VTT

FinnFusion Yearbook 2023

Jari Likonen | Tommi Lyytinen (Eds.)

VTT TECHNOLOGY 427

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Technical Research Centre of Finland Ltd

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Preface

Fusion research kept making history in 2023 with new achievements and developments. This is anticipated, as fusion research has been progressing in many areas, particularly with the involvement of new actors from the private fusion sector. In addition, other news emerged as JET's success story concluded with the final JET plasma discharge in December 2023, and ITER is undergoing a major re-planning.

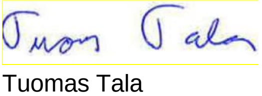
In the final deuterium-tritium experiments (DTE3) on JET, high fusion power was steadily produced for 5 seconds, resulting in a groundbreaking record of 69 megajoules using only 0.2 milligrams of fuel. Throughout its lifecycle, JET has been extremely useful as a precursor to ITER; in the testing of new materials, in the development of innovative new components, and most of all in the generation of scientific data from deuterium-tritium fusion campaigns. The results obtained here will directly and positively impact ITER, confirming the way forward and enabling us to advance faster toward our performance goals. JET finished its scientific operations at the end of December 2023.

EAST tokamak in Hefei China demonstrated 403 seconds long stationary H-mode plasma condition on a repeatable basis. This is by far the longest record of high-performance plasma discharge, being as long as targeted in the high-performance ITER plasmas. Commonwealth Fusion Systems Inc. built the world-record super conducting magnet, an impressive B=20.1T. It is based on a compact, high field REBCO high-temperature superconducting technology. Commonwealth Fusion Systems also opened its new campus in Devens, near Boston, to construct its high-field high-temperature superconducting SPARC tokamak, aiming DT operation towards the end of this decade. JT-60SA tokamak (QST, Naka, Japan) was inaugurated on 1 December 2023, with the presence of EU energy commissioner, Japanese ministers and F4E and EUROfusion directors. The joint Japanese-European fusion device JT-60SA will be the most powerful fusion device to date. JT-60SA has been designed to support the operation of ITER by following a complementary research and development programme. The facility will also investigate how best to optimise the operation of fusion power plants that are built after ITER, including the demonstration fusion power plant DEMO. JT-60SA is scheduled to begin scientific experiments in approximately two years. These will be jointly organised and run by Europe, represented by EUROfusion, and Japan.

ITER is undergoing a re-baselining, which accommodates very significant design and operational changes, the three largest ones being the change of the beryllium wall to tungsten, increase of ECRH heating from 20MW to above 50MW and plasma operation starting almost directly with Deuterium. The re-baselining schedule and cost will be officially agreed on the council level in 2024, but the teams are already working taking into account the re-baseline. The TF and PF coils are on site in the cold testing phase. The vacuum vessel sectors are being repaired. The F4E Governing Board elected Marc Lachaise as the new F4E director. F4E signed a strategic partnership with Korea on tritium Test Blanket Module development programme.

The European roadmap for fusion energy was updated in 2023, responding to the recent achievements and records, and thanks to the enormously increased interest in fusion. In parallel to this, EUROfusion has mandated “The Working Group Licensing for Fusion” (WGLF) to recommend the first principles of regulation adapted to a fusion facility in Europe. From FinnFusion, Markus Airila is an active nominated member in that working group. Licencing of various future fusion DEMO and pilot plants has become an active and urgent issue to be solved quickly, and UK and US have already developed policies and legislation on how to licence a future fusion reactor practically and safely. The new legislation will also be needed in Finland urgently.

The FinnFusion annual seminar 2023 was organised together with the Swedish and Danish colleagues as the 4th Nordic Fusion Seminar, taking place at Chalmers in Gothenburg in June. The plenary talks discussed JET DT campaign and fusion landscape in UK with its STEP prototype reactor development. In addition, two private fusion enterprises introduced their results, Tokamak Energy and Novatron, which has Stockholm as the registered office. The seminar attracted around 100 participants. There were many excellent contributions from several Finnish fusion laboratories given in the seminar, and good path for Nordic collaboration on fusion was being established. Finally, I like to thank all the Finnish fusion researchers who have eagerly brought fusion research ahead in Finland and contributed to these great fusion research results published in this FinnFusion annual yearbook.



