities include, among others, training of new operators, organization of workshops and conferences on the topic of electron microscopy, providing services for industrial partners and implementation of new analytical techniques. The CEMM personnel are also responsible for the dissemination of electron microscopy techniques to the general public in the scope of organized visits to the IJS, as well through publications in traditional and digital media.

Examples of microstructural and nanostructural investigations of materials using the CEMM equipment

The examples of analyses of structural and chemical characterisations of different materials using electron microscopy techniques were contributed by the operators from different IJS departments and by the CEMM personnel.

1. Role of cerium valence in the conversion temperature of $H_2Ti_3O_7$ nanoribbons to TiO_2-B and anatase nanoribbons, and further to rutile

Analysis of CeO_2 nanoparticles on the surface of TiO_2 nanoribbons. Nanoparticles at the Ce^{4+} batch were observed at 750 °C, while for the Ce^{3+} batch, they were observed at 860 °C. SEM images using a back-scattered electron detector were taken at the same magnification.
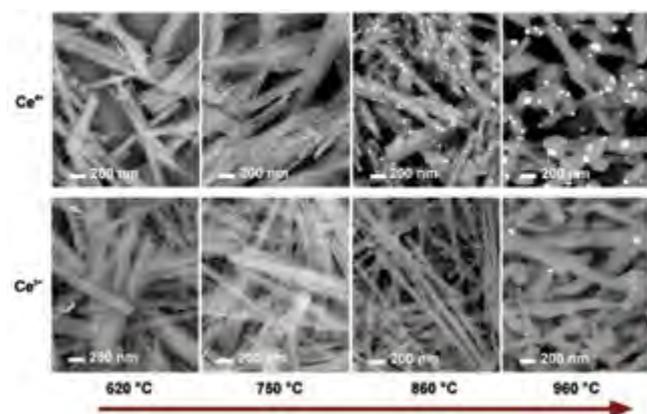

Figure 5: SEM images of evolution of CeO_2 nanoparticles on the surface of TiO_2 nanoribbons and fragmentation of nanoribbon morphology with increasing calcination temperatures for Ce^{4+}-HTiNRs (top) and Ce^{3+}-HTiNRs (bottom), which were calcined at 620, 750, 860 and 960 °C. The areas with CeO_2 nanoparticles in the images appear brighter. (Polona Umek, F5, SEM Verios G4 HP)

Reference: Umek, Polona, Dürrschnabel, Michael, Molina-Luna, Leopoldo, Škapin, Srečo D., Cerc Korošec, Romana, Bittencourt, Carla. The role of cerium valence in the conversion temperature of $H_2Ti_3O_7$ nanoribbons to TiO_2-B and anatase nanoribbons, and further to rutile. Molecules. 2023, vol. 28, 15, pp. 1–14, illustr. ISSN 1420-3049. https://www.mdpi.com/1420-3049/28/15/5838, DOI: 10.3390/molecules28155838. [COBISS.SI-ID 160531203]

2. Iron-oxide nanoparticles

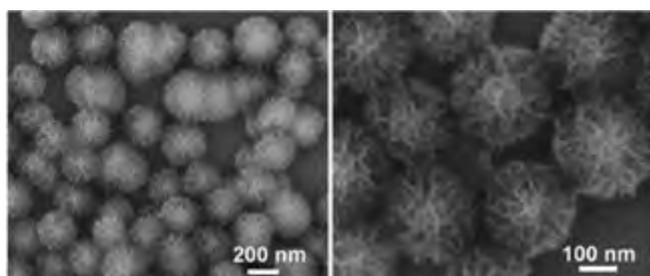Study of iron-oxide nanoparticles coated with mesoporous silica shell.

Figure 6: SEM images of iron-oxide nanoparticles coated with mesoporous silica shell (Sebastjan Nemec, K8, SEM Verios G4 HP)

3. Analysis of RHEA nanotubes

Study of RHEA nanotubes of a high entropy alloy including Ti, Zr, Hf, Nb, Ta and Zn.
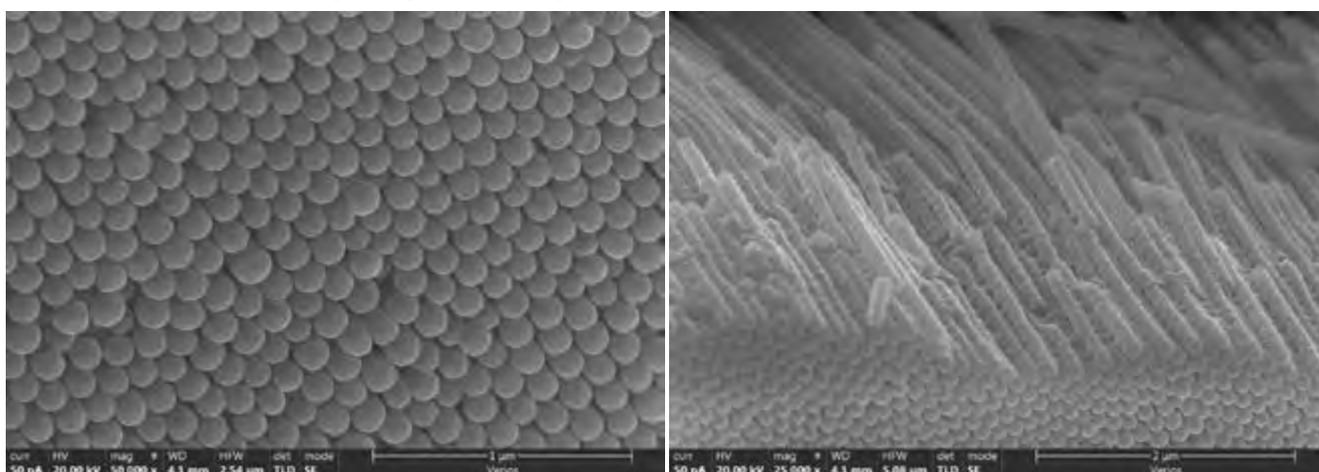

Figure 7: SEM image of RHEA nanotubes (Bor Arah, CEMM, Barbara Ljubec Božiček, K7, SEM Verios G4 HP)

4. Analysis of river sediments

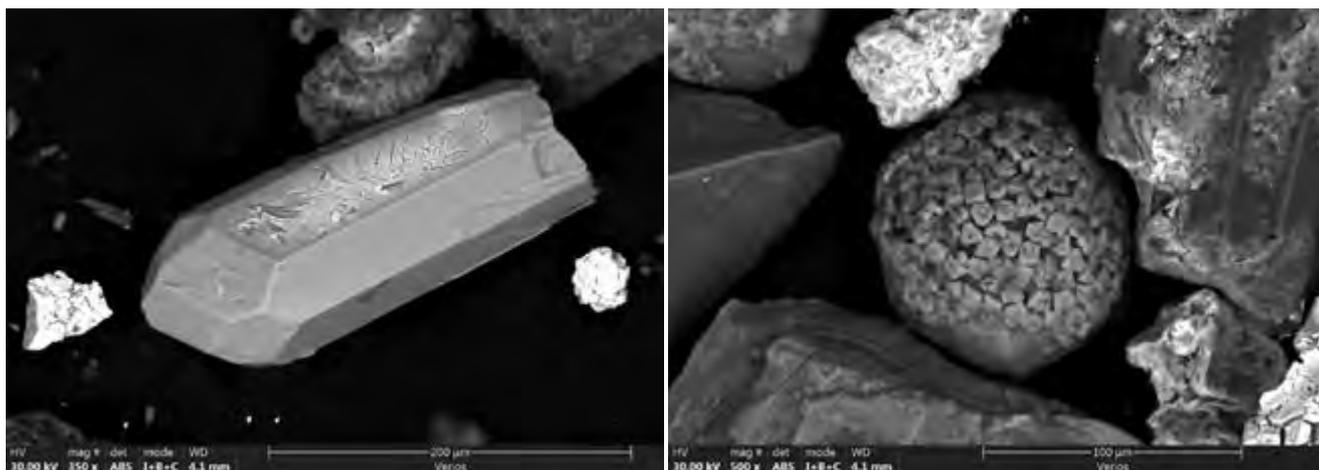Study of the river sediments of the Mežica River.

Figure 8: SEM image of river sediments (Aleksander Učakar, CEMM, SEM Verios G4 HP)

5. Morphological characterization of aerosol-deposited $Pb(Mg_{1/3}Nb_{2/3})O_3$–$PbTiO_3$ thick film

Dark field STEM image of the interface between the aerosol-deposited $Pb(Mg_{1/3}Nb_{2/3})O_3$–$PbTiO_3$ thick film and stainless steel substrate with the corresponding divergence map obtained from the 4D STEM dataset using differential phase contrast. The areas with a higher contrast in the divergence map represent a higher local strain. The 4D STEM data was obtained using a Merlin pixelated detector (Quantum Detectors, Oxford, UK).
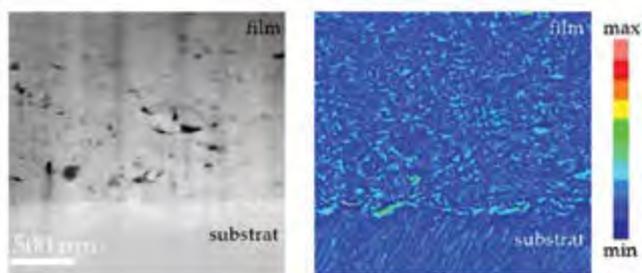
6. Study of heterogeneous nucleation and orientation relationships of an icosahedral phase with TiB$_2$ inoculants

The study confirms that crystalline TiB$_2$ particles can act as potent sites for the heterogeneous nucleation of the metastable icosahedral quasicrystalline phase (IQC) formed in cast Al-Mn-Si-Cu-Mg alloys. The results show that a primary metastable IQC phase nucleates on the facets of TiB$_2$ particles. The material thus acquires the properties of a light alloy useful in the automotive and aerospace industries.
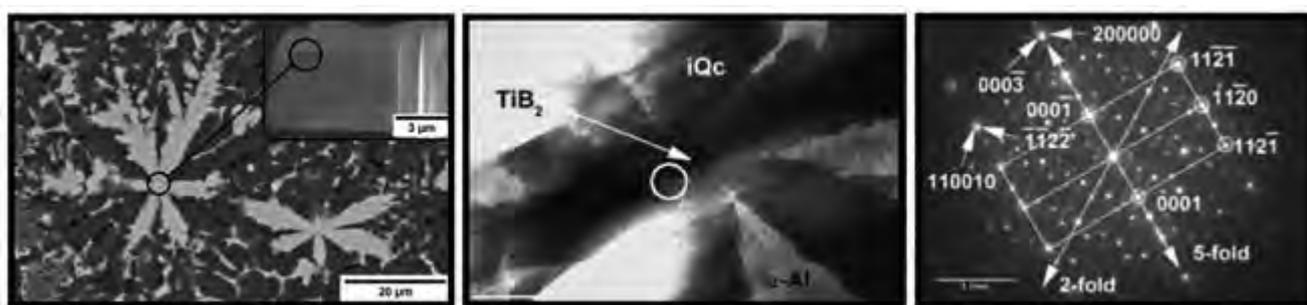

Figure 10: (Left) SEM image of the primary IQC phases with two TiB$_2$ particles in the middle; the inset shows a FIB lamella extracted from the centre of the IQC phase including a TiB$_2$ particle. The circles show the areas of interest. (Middle and right) Bright-field image and selected-area electron diffraction (SAED) pattern of a TEM sample. (Middle) IQC phase with a TiB$_2$ particle in the centre, and the surrounding αAl-matrix. (Right) SAED pattern of the interface between TiB$_2$ and the IQC phase. The white circle in the middle image denotes the location where the SAED pattern was taken, while the white circles in the image on the right denote peaks representing TiB$_2$ planes. The matching planes between TiB$_2$ and IQC are marked with white arrows. (Sandra Drev, CEMM, Blaž Leskovar, NTF, Spectra 300)

7. Study of the "weld" of two high-strength Al alloys

The STEM analysis shows a complex microstructural study of the "weld" of two high-strength Al alloys (Al-Cu-Mg and Al-Cu-Mg-Zr) imaged on the new Spectra 300 STEM microscope. The alloy consists of many intermetallic phases (precipitates/exclusions, dispersoids, insoluble phases, etc.). This is a demonstration of one of the many phases in the alloy resulting from the inclusion of alloying elements, improving the strength, corrosion resistance, crystal grain size control and subsequent heat treatments (homogenization + solvent annealing + precipitation hardening). A HAADF detector (a collection angle of 49–200 mrad) with a camera length of 115 mm was used to capture the STEM image in the nano probe mode in a series of 10 consecutive images. Subsequently, the integrated DCFI function (optimized for periodic images) was applied to the image for drift correction, which significantly increased the contrast and reduced the situational drift and instability.

8. Analysis of Fe–Mn–C layer and W–Fe–Mn–C biodegradable coating

A high-resolution HAADF-STEM analysis of the interfacial region of a Si substrate, Fe–Mn–C layer and magnetron sputtered W–Fe–Mn–C biodegradable coating, obtained from two samples with different deposition temperatures (sample A and sample B) was carried out. The HAADF-STEM results were obtained from the cross-sectional lamellae of sample A: (a)–(b), and sample B: (c)–(d). Various layers are marked clearly on the low-magnification images (a and c). The atomic-scale HAADF-STEM images (b and d) show the structure of the layers at the interface. The FFT patterns of each layer are shown as the insets of the images and show the underlying structure. The blue circles in image (b) show the nano-sized α-W crystals in the mainly amorphous matrix phase.
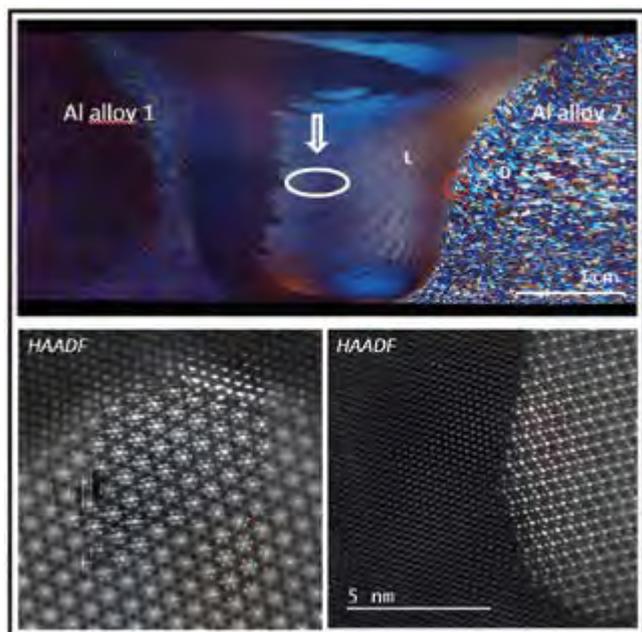
Figure 11: Image of the "weld" of two aluminum alloys (above) and STEM images of the details of the crystal structures with the structural model (below) (Sandra Drev, CEMM, Spectra 300)
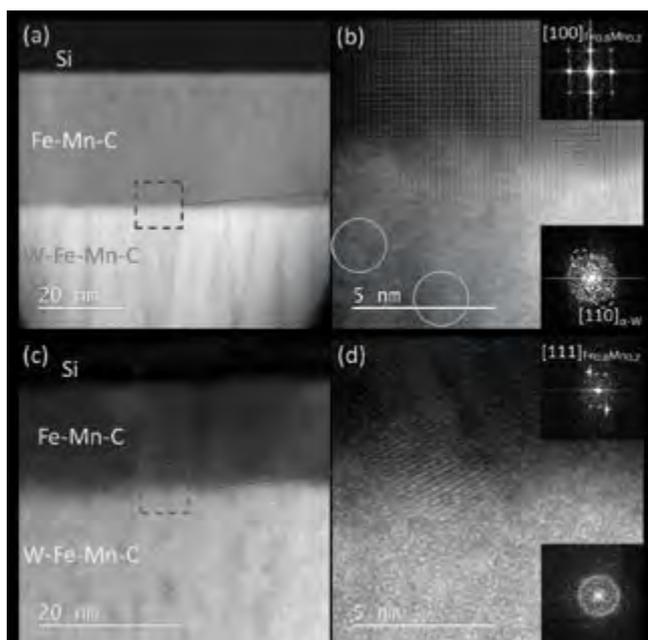

Figure 12: High-resolution HAADF-STEM images at the interfacial region of the Si substrate, Fe-Mn-C layer, and W-Fe-Mn-C coating, obtained from the cross-sectional lamellae of sample A25 (a)-(b), and sample B25 (c)-(d). Various layers are marked clearly on the low-magnification images (a and c). The atomic-scale HAADF-STEM images (b and d) show the structure of the layers at the interface. The FFT patterns of each layer are shown as the insets of the images, indicating the underlying structure. The blue circles on image (b) show the nano-sized α-W crystals in the mainly amorphous matrix phase. (Sorour Semsari Parapari, K7, JEM-ARM 200CF; JEOL)

Figure 13: STEM study of rutile fibres showing their close intergrowth. (a) The (110) interfaces between the fibres are sharp and well-defined. (b) The upper part of the figure shows an experimental high-resolution ABF-STEM image of rutile-rutile interface in the [1-10] projection (outlined in Fig. 3a) displaying systematic lateral κ[110] and vertical ν[001] displacements of 0.284 and 0.148 nm. These features are used to construct the starting Rf1 interface model, superimposed on the processed ABF-STEM image (highlighted). (c) The rutile-rutile interface viewed along the [1-11-] projection displaying the translation of (011) lattice planes across the interface. (d) HAADF-STEM image of the thin part of the crystal with the Rf1 model (above) and its DFT relaxed variant with 1x H_2O at the interface. (e) HAADF-STEM image of the thick part of the crystal with the overlaid DFT relaxed variant of the Rf1 model with 2x H_2O at the interface (below). (f) HRTEM image of rutile fibres along the [001] projection showing individual fibres along the c-axis indicating that the fibres are terminated by {110} planes. Following these lattice planes (white lines) no additional shift is observed in this projection. (g) FFT filtered HRTEM image with enhanced contrast (green ct) displaying a maze-like texture of the fibres. (Aleksander Rečnik, K7, Jeol-ARM)

Reference: Vesna Ribić, Vanja Jordan, Sandra Drev, Janez Kovač, Goran Dražić and Aleksander Rečnik. Mnemonic rutile-rutile interfaces triggering spontaneous dissociation of water. Advanced Materials 36/4 (2023) e2308027. DOI: 10.1002/adma.202308027