Tuomas Tala
Head of Research Unit
FinnFusion Consortium

Contents

List of acronyms and names

ACH	Advanced computing hub, hosted by UH
APROS	Software used for modelling, dynamic
ASCOT	Accelerated Simulation of Charged Particle Orbits in Tori (particle tracing code)
AU	Aalto University, Espoo/Helsinki, Finland
AUG	ASDEX Upgrade (tokamak facility)
BMC	Backward Monte Carlo
BB	Breeding blanket
BOP	Balance-of-plant
CCFE	Culham Centre for Fusion Energy
CFC	Carbon fibre composite
CFD	Computational Fluid Dynamics
CSC	IT Center for Science Ltd, Finland
CX	Charge exchange
DIII-D	Tokamak facility at General Atomics, San Diego
DEMO	Future demonstration fusion power plant
DONES	DEMO oriented neutron source
DCLL	Dual-Coolant Lithium Lead (Breeding blanket concept)
DPA	Displacement-per-atom
DT	Deuterium-tritium
DTP2	Divertor test platform phase 2 (test facility in Tampere)
EDGE2D	Fluid plasma simulation code
EDP	Erosion-deposition probe
EIRENE	Neutral particle simulation code
ELM	Edge localised mode (plasma instability)
ELMFIRE	Gyrokinetic particle-in-cell simulation code
ENR	Enabling research

ENS	Early neutron source
ERO	Monte Carlo impurity transport simulation code
EUROfusion	European consortium implementing the Fusion Roadmap
F4E	Fusion for Energy (the European Domestic Agency of ITER)
FDS	Fire Dynamics Simulator
FILD	Fast-ion loss detector
FP9	EUROfusion European Framework Program 9
FPP	Fusion power plant
GPU	Graphics Processing Unit
HCPB	Helium Cooled Pebble Bed (Breeding blanket concept)
HEA	High entropy alloy
HELIAS	Helical-axis advanced stellarator
HHFM	High heat flux materials
HLCS	High level control system
HPC	High-performance computing
HRP	Hot Radial Pressing
IAEA	International Atomic Energy Agency
IBA	Ion beam analysis
ICRH	Ion cyclotron resonance heating
IFMIF	International Materials Irradiation Facility (under design)
ILW	ITER-like wall
IMAS	ITER Integrated Modelling and Analysis Suite (collection of codes)
IPP	Institut für Plasmaphysik, Garching/Greifswald
ITER	Next step international tokamak experiment under construction in Cadarache, France (“the way” in Latin)
ITPA	International Tokamak Physics Activity
JET	Joint European Torus (tokamak facility)
JINTRAC	Set of plasma simulation codes
KSTAR	Korea Superconducting Tokamak Advanced Research (tokamak facility)
LAMMPS	Classical molecular dynamics simulatior code
LUT	Lappeenranta-Lahti University of Technology
MAST	Mega Amp Spherical Tokamak (tokamak facility)
MAST-U	MAST Upgrade
MCNP	Monte Carlo N-Particle Transport
MD	Molecular dynamics (simulation method)

MEAE	Ministry of Employment and Economy
ML	Machine learning
NBI	Neutral beam injection
OTSG	Once-through steam generator
PCS	Power conversion system
PFC	Plasma-facing component
PIE	Post irradiation experiment
PRA	Probabilistic risk assessment
RACE	Remote applications in challenging environments (research facility)
RBS	Rutherford backscattering spectrometry
RH	Remote handling
RM	Remote maintenance
RU	Research Unit (member of EUROfusion)
Serpent	Monte Carlo reactor physics simulation code developed at VTT
SIMS	Secondary ion mass spectrometry
SOL	Scrape-off layer
SOLPS	Scrape-off Layer Plasma Simulation (fluid plasma simulation code)
SRIM	Stopping and Range of Ions in Material (stopping power calculations)
STEP	Spherical Tokamak for Energy Production (planned tokamak facility)
TCV	Tokamak à Configuration Variable (tokamak facility)
TDS	Thermal desorption spectrometry
TOF-ERDA	Time-of-flight elastic recoil detection analysis
TUNI	Tampere University
UH	University of Helsinki
VTT	VTT Technical Research Centre of Finland Ltd
W7-X	Wendelstein 7-x stellarator (stellarator facility)
WCLL	Water-cooled lithium-lead
WEST	Tungsten (W) environment in steady-state tokamak (tokamak facility)

1. FinnFusion organization

1.1 Programme objectives

The Finnish Fusion Programme, under the FinnFusion Consortium, is fully integrated into the European Fusion Programme, which has set the long-term aim of the joint creation of prototype reactors for power stations to meet the needs of society – operational safety, environmental compatibility, and economic viability. The objectives of the Finnish programme are:

- Develop fusion technology for ITER+DEMO and other future fusion devices in collaboration with Finnish industry
- Provide a high-level scientific contribution to the accompanying Euratom Fusion Programme under the EUROfusion Consortium.