9. Study of fibrous rutile structures displaying spontaneous dissociation of water

Surface mineral-water interactions are decisive for any photocatalytic process. In this work, fibrous rutile, homoepitaxially grown on twinned rutile seeds with a specific interface structure that displays the ability to spontaneously dissociate water is investigated. This is thought to be the first example of an interface with mnemonic behaviour capable of transmitting structurally encoded properties to a new environment.
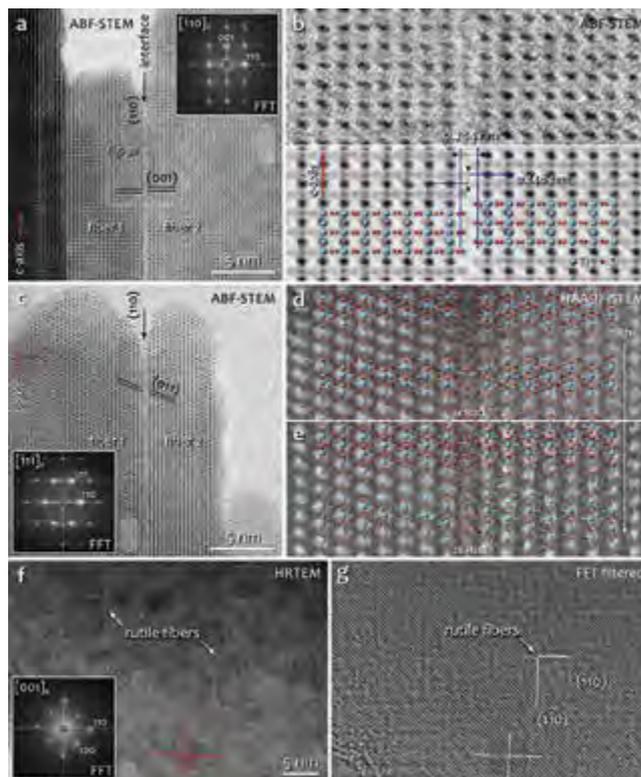
10. Analysis of Ni-P/C-based electrocatalyst

Bright-field images of Ni-P/C-based catalysts that contain Ni-P nanoparticles supported by a carbon matrix.
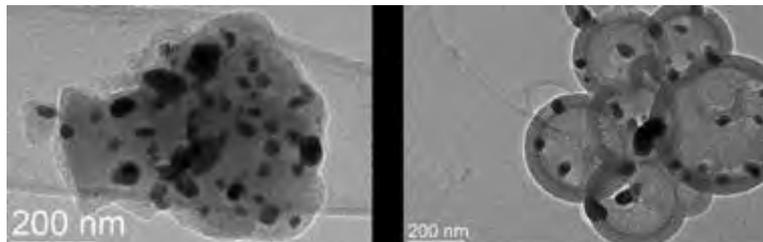
Figure 14: (Left) TEM image of a Ni-P/C-based electrocatalyst with a phosphorous/ polydopamine ratio of 0.15. (Right) TEM image of a Ni-P/C-based electrocatalyst with a phosphorous/polydopamine ratio of 0.6. (Petra Drnovšek, CEMM, JEM–2100)

References: L.A. Stern, L. Feng, F. Song, X. Hu, Ni_2P as a Janus catalyst for water splitting: The oxygen evolution activity of Ni_2P nanoparticles. Energy Environ. Sci. 8 (2015) 2347–2351

S. Hou, X. Xu, M. Wang, Y. Xu, T. Lu, Y. Yao, L. Pan, Carbon-incorporated Janus-type Ni2P/Ni hollow spheres for high performance hybrid supercapacitors. J. Mater. Chem. A. 5 (2017) 19054–19061

Q. Wang, S. Chen, F. Shi, K. Chen, Y. Nie, Y. Wang, R. Wu, J. Li, Y. Zhang, W. Ding, Y. Li, L. Li, Z. Wei, Structural Evolution of Solid Pt Nanoparticles to a Hollow PtFe Alloy with a Pt Skin Surface via Space-Confined Pyrolysis and the Nanoscale Kirkendall Effect. Adv. Mater. 28 (2016) 10673–10678

INTERNATIONAL PROJECTS

1. HE - EUROfusion; WP07: ENR-DeHydroc-1,2,3_HE-FU
   Dr. Andreja Šestan Zavašnik
   European Commission
2. HE - EUROfusion; WP18: MAT_HE-FU, IREMEV-MAT-1_HE-FU, IREMEV-MAT-2_HE-FU, IREMEV-MAT-3_HE-FU
   Dr. Andreja Šestan Zavašnik
   European Commission

R&D GRANTS AND CONTRACTS

1. External Services (Export), Electron Microscopy and Microanalysis, Sample Preparation and Microscopy
   Prof. Miran Čeh

NEW CONTRACT

1. Characterization of the primary coating, tendency of the primary coating to delamination of glass, characterization of contact and non-contact materials
   Prof. Miran Čeh
   Lek d. d.

STAFF

Researcher
1. Prof. Miran Čeh, Head

Postdoctoral associates
2. Dr. Bor Arah
3. Dr. Sandra Drev

Postgraduates
4. *Dr. Andreja Šestan Zavašnik, 20.03.23, transferred to Department F2*
5. Aleksander Učakar, B. Sc.

Technical officers
6. Petra Drnovšek, B. Sc.
7. *Dr. Jitka Hreščak, left 01.10.23*

CENTRE FOR KNOWLEDGE TRANSFER IN INFORMATION TECHNOLOGIES CT-3

The Centre for Knowledge Transfer in Information Technologies performs educational, promotional and infrastructural activities linking researchers and the users of their results. Through its successful involvement in European research projects, the Centre is also expanding its research and development activities, especially in the field of knowledge management in traditional, networked and virtual organizations. Within the Centre, the UNESCO Chair on Open Technologies for Open Educational Resources is active, with a wide range of activities in the field of open education. Among others, we are involved in the implementation of the Master's programme in Open Education Leadership and Planning at the University of Nova Gorica, and in cooperation with the Ministry of Education and Science, we have again organised and implemented in 2023 the further education and training of education professionals and a UNESCO Consultation with Rectors of Higher Education Institutions on the Future of Higher Education. Both at school and the national level, we held the 17th ACM Competition in Computer Science and Informatics in the spring. This year, the videolectures.net (VLN) team has been involved in the organisation of more than twenty high-profile international and national events, such as Extended Semantic Web Conference (ESWC 2023), International Semantic web Conference (ISWC 2023) and the International conference on Web Search and Data Mining-(WSDM 2023).

Head:
Mitja Jermol, M. Sc.

The Centre is involved in a number of international, EU and Slovenian projects. In 2023, we implemented for the sixth time the international mentoring programme "Open Education for a Better World" and the project "OER Dynamic Coalition" under the auspices of UNESCO. Fifteen European projects were successfully implemented, including a number of Horizon projects: enRichMyData, PREPARE, Plooto, GraphMassivizer, FAME, TWON, AI4Gov, HumAIne, Erasmus+ Bridges and the European Statistics Award.

Open Education for a Better World – international mentorship programme

In 2023 the 6th year of the international mentoring program "Open Education for a Better World" was managed by the UNESCO Chair on Open Technologies for Open Educational Resources and Open Learning, the Jožef Stefan Institute and the University of Nova Gorica. The conference began on June 2 with a pre-event workshop focused on "Artificial Intelligence in Education and the Role of ChatGPT." It continued as a hybrid event on June 5, held both in person at UNG in Vipava and online via the MiTeam platform. From June 6 to 7 the conference was conducted entirely online.

Within the center, the UNESCO Chair on Open Technologies for Open Educational Resources operates, through which we conduct various activities in the field of open education.

The purpose of OE4BW EDUSCOPE 2023 was to exchange ideas and experiences, foster new networking opportunities, and support the diversity of goals, backgrounds, and cultures, while also contributing to the implementation of UNESCO's Recommendation on Open Educational Resources (OER) and addressing various Sustainable Development Goals (SDGs).

Participants included students, OER experts, academics, policymakers, program officers, administrators, and education and international development technologists. More than 200 participants from various sectors engaged in four days of intensive discussions highlighting the role of Open Education (OE) and ChatGPT, best practices in open pedagogy, open education, and an inclusive knowledge society. Issues related to governance, language, open-source authoring tools for OER, visual communication technologies, and their application in education were also addressed. Participants gained insights from OER experts on aligning OE with developmental and strategic goals.

OER Dynamic Coalition

The UNESCO project OER Dynamic Coalition was launched in 2022 to develop a platform that will offer communication and networking opportunities in addition to content and knowledge management. In line with the principles of the UNESCO Recommendation on OER, we will pursue openness, multilingualism and accessibility on the portal. The portal will bring together national, regional and global platforms and networks in a single place, creating an access point for sharing and promoting knowledge in the field of open educational resources as well as activities and existing or new initiatives.

From October 1ˢᵗ, the platform is public and accessible on the website: https://oerdynamiccoalition.org/.

AI4Gov

The Horizon Europe project AI4Gov (Trusted AI for Transparent Public Governance fostering Democratic Values) is aimed at exploring the possibilities of Artificial Intelligence (AI) and Big Data technologies for developing evidence-based innovations, policies, and policy recommendations to harness the public sphere, political power, and economic power for democratic purposes. The project intends to contribute to the research landscape that addresses ethical, trust, discrimination, and bias issues, and provide solutions to the challenges faced by stakeholders in modern democracies. CT3 is leading the WP5 Citizen-centric training for creating awareness and change, and contributes to the communication, dissemination and exploitation activities. We are collaborating with E3, which develops the Virtualized Unbiasing Framework (VUF).

FAME

The Horizon Europe project FAME (Federated decentralized trusted dAta Marketplace for Embedded finance) has as its main goal to develop, integrate, validate and offer as a publicly accessible service Europe's first federated, decentralized, trusted and energy-efficient data assets marketplace for EmFi. CT3 is involved in training programmes, dissemination and exploitation, and is collaborating with E3, which develops techniques for explainable and trustworthy artificial intelligence.

Erasmus+: Bridges

As partners, we participated in the Erasmus+ project Bridges: Overcoming Emergency Situations in Education through Digital Pedagogy. Within this project, we conducted research interviews with higher education educators to assess their needs for additional training in open and distance education. Together with our partners, we developed a series of educational video content, produced in collaboration with the Videolectures.NET team. We also attended the final conference organized by our partners from the Future Education Institute in Modena, Italy.

The center participates in numerous international, EU, and national projects in Slovenia. In 2023, under UNESCO's auspices, we organized the international mentoring program Open Education for a Better World for the sixth time and led the OER Dynamic Coalition project. We successfully carried out fifteen European projects, including several funded by Horizon 2020, Horizon Europe, and Erasmus+ programs.

European Statistics Award

In collaboration with the Laboratory for Artificial Intelligence (E3), we participated in a series of competitions in 2023 focused on nowcasting (predicting current events) and web intelligence. Our role included managing the promotion and visual branding of both competitions. The primary objective is to identify promising methodologies and data sources that could enhance the preparation of European statistics. New approaches based on advanced modelling (potentially using alternative, near-real-time data) hold great potential for providing accurate estimates of key indicators much faster than in the past. As part of the program, which will run until the end of 2025, we organized another nowcasting competition in 2023 on the topic of Energy Challenges and a web intelligence competition focused on classifying professions in online job advertisements.

PREPARE

The Horizon Europe project PREPARE (Personalized Rehabilitation Via Novel AI Patient Stratification Strategies) is focused on medical rehabilitation and AI. Providing rehabilitation care for patients with chronic non-communicable diseases can be exceedingly complex and challenging. The highly personalised nature of each patient's condition makes prediction tools and patient stratification unreliable. Despite efforts using big data, existing datasets often give rise to new challenges. PREPARE aims to address these challenges through a combination of innovative clinical, socio-behavioural, and public health research, coupled with advanced AI and data-science methods. Additionally, patient datasets will be used to stratify patients and identify new predictors for rehabilitation outcomes. CT3 is involved in communication, dissemination and exploitation activities, and is collaborating with E3, which is developing tools to convert and merge unstructured and structured healthcare data.

Kleefstra Syndrome Scientific Conference

The EJP RD grant titled "Kleefstra Syndrome Scientific Conference 2023: "Moving towards the uptake and use of Artificial Intelligence (AI) in research and clinical work" was active from February to August 2023. The main aim of this networking support scheme was to bring together experts working on Kleefstra syndrome, a rare genetic disorder, on one hand, and AI/ML and data science experts, on the other, to start new interdisciplinarity teams and research. The conference event brought together Kleefstra syndrome patient advocates, clinicians and researchers from different domains having a common interest: share new research findings related to Kleefstra syndrome that

will lead the Kleefstra community to optimize current care and the discovering of a life-changing treatment and cure for Kleefstra syndrome. A special focus was given to AI, which is generally still something new for the rare-disease communities, but it can play a crucial role, especially in shortening the time needed for new research insights.

Plooto

The Plooto project brings together 20 partners from eight countries, each contributing expertise and experience toward developing innovative solutions for a more sustainable economy. The aim of the Plooto project is to create an advanced Information System to support manufacturers in their green, digital, and circular transition. Focusing on the reuse and recycling of materials, Plooto seeks to enhance waste-management practices.

The Information System under development will enable waste reduction and provide full traceability of secondary raw materials across the entire supply chain through a network of interconnected digital services. This system will facilitate real-time decision-making, monitoring, and certification of materials and products.

Our solution is currently being piloted within three distinct circular supply chains. These pilot projects will verify whether the Information System can reduce waste, increase the reusability of production scraps and by-products, and introduce operational improvements within manufacturing processes.

ACM Competition in Computer Science and Informatics

In 2023 we held the 18th ACM Competition in Computer Science and Informatics. The competition was conducted in two stages: school-level and national-level. The school-level competition was organized by 31 secondary schools, institutions, and gymnasiums, involving 251 students. The national competition took place in March 2023 at the Faculty of Computer Science and Informatics, University of Ljubljana. 120 secondary school students competed across three difficulty levels. In the web application development branch, 9 students participated, while 4 competitors took on the challenge in the off-line task. This year, the production of educational videos featured strong competition among 19 secondary school submissions, with the winning video titled "Why Do We Age?" Additionally, 2023 marked the pilot launch of a programming competition called "Mladi RTK" (Young RTK), which included 20 primary school students competing in two difficulty levels. In the programming branch, we awarded 48 silver and 7 gold prizes, while at the school-level competitions held in January, 84 bronze prizes were distributed. As in previous years, we presented practical prizes to the top competitors in each category.

The results of the whole competition are available at: https://rtk.ijs.si/2023/rezultati.html#offline

Videolectures.net (VLN)

Videolectures.net (VLN) currently offers nearly 31,000 recordings of various scientific events. The primary purpose of this video portal is to provide free and open-access video lectures by esteemed scientists and experts from the most up-to-date events. Videolectures.net serves as a free knowledge hub, offering online education accessible to everyone. The aim of VLN is to share educational content, promote science, and enable audiences to learn and connect globally.

In 2023 we collaborated with over 20 Slovenian institutions from the public and private sectors, providing technical support and assistance in event organization. Both domestically and internationally, we partnered with organizers of numerous renowned conferences, most of which were conducted in hybrid formats—combining physical locations and online platforms. From creating promotional videos, educational materials, workshops, and interviews to participating in EU dissemination projects, we supported events on over 30 of the most current and relevant topics for our users.

We facilitated recordings at physical locations, provided technical support to numerous event organizers, and worked across platforms such as Zoom and YouTube. Following technical guidelines and focusing on current topics, we published recordings of various international and national conferences and events, obtaining necessary permissions and ensuring the reliability of the prepared video content.

Some of the most prominent events we facilitated and published in 2023 include: ESWC 2023 - Extended Semantic Web Conference, ISWC 2023 - International Semantic Web Conference , WSDM 2023 - International Conference on Web Search and Data Mining, KDD 2023 - International Conference on Knowledge Discovery and Data Mining, Euralex 2023, Symposium of Slovenian Researchers, Intersection of Ethics, Integrity, and Gender Equality, Missions: The Novelty of the Horizon Europe Program, 8th Marathon of Positive Psychology, Maribor Marathon of Positive Psychology, School for Parents, Lecture series within the Science on the Road project.

We also partnered with numerous prominent domestic and international institutions, such as:
—   Ministry of Higher Education, Science, and Innovation
—   Association of Doctoral Students and Early Career Researchers – Young Academy
—   Faculty of Architecture, University of Ljubljana
—   Jožef Stefan Institute

- National Institute of Chemistry
- National Institute of Biology
- Ministry of Education, Science, and Sport
- University of Nova Gorica
- Primera Group, and
- Organizers of the aforementioned high-profile international events

Internally, we recorded major conferences such as ESSAI and ACAI, held in December 2023, and, as every year, provided live broadcasts of the events during the 32nd Jožef Stefan Days.

We continued our collaboration on European projects such as Erasmus+ Bridges and nurtured long-term partnerships with the Faculty of Architecture at the University of Ljubljana and the University of Nova Gorica. We broadcasted lecture series such as Science on the Road, Positive Psychology, and Lectures for Schools and Parents. Additionally, we began recording literary evenings in libraries across Slovenia and continued documenting events at the National Institute of Biology and the National Institute of Chemistry in Ljubljana.

INTERNATIONAL PROJECTS

1. ERASMUS+: BRIDGES - Bridging Educational Emergency to Digital Pedagogies
   Anja Polajnar, M. Sc.
   Agenzia Nazionale Erasmus Plus Indire
2. H2020 - INFINITECH; Tailored IoT&BigData Sandboxes and Testbeds for Smart, Autonomous and Personalized Services in the European Finance and Insurance Services Ecosystem
   Mitja Jermol, M. Sc.
   European Commission
3. H2020 - FACTLOG; Energy-aware Factory Analytics for Precess Industries
   Mitja Jermol, M. Sc.
   European Commission
4. H2020 - A-CINCH; Augmented Cooperation in Education and Training in Nuclear and Radiochemistry
   Mihajela Črnko
   European Commission
5. H2020 - STAR; Safe and Trusted Human Centric Artifical Intelligence in Future Manufacturing Lines
   Mitja Jermol, M. Sc.
   European Commission
6. H2020 - ODEUROPA: Negotiating Olfactory and Sensory Experiences in Cultural Heritage Practice and Research
   Mitja Jermol, M. Sc.
   European Commission
7. HE - enRichMyData; Enabling Data Enrichment Pipelines for AI-Driven Business Products and Services
   Mitja Jermol, M. Sc.
   European Commission
8. HE - Graph-Massivizer; Massive Graph Processing of Extreme Data for a Sustainable Economy Society and Environment
   Mitja Jermol, M. Sc.
   European Commission
9. HE - Plooto; Product Passport through Twinning of Circular Value Chains
   Mitja Jermol, M. Sc.
   European Commission
10. HE - Ai4Gov; Trusted AI for Transparent Public Governance Fostering Democratic Values
    Mitja Jermol, M. Sc.
    European Commission
11. HE - FAME; Federated Decentralized Trusted Data Marketplace for Embedded Finance

Mitja Jermol, M. Sc.
European Commission
12. HE - TWON; TWin of Online social Networks
    Mitja Jermol, M. Sc.
    European Commission
13. HE - PREPARE; Personalized Rehabilitation via Novel AI Patient Stratification Stategies
    Dr. Tanja Zdolšek Draksler
    European Commission
14. HE - HumAIne; Hybrid Human-AI Decision Support for Enhanced Human Empowerment in Dynamic Situations
    Mitja Jermol, M. Sc.
    European Commission
15. Dynamic Coalition; OER Dynamic Coalition Portal
    Mitja Jermol, M. Sc.
    UNESCO