This can be achieved by close collaboration between the Research Units and industry, and by strongly focusing the R&D effort on a few competitive areas. Active participation in the EUROfusion Work Programme and accomplishing ITER technology development Tenders & Grants by F4E and ITER provide challenging opportunities for top-level science and technology R&D work in research institutes and Finnish industry. The goal is to establish an active fusion ecosystem in Finland and supporting companies through business research. Participating in industry activation tasks facilitated by FinNuclear supports wider networking and ecosystem expansion.

1.2 EUROfusion and FinnFusion Consortia

During the Horizon Europe framework program, the Euratom Fusion Research program is organised under the EUROfusion Consortium with 29 beneficiaries, practically one per member state. IPP from Germany acts as the co-ordinator of the Consortium. VTT acts as the beneficiary to EUROfusion in Finland. EUROfusion Consortium implements the activities described in the Roadmap to Fusion during Horizon Europe through a Joint programme of the members of the EUROfusion consortium. A 547 M€ grant for the period 2021–2025 forms the basis of Euratom Fusion Research program and its funding.

In order to govern the fusion research activities in Finland, FinnFusion Consortium was established and the consortium agreement signed among the participating research units in November 2014. Towards the European Commission and the EUROfusion Consortium, Ministry of Employment and Economy acts as the program owner. Now within the EUROfusion Consortium, VTT is the beneficiary and therefore acts as the program manager towards the Commission. The universities carrying out fusion research in Finland and Fortum and CSC are acting as Affiliated Entities to the Consortium. The FinnFusion organigram is presented in Figure 1.1.

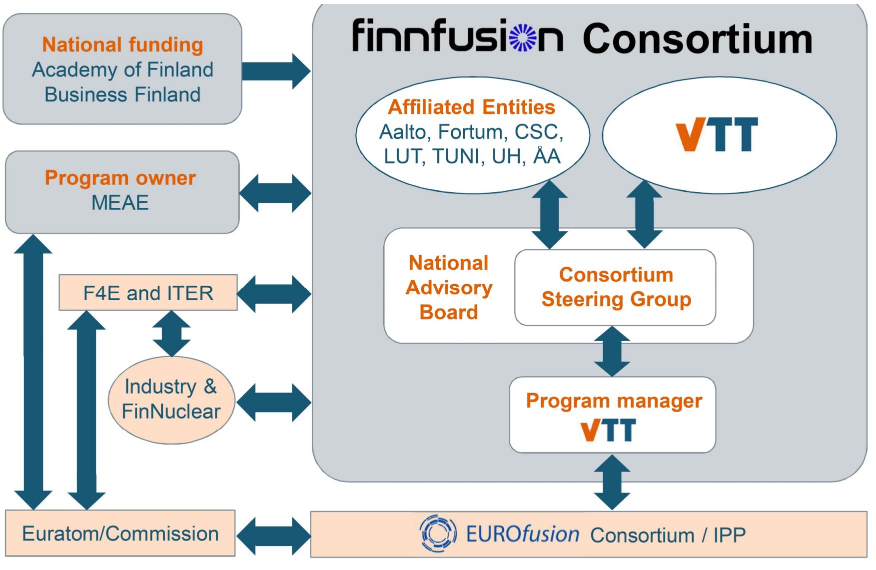


Figure 1.1. Organigram of Finnish Fusion Research Community in 2021–2025.

1.3 Research Unit

The Finnish Research Unit, FinnFusion, consists of several research groups from VTT, universities and industry. The Head of the Research Unit is Prof. Tuomas Tala from VTT. The following institutes and universities participated in 2023:

VTT Technical Research Centre of Finland

Activities: Co-ordination, tokamak physics and engineering
Members: Prof. Tuomas Tala (Head of Research Unit), Dr. Leena Aho-Mantila, Dr. Markus Airila, Dr. Antti Hakola (Project Manager), Dr. Aaro Järvinen, Dr. Juuso Karhunen, MSc. Anu Kirjasuo, Adam Kit, Dr. Jari Likonen, MSc. Tommi Lyytinen, MSc. Sixten Norrman, Ulla Peltonen (administration), Mr. Samuli Saari, Dr. Antti Salmi, Kirsi Selin (administration), Dr. Antti Snicker, Dr