R&D GRANTS AND CONTRACTS

1. OE4BW - International mentoring programme, UNESCO Office
   Mitja Jermol, M. Sc.
   Ministry of Higher Education, Science and Innovation
2. Videorecording and Post-Processing
   Mitja Jermol, M. Sc.
3. Management of the European Statistics Award for Web Intelligence - LOT 1
   Anja Polajnar, M. Sc.
   European Commission
4. Management of the European Statistics Award for Nowcasting - LOT 2
   Anja Polajnar, M. Sc.
   European Commission
5. TIDES: Connect AI
   Mitja Jermol, M. Sc.
   TIDES Foundation
6. Kleefstra Syndrome Scientific Conference 2023
   Dr. Tanja Zdolšek Draksler
   Zonmw - Zorgonderzoek Nederland
7. Students of UL in the working environment
   Dr. Matej Kovačič
   Ministry of Higher Education, Science and Innovation

STAFF

Postgraduate
1. Anja Polajnar, B. Sc.
Technical officers
2. **Mitja Jermol**, M. Sc., Head
3. Dr. Matej Kovačič
4. Simon Marolt, B. Sc.
5. Dr. Gregor Potočnik*
6. Iztok Renčelj, B. Sc.
7. Dr. Tanja Zdolšek Draksler
Technical and administrative staff
8. Aleš Buh

9. Ana Fabjan, B. Sc.
10. Adis Krečo, B. Sc.
11. Monika Kropej, B. Sc.
12. Matija Ovsenek
13. *Kim Sevšek, B. Sc., left 01.03.23*
14. Špela Sitar, B. Sc.
15. Martina Vilhar, B. Sc.

Note:
* part-time JSI member

MILAN ČOPIČ NUCLEAR TRAINING CENTRE ICJT

The mission of the nuclear training centre ICJT is training in the field of nuclear technologies and radiation protection. In addition, ICJT is actively informing the public about these technologies.

2023 was one of the more important years for ICJT, since a complete overhaul of the information centre was completed. The more than 20-year-old design of the centre was replaced by a new version, also updated in terms of content with new interactive exhibits and a simple simulator of the Krško nuclear power plant.

Training in nuclear technologies is our primary mission. The *Nuclear Technology* (TJE) course is the first, theoretical phase of training of future control-room operators. Last year was important in this area as well, since it was the first time that two TJE courses ware conducted at the same time, in parallel. They started in October and December, respectively, and will end in 2024. In the first half of the year we also conducted two courses *Basics of Nuclear Technology* course (OTJE). The first was held in January and February and the second in May and June. In addition to these established courses there were also two courses *Nuclear Energy in Short* (JEK) for non-technical staff of the Krško Nuclear Power Plant. Furthermore, in collaboration with the Reactor Physics Division, there were two 1-day courses on nuclear fuel.

There were 28 **radiological protection training** courses for the medical, industrial and research use of radioactive sources.

In collaboration with the Reactor Physics Division and the Reactor Infrastructure Centre six **international courses** were organized.

Public information remains an important part of our activities. The lectures were offered on electricity from nuclear energy, sources of electricity in Slovenia, fusion, isotopes, energy in general, the use of radiation in industry, medicine and research and on the safety of nuclear power plants. In 2023, a lecture on low-carbon energy sources was added. For younger visitors, a workshop on energy was offered. Altogether, there were 157 groups with a total of 6182 participants in 2023. Since 1993, there were 202,889 students, teachers and others, who visited our information centre. We have also continued monitoring and analysing media reports on nuclear energy.

Head:
Dr. Igor Jenčič

In 2023 two courses on Nuclear Technology (TJE) were held in parallel, for the first time since the establishment of ICJT.

Figure 1: Trainees in the lecture room during of the Basics of Nuclear Technology course, January 2023

Figure 2: Experimental training session at the Basics of Nuclear Technology Course

Table of training activities at the Nuclear Training Centre in 2023

Date	Title of the course	Partici-pants	Lecturers	Weeks	Participants × weeks
9.1. - 7.2.	Basics of nuclear technology, theory	17	14	4,4	74,8
11.1. - 2.2.	Hands-on activities in the framework of the International Master`s track Experiments: Neutron flux mapping, Primary water activation, calorimetry	6	11	0,8	4,8
26. - 27.1.	Radiation protection for industrial and other practices (radiography) - refresher course	5	2	0,4	2
9.2. - 3.3.	Basics of nuclear technology, systems	21	8	3,4	71,4
13. - 15.2.	Radiation protection for baggage-screening systems	9	2	0,4	3,6
6. - 8.3.	Radiation protection for industrial and other practices (radiography)	2	4	0,6	1,2
6. - 10.3.	Radiation protection for handheld XRF spectroscopy	2	4	1	2
6. - 8.3.	Radiation protection for industrial and other practices (measurement of roadway density and humidity)	9	4	0,6	5,4
13.3.	Radiation protection for Nuclear Medicine Dpt.	10	4	0,2	2
13.3.	Radiation protection for baggage-screening systems	3	4	0,2	0,6
13. - 14.3.	Radiation protection for industrial and other practices	1	5	0,4	0,4
13. - 16.3.	Radiation protection for industrial and other practices (unsealed sources)	8	7	0,8	6,4
16.3.	Radiation protection for industrial and other practices - refresher course	5	2	0,2	1
16.3.	Radiation protection for industrial and other practices (unsealed sources) - refresher course	3	2	0,2	0,6
16.3.	Radiation protection for handheld XRF spectroscopy - refresher course	15	2	0,2	3
16. - 17.3.	Radiation protection for industrial and other practices (measurement of roadway density and humidity) - refresher course	3	2	0,4	1,2
16.3.	Radiation protection for industrial and other practices (radiography) - refresher course	5	3	0,2	1
16.3.	Radiation protection for baggage-screening systems - refresher course	4	2	0,2	0,8
17. - 19.4.	Nuclear Energy in Short	17	5	0,6	10,2
3.5. - 2.6.	Basics of nuclear technology, theory	6	14	4,6	27,6
29.5. - 2.6.	Regional Workshop on Nuclear and Radiation Education	36	2	0,8	28,8
5. - 28.6.	Basics of nuclear technology, systems	5	8	3,6	18
18. - 20.9.	Nuclear Energy in Short	17	5	0,6	10,2
25. - 29.9.	Radiation protection for industrial and other practices (radiography)	9	6	1	9
25. - 27.9.	Uppsala University Dedicated Practical Educational Course „Experimental reactor physics"	1	4	0,6	0,6
25. - 29.9.	Radiation protection for handheld XRF spectroscopy	3	4	1	3
25. - 27.9.	Radiation protection for industrial and other practices (measurement of roadway density and humidity)	3	4	0,6	1,8
2.10. - (5.3.2024)	Radiation protection for industrial and other practices	20	16	12	240
2.10.	Radiation protection for baggage-screening systems	11	4	0,2	2,2
2. - 5.10.	Radiation protection for workers exposed to radon and thoron	1	4	0,2	0,2
2.10.	Nuclear Technology, Theory	9	4	0,2	1,8
2. - 3.10.	Radiation protection for industrial and other practices (unsealed sources)	3	5	0,4	1,2
5.10.	Radiation protection for industrial and other practices (measurement of roadway density and humidity) - refresher course	4	3	0,2	0,8

Table of training activities at the Nuclear Training Centre in 2023

Date	Title of the course	Partici-pants	Lecturers	Weeks	Participants × weeks
5.10.	Radiation protection for industrial and other practices (radiography) - refresher course	6	2	0,2	1,2
5. - 6.10.	Radiation protection for industrial and other practices - refresher course	1	2	0,4	0,4
5.10.	Radiation protection for handheld XRF spectroscopy - refresher course	1	2	0,2	0,2
5.10.	Radiation protection for industrial and other practices (unsealed sources) - Refresher course	1	2	0,2	0,2
16.10. - 3.11.	18th EERRI Research Reactor Group Fellowship Training Course	8	10	2,6	20,8
17.10.	Radiation protection for industrial and other practices	9	2	0,2	1,8
10.11.	Pulse experiment exercise for students	30	6	0,2	6
4. - 7.12.	Fundamentals of neutron detection	11	13	1	11
11.12. - (10.5.2024)	Nuclear Technology, Theory	12	14	2	24
15.12.	Update of the interpolation and extrapolation algorithm in the FAR program	5	2	0,2	1
20.12.	Analysis of monitoring of the Krsko NPP operation in cycle 31 and 32	4	1	0,2	0,8
TOTAL		361	226	48,8	881,0

Figure 3: Energy workshop for preschool children, April 2023

Figure 4: Open day of the Jožef Stefan Institute - at the exhibition in the Nuclear Training Centre, March 2023

R&D GRANTS AND CONTRACTS

1. Implementation of the Nuclear Technology Training Centre Program
   Dr. Igor Jenčič
2. Education and Training in Energy and Nuclear Energy in Central Slovenia
   Dr. Igor Jenčič
3. Training in Radiation Protection
   Matejka Južnik, M. Sc.
4. Training Courses for TJE and OTJE
   Dr. Igor Jenčič

STAFF

Researcher
1. **Dr. Igor Jenčič, Head**
Technical officers
2. *Matjaž Koželj, M. Sc., retired 01.07.23*
3. Gabi Novak, B. Sc.
4. Urban Pompe, B. Sc.
5. Tomaž Skobe, M. Sc.

6. Vesna Slapar Borišek, B. Sc.
7. Marjan Tkavc, M. Sc.
Technical and administrative staff
8. Saša Bobič
9. Matejka Južnik, M. Sc.
10. *Borut Mavec, B. Sc., retired 01.09.23*
11. Marko Videčnik

RADIATION PROTECTION UNIT

SVPIS

SVPIS has been involved in ionizing-radiation measurements and radiation protection since the commissioning of the TRIGA MARK II Research Reactor in 1966. SVPIS is responsible for the radiation control of all the activities at the Institute dealing with ionizing radiation. Our main task is the supervision of work in the reactor with the Hot-Cell Facility, and we are authorised by the regulatory authority to perform environmental monitoring.

SVPIS also controls 17 laboratories that use sources of ionising radiation in their research work. There are different sources of radiation used at the JSI that need regulatory control. Furthermore, we are involved in radioactive-waste management.

SVPIS is authorized by the Slovenian radiation-protection administration and nuclear-safety administration to perform control in industrial and research institutions using sources of radiation. The measurements of dose rates, contaminations and radon-activity concentrations, as well as gamma spectrometry, are performed using accredited methods (LP-022, EN ISO/IEC 17025).

Head:

Matjaž Stepišnik, M. Sc.

Personal dosimetry

Personal doses of 149 workers that regularly or occasionally deal with ionizing radiation were monitored with Thermo Luminescent Dosimeters. The maximum individual yearly dose was 0.23 mSv. This is 1 % of the regulatory limit for occupational exposure (20 mSv per year). The collective dose at the JSI in 2022 was 2.3-man mSv.

Supervision of the Research Reactor and laboratories

The controlled area of the Research Reactor, the Hot-Cell Facility and the Department of Environmental Sciences were monitored on a weekly basis. During certain activities, the constant presence of a radiation-protection worker was needed (i.e., for the opening of activated samples or radioactive-waste management). Measurements of dose rates, surface contamination, contamination of different objects and personal contamination were performed routinely. In most cases, no or very low contamination levels were measured. Locally elevated radiation levels were measured mainly in the reactor's controlled area.

At present, more than 100 radioactive sources (open and sealed) and 15 devices with ionizing radiation (X-ray units and accelerator TANDETRON) are in use, requiring regulatory control and additional 450 low-activity sources in different laboratories. In 2023, a total of 15 detailed radiological surveys were performed in JSI laboratories. An independent inspection by an external authorized institution was performed in the SVPIS laboratory and two other laboratories at the JSI. No deficiencies that could be important for radiation protection were identified.

Environmental monitoring of the reactor

The environmental monitoring of the Reactor Centre was performed according to the existing programme. This programme consists of effluent measurements and measurements of samples in the environment. Activity concentrations of gamma emitters in water samples, filters, noble gases, soil samples and sediment samples were measured periodically. About 500 different samples for the reactor and different laboratories have been measured with gamma spectrometry. Environmentally passive dosimeters have been used to monitor the radiation levels in the surroundings of the reactor.

Based on the effluent measurements and a conservative environmental transfer model, the effective dose to the reference group of the public was estimated to be less than 1 μSv/year. **In 2023 the public exposure due to activities at the Reactor Centre was insignificant**.

Expert assessments and measurements for outside customers

The Radiation Protection Unit is authorized for supervision measurements and expert assessments in the field of radiation protection and radon measurements. In the past year several radiological control investigations were carried out in industrial and research institutions (in total 46). Our group has participated in evaluating the radiological monitoring of Krško NPP, research reactor TRIGA, storage for low- and intermediate-level waste in Brinje and in the preparation of the Evaluation of the justification for using consumer products and geological samples containing radioactive substances.

INTERNATIONAL PROJECTS

1. Training Costs for IAEA"s Fellows Messrs. Albarqi Mubarak Mohammed M and Alsulami Raed Atiah M (EVT2205710: SAU1007), 20 February 2023 - 24 February 2023
Matjaž Stepišnik, M. Sc.
IAEA - International Atomic Energy Agency

R&D GRANTS AND CONTRACTS

1. Implementation of Systematic Monitoring and Radon Measurements in Educational and Other Institutions for the Period 2024-2025
Matjaž Stepišnik, M. Sc.
Ministry of Health

2. Uranyl acetate storage
Matjaž Stepišnik, M. Sc.
National Institute of Biology
3. Hot Cell Facility Usage
Matjaž Stepišnik, M. Sc.
ARAO - Agency for Radioactive Waste Management
4. Conducting a survey of ionizing radiation sources
Matjaž Stepišnik, M. Sc.
Ministry of Defence
5. Radiological Inspection of Sources of Ionizing Radiation - Minor Services / Various Foreign Customers
Matjaž Stepišnik, M. Sc.
6. Irradiations on the TRIGA Reactor
Matjaž Stepišnik, M. Sc.
7. Irradiations of FT-TIMS Capsule on the TRIGA Reactor for Years 2020-2023
Matjaž Stepišnik, M. Sc.
CEA-Commissariat a l' Energie Atomique et aux

STAFF

Technical officers
1. Dr. Tinkara Bučar
2. Mitja Eržen, B. Sc.
3. **Matjaž Stepišnik, M. Sc., Head**

Technical and administrative staff
4. Thomas Breznik, B. Sc.
5. Tanja Murn, B. Sc.
6. Nina Udir, B. Sc.

CENTER FOR SMART CITIES AND COMMUNITIES CSC&C

The Centre for Smart Cities and Communities (C SC&C) was established in 2017. Its priority is to coordinate and manage the Strategic Development and Innovation Partnership Smart Cities and Communities (SRIP SC&C) through the first, second and third phases of the SRIP SC&C operation (closed on 30 September 2023).

The C SC&C promoted cross-sectoral cooperation at the Jožef Stefan Institute and thus also contributed to supporting the SRIP SC&C in the priority area of Smart Cities and Communities, in line with the orientations of the Slovenian Sustainable Smart Specialisation Strategy S5.

From 1 January 2019 the Center was headed by Nevenka Cukjati, Ph.D.

Head:
Dr. Nevenka Cukjati

SRIP SC&C project

The Strategic Development Innovation Partnership Smart Cities and Communities is a partnership where stakeholders join forces to develop and sell solutions to raise the quality of life in the cities of tomorrow.

The aim of the SRIP SC&C is to bring together companies and research institutions in a particular field to form value chains, to prioritise development investments and to coordinate R&D activities. We are building a good support environment for knowledge and experience sharing in the form of workshops, seminars and joint events; we offer access to test environments, laboratories, databases; assistance in market analysis, human-resources development, intellectual property protection and internationalization assistance.

In accordance with the Call for tender for the selection of operations Support to Strategic Development Innovation Partnerships (SRIP) for the period 2023–2026, published in the Official Gazette of the Republic of Slovenia, No 106/23, of 13.10.2023, we submitted an application to the Ministry of Higher Education, Science and Innovation (MVZI) on 10 November 2023, together with consortium partners the Urban Planning Institute of the Republic of Slovenia (UIRS) and the Chamber of Commerce and Industry of Slovenia (CCIS). We received a positive decision from the MVZI, dated 19 December 2023.

The SRIP SC&C currently has 84 members (data for the end of the year 2023) comprising 25 % micro enterprises, 31 % small enterprises, 6 % medium-sized enterprises, 11 % large enterprises, 18 % faculties or institutes and 9 % municipalities or associations. The open-source online SRIP SC&C platform is available to SRIP SC&C members: Technology Casino and Solutions Market. In the Technology Casino they can learn about and try out different technologies and platforms (playground) for developing innovative solutions in the field of smart cities and communities. They can share and promote their solutions in a common digital marketplace.

We are actively involved in the Climate Neutral Cities Mission process at the EU Commission level: we were the initiators of the active involvement of Slovenian cities in the Mission for 100 Climate Neutral Cities by 2030. Nevenka Cukjati, Ph.D., participates as a national delegate in the Smart Cities Working Group at the RS and EU levels. We inform and encourage members to connect with Slovenian cities by exchanging expertise, products and services. Together with key stakeholders in the Republic of Slovenia, we have initiated, within the Slovenian Institute for Standardization (SIST), the creation of a technical group for the translation and implementation of EU standards in the field of climate-neutral sustainable smart cities in the Slovenian space.

We participate in the development of the macro-regional EU Strategy for the Adriatic and Ionian Region (EUSAIR 2021–2027), whose overall objective is to promote economic and social prosperity and growth in the region by improving its attractiveness, competitiveness and connectivity in the thematic areas of sustainable tourism, blue growth, regional integration and environmental quality. Together with the EIT Climate-KIC, we are participating in the Deep Demonstration project, a model for a systemic transition to a circular, regenerative, carbon-free economy, with the aim of decarbonising Slovenia and becoming an example of good practice for all those who recognise that the transition to a low-carbon economy will only be effective if it is understood and implemented in a systemic way.

We were a partner of the Digital Health 2023 conference, which was organised by SRIP SC&C member, Technology Park Ljubljana d.o.o. and the Ljubljana University Incubator on 23 February 2023 at the Fužine Castle in Ljubljana. Under the auspices of DIGI-SI, a parallel Show of Innovation programme was held, where technological solutions for use in the healthcare system were presented at stands to investors and strategic partners.

On 16 May 2023 the Network NGO for an Inclusive Information Society, the Plan B Network of Environmental Organisations for Slovenia and the Space Network, with the support of the Consortium of NGO Content Networks and SRIP SC&C, organised a panel discussion at the House of the EU in Ljubljana: Where and how do the green

and digital transitions meet? Participants learned about the mechanisms of the green and digital transitions and the points and ways in which they intersect. We also discussed how the green and digital transitions are linked in Slovenia and what challenges we still need to tackle.

On 5 September 2023, together with SRIP FoF and META Circularity, we organised at the JSI a workshop on Dual Transition Projects (Green/Digital), where we presented innovation support and opportunities to participate in European projects such as EIT-Manufacturing, I3 and the Climate Neutral and Smart Cities Missions.

SI4CARE project

The Interreg ADRION SI4CARE project - Social innovations for the integrated care of the ageing population in the ADRION regions started on 1 December 2020 and ran until 31 May 2023. The SI4CARE project was co-founded by the Interreg ADRION programme (European Regional Development Fund - ERDF) for a total amounting of just over 2 million euros. The lead partner of the project was the University of Ljubljana with 8 partners from 7 countries. Within JSI, we collaborated with the Computer Systems (E7) and Intelligent Systems (E9) sections.

The aim of the project was to ensure that the ageing population in the ADRION regions is provided with health care. The main purpose of the project was to bring strategies and action plans in each country (Slovenia, Italy, Croatia, Bosnia & Herzegovina, Greece, Montenegro, Serbia) and to put them into practice to help the elderly, especially in remote places.

The project established the Multidisciplinary Research and Development Centre for Social Innovation for Active and Healthy Ageing (MRRC), which fosters a commitment to finding and delivering new solutions and modern concepts for active and healthy ageing in the ADRION regions. The Multidisciplinary Research and Development Centre will promote and build on the results of SI4CARE and will continue to operate the international ecosystem after the end of the project. More specifically, the activities of the centre include the organization of meetings and workshops, professional support for training and education of older people to increase their digital literacy and will aim at a general international exchange of knowledge between the stakeholders involved in the field of active and healthy ageing, notably through its annual conference, with representatives of different organizations from the ADRION region.

The 1st International Conference on Active and Healthy Ageing "Social Innovations for Active and Healthy Ageing" was organized in the framework of the SI4CARE final event, which took place on 19–20 April 2023 in Ljubljana. Important topics in the field of social innovation for the present and future of active and healthy ageing were addressed. In the framework of the SI4CARE conference, the participating countries will sign a Memorandum of Understanding for Healthy and Socially Engaged Ageing.

WEFE4MED project

The PRIMA WEFE4MED project - For the Mediterranean Community of Practice WEFE Nexus started on 1 October 2022 and will run until 30 September 2026. The project is supported and founded by Horizon 2020, the European Union's research and innovation programme, for a total amount of just under €2 m. The Cyprus Institute is the project's lead partner, with 10 partners from 8 countries. Within the JSI, we are working with the Computer Systems (E7) and Knowledge Technologies (E8). So far, over 30 public events and demos have been organized, which encourage changes in habits in the context of promoting sustainable and circular environmental management.

The overall objective is to promote the adoption of the Water-Energy-Food-Ecosystems (WEFE) Nexus approach in the Mediterranean through the Nexus Community of Practice to address the climate and environmental challenges facing societies and agro-ecological systems. The community will bring together practitioners, scientists, policy makers, civil society, media, entrepreneurs, innovators and investors. It will gather and share knowledge, build capacity by introducing best practices and science-based policies and innovative solutions inspired by demonstration sites, and demonstrate the benefits of integrated natural resource management for sustainable and climate-resilient development in the Mediterranean.

UA-CITINET project

As one of 29 consortium partners from 11 countries, we applied to the CSA Horizon tender from the Missions for Climate-Neutral Smart Cities: "Associating Ukrainian cities to the Climate-neutral and smart cities Mission" on 6 September 2023. The aim of the project is to determine the most modern, environmentally sustainable technologies of smart cities and to include them in the core group of selected Ukrainian cities that strive to achieve the goal of climate neutrality. The project was not selected for financing; however, we established contacts with key stakeholders in the European economic, development research and political space.

NACHIP project

As the applicant of a consortium of 12 partners from 3 countries, we applied on 17 October 2023 to the NACHIP project NORTH ADRIATIC CLEAN (RENEWABLE) HYDROGEN INVESTMENT PLATFORM (NACHIP), which aims to

accelerate and strengthen innovation related to the hydrogen ecosystem of the Northern Adriatic, focusing on investments in renewable hydrogen-related technologies with three value chains: manufacturing, urban areas and mobility, and scaling up impact through efforts to implement an investment platform that will be used to further integrate and disseminate advanced technologies. The project will last 36 months and has been recognized as good by the EU. We are starting to realize it in 2024. It is about the upgrading or implementation of environmentally friendly and sustainable technologies, which are broadly related to the project so called "Great hydrogen valley" (NAHV), which is coordinated by Holding Slovenske elektrarne d. o. o. (HSE) and started in the middle of 2023.

INTERNATIONAL PROJECTS

1. PRIMA; WEFE4MED - Towards a Mediterranean WEFE Nexus Community of Practice
   Dr. Nevenka Cukjati
   Prima Foundation - Partnership for Research and Innovation in the Mediterranean Area

R&D GRANTS AND CONTRACTS

1. Social Innovation for Integrated health CARE of ageing population in ADRION Regions-SI4CARE
   Dr. Nevenka Cukjati
   The Emillia-Romagna Region

2. Support for Strategic Research and Innovation Partnership (SRIP) in priority areas of Smart Specialization
   Dr. Nevenka Cukjati
   Ministry of Higher Education, Science and Innovation

3. Support for Strategic Research and Innovation Partnerships (SRIP) and Priority Areas of Smart Specialization (SRIP PMiS)
   Dr. Nevenka Cukjati

STAFF

Technical officer
1. **Dr. Nevenka Cukjati, Head**
Technical and administrative staff
2. *Mojca Kristl, B. Sc., left 01.10.23*
3. Jan Kunc, B. Sc.

CENTER FACTORIES OF THE FUTURE

CFoF

The Center was established in early 2017. On January 1, 2023, the leadership of CFoF was taken over by Asst. Prof. Dr. Igor Kovač. The main task of the center is to coordinate and operate the Strategic Development and Innovation Partnership of Factory of the Future (SRIP FoF). In addition, the CFoF also encourages cooperation and the creation of research and business synergies between research and industrial partners within Slovenia, in particular integrating the competences and capacities in the field of cutting-edge technologies of the Jožef Stefan Institute and other members of the SRIP, as well as focusing on internationalisation, entrepreneurship and familiarisation with intellectual property in cooperation with units within the JSI. CFoF contributes to supporting the latest technology partnership and at the same time actively participating in the development of R&D policies in the coming years, in collaboration with industry and the state

Head:
Asst. Prof. Igor Kovač

What does the Factory of the Future Strategic Development Innovation Partnership offer?

The strategy of the SRIP Factory of the Future (SRIP FoF) is to gather and integrate Slovenian research and innovation knowledge and experience in the industrial and academic spheres and highlight the priority breakthroughs of new products, technologies and services for Factories of the Future. We have established a supportive environment with expert services for industry and research organizations, with an emphasis on developing new, cutting-edge technologies that combine and build on existing Slovenian research and innovation achievements.

Key functions of the strategic long-term interconnectivity are the definition and supplementation of the strategic action plan in the field of Factories of the Future, activities in the scope of the development of joint services, internationalization, development of human resources and entrepreneurship, representation of joint interests towards the state, etc. Part of the services will be carried out in cooperation with other institutions.

SRIP FoF **creates and supports** business and research synergies in the area of the smart factories for new products, services and technologies, and helps businesses enter the global market by focusing on niche areas. The members of SRIP FoF come from various companies, associations or institutions from Slovenia. The operation of SRIP FoF focuses on a greater integration of knowledge and joint appearance of stakeholders in domestic and foreign markets. The primary goals are to increase the share of high-tech industrial products in exports and to increase the added value and productivity of Slovenian industry.

Key areas of activity

The SRIP ToP organisation scheme includes five domains (vertical value chains, VVCs) through which five horizontal networks with key enabling technologies (KETs) were interwoven (Figure 1).

In a two-dimensional matrix structure, where enabling technologies and vertical value chains are intertwined, JSI manages the following: VVC - Robotic and laser systems and components, Advanced green technologies, and KET - Robotics, Photonics, Plasma technologies, Modern production methods for materials and nano and quantum technologies.

By effectively directing R&D and introducing knowledge and technologies that enable the production of better-quality products, reducing the consumption of energy and raw materials, reducing environmental pollution, improving human involvement, etc., SRIP FoF also indirectly contributes to accelerating the transition to a low-energy, energy-efficient economy, greenhouse-gas emissions, to intensively promote the transition to a low-carbon society and to a green, circular economy. The essence of the concept of factories of the future is mainly reflected in the greater potential for the reuse of raw materials, made possible by more flexible and optimally managed production.

Figure 1: Scheme of SRIP FoF domains

In the field of **internationalization**, we organised a high-profile international event "Innovation Day in Ljubljana" in December 2023, where we presented the content together with the Department of Nanostructured Materials (K7) and EIT Manufacturing. Some members of SRIP FoF also participated in the event, while others were present as participants.
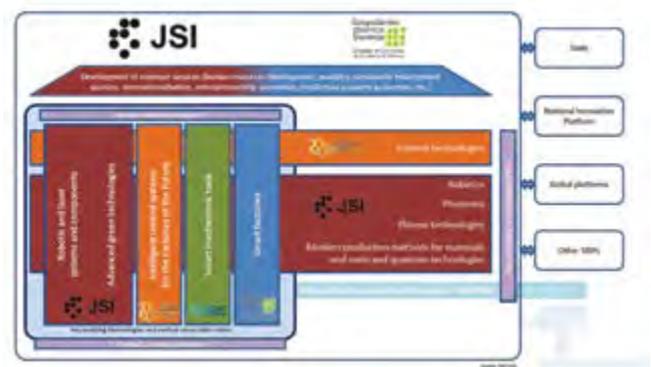
To expand and consolidate its activities in the field of innovation at home and abroad, JSI, as the coordinator of SRIP FoF, is actively involved in various European initiatives. One of these is the **European Institute of Innovation and Technology (EIT)**, which enables innovators and entrepreneurs to develop solutions to create growth and jobs.

Thus, SRIP FoF has been actively present in the field of manufacturing through the JSI since the beginning of the creation of the **EIT Manufacturing - EITM community** (https://eitmanufacturing.eu/), and in 2021 it became a full core member. To support the implementation of the EITM program at the JSI, the institute was organized internally. It sent an informative invitation to all sections and centres at the JSI in the development phase, to which seven departments responded, all of which are members of the SRIP FoF in addition to the Centre Factory of the Future.

In doing so, the rules for joining the EITM were concluded and adopted. Based on this, the JSI as a member and coordinator of SRIP FoF worked in the EITM innovation ecosystem, participated in the development of key topics in production technologies and processes, participated in decision-making on global issues, exchanged industry experience at the European level, defined key requirements and applied to calls for EITM projects. As a core member, JSI was also able to invite external partners who are not members of the EITM to participate in the projects, but of course SRIP FoF members had priority.

In 2023 the following units were involved in the EITM as members of the SRIP FoF:
– JSI, Department of automation, biocybernetics and robotics (E1),
– JSI, Department of systems and control (E2),
– JSI, Artificial intelligence (E3),
– JSI, Thin layers and surfaces (F3),
– JSI, Surface technology and optoelectronics (F4),
– JSI, Nanostructured materials (K7),
– JSI, Advanced materials research (K9), - JSI, Centre - Factories of the Future (CFoF).
– JSI, Communication Systems – E6

We presented our activities to the EITM Advisory Board. JSI members participated in networking events (EITM MatchMaking Events), short presentations of project ideas (Idea Pitch) and workshops to help prepare project applications. We were also active in the preparation of project applications. In the last EITM call for innovation-based projects, JSI as lead partner submitted one project. Let us stress that these are projects with a Technology Readiness Level (TRL) of 5 to 6. Therefore, the need for commercialisation of results and a go-to-market strategy is very clear. In the future, we want to attract as many partners as possible who are members of SRIP ToP to participate in our projects and to win as many projects as possible in the field of innovation, business and education, especially in the area of RIS calls.

The year 2023 was marked by conclusion of **the 3rd phase of the SRIP FoF project** and **application for the new SRIP 2023–2026 public tender**, which we successfully obtained and as a result we continue to manage the SRIP FoF project. In implementing the activities, we followed the action plan for the 3rd phase of the SRIP operation, met with the coordinators of individual vertical value chains and horizontal networks and encouraged them to connect with members in preparing joint projects and preparing and implementing events of interest to members of the research sector and industry. We continued to cooperate with other SRIPs, with key ministries that are important for our work (Ministry responsible for the economy, Ministry responsible for education) and with the Government Office for Development and Cohesion Policy (SVRK). After the reorganization of the ministries, as a result of the new government of the Republic of Slovenia, in 2023 the Ministry of Higher Education, Science and Innovation took over responsibility for SRIPs. We established contacts with new teams in key ministries and actively participated in the discussion and preparation of operational programmes for the new SRIP public tender. We submitted the application for the new SRIP 2023–2026 public tender on 27 October 2024 and received the approval decision in December 2023.

In 2023 we started the activities of establishing a new Center for Development Innovation Partnership (CRIP), for the needs of the most efficient and lean organization possible in the implementation of support services in the priority areas of Factories of the Future and Smart Cities and Communities within the framework of the new Smart Specialization Strategy S5. The initiative to establish a new centre was approved by the JSI Scientific Council in 2023 and by the JSI Board of Directors at the end of 2023.

At SRIP FoF, the process of entrepreneurial discovery is constantly taking place, which relates to changes in certain product and development areas, which are included in the renewed strategy of smart specialization for the period 2021–2027. We have highlighted the importance of National Smart Factory Demo Center and inclusion of key enabling technologies, the development and financing of which is crucial for the success of the entire Slovenian smart specialization, as well as for JSI.

We conducted SRIP FoF presentations at various events and presented SRIP FoF and our activities at various meetings at home and abroad. We were active in collecting and preparing news for members, and our website is

constantly updated and has been well visited as it is a hub of news from the field of technology and our activities. In combination with social networks, an increasing circle of followers is acquainted with our activity. We regularly published news that was appreciated by the recipients.

To encourage companies and organizations to join SRIP FoF, **we conducted several presentation events** of SRIP FoF in 2023. Among the most resounding events were: By connecting and exploiting synergies to innovative solutions and co-financed projects (March and May 2023), By measuring mechanical quantities to innovation breakthroughs (April 2023), EIT Manufacturing workshop (May 2023), Innovation day in Ljubljana (December 2023), Double transition projects (September 2023). As part of a series of events entitled "Steps to a smart factory", which we organized in cooperation with the company Kolektor Sisteh, 2 events took place in 2023. At the events, experts shared their practical experience with the participants on various topics in the field of smart factories.

We participated fairs such as IFAM fair (March 2023), Forum IRT (June 2023), MOS Fair (September 2023), Viva Technology fair in Paris, participation of members in the largest European fair in the field of innovation (June 2023). We collaborated with the Slovenian Institute for Quality and Metrology (SIQ) in the implementation of training as part of the multi-day Industry 4.0 School.

In 2023 we established an informal association of Slovenian robotics and automation technology integrators in the field of Factories of the Future. The aim is to connect Slovenian integrators from the field of Factories of the Future, because in this way information exchange and synergy can be created between them, which will enable greater development progress for the entire Slovenian industry.

We have maintained the connection we have developed with KOC-FoF in the past, giving our members access to workshops and conferences organized by KOC-FoF.

In 2023, 13 new members joined SRIP FoF: Bizjan orodjarstvo d.o.o., DSI Expert d.o.o., Faculty of Environmental Protection , Gorenje household appliances d.o.o., JSI Department for Communications Systems (E6), Plasil plazemske tehnologije d.o.o., Rudolfovo, SCAN d.o.o., SPR d.o.o., Teces, Tenovis d.o.o. and High School for Manufacturing Engineering.

In 2023 we successfully continued the implementation of the Horizon Europe **ZOOOM project - 3Os and IP awareness raising for collaborative ecosystems**. The project aims to raise awareness about the importance of IP creation and management in collaborative innovation ecosystems that rely on three key assets: software, hardware and data. In practice, there is a perceived lack of competence in companies creating products based on the three O's (open software, open hardware, open data). Companies therefore want to offer their services/products openly, for free, but have difficulties in aligning their business models with the relevant IPR licences. This prevents the further development and expansion of innovation potential. The project will develop tools (videos, web platforms, educational models, etc.) to promote open licensing in industry. These models will include both the legal and business aspects of open licensing.

We are working with prestigious European institutions on this project. Our partners are coming from Belgium, Finland, Bulgaria, Denmark, Austria, Germany and Italy: KU Leuven, Teknologian tutkimuskeskus VTT OY, Fondatsiya LiBRE, EIT Manufacturing South Srl, AALBORG University, Innovations und technologietransfer Salzburg Gmbh, Free software foundation Europe E.V., Hub Innovazione Trentino – Fondazione, Universita degli studi di Trento.

The aim of the project is to provide business solutions and useful tools for business, and in particular industry, to make appropriate decisions on which open licensing strategies best fit certain business models.

We are actively supporting our partners in the preparation of innovation programs and facilitating the exchange of good practices. Through expert consultations, workshops, and events like Workshop Double Transition Projects (Green/Digital) or the Workshop in Ljubljana, in collaboration with the EIT Manufacturing network and CLC East, we have enhanced our partner' access to the European expert community. We highlighted the EIT RIS Hub services and offered help and support in manufacturing area to the SLO community with networking and connecting in innovation ideas. We are actively involved in bilateral projects with neighbouring countries and are gearing up for high-profile international workshops and events, such as the Innovation Day Ljubljana. Expanding our network has been a priority, and we have successfully welcomed new partners.

INTERNATIONAL PROJECTS

1. HE - ZOOOM; 3Os and IP Awareness Raising for Collaborative Ecosystems
   Asst. Prof. Igor Kovač
   European Commission
2. EIT M; EIT Manufacturing RIS HUB in Slovenia for 2023
   Asst. Prof. Igor Kovač
   EIT Manufacturing East Gmbh

R&D GRANTS AND CONTRACTS

1. Strategic Research & Innovation Partnership Factories of the Future (SRIP FoF)
   Asst. Prof. Igor Kovač
   Ministry of Higher Education, Science and Innovation
2. EIT M East - JSI; Sponsorship for Operation of the SRIP FoF
   Asst. Prof. Igor Kovač
   EIT Manufacturing East GmbH

STAFF

Researcher
1. **Asst. Prof. Igor Kovač**, Head
Technical officers
2. Petra Hauschild, B. Sc.
3. *Marko Keber, B. Sc., left 22.05.23*

4. Matjaž Logar, B. Sc.
5. Nataša Pibernik, B. Sc.
6. Nataša Vertot Rakun, B. Sc.
Technical and administrative staff
7. Tamara Hrabar Vovk, B. Sc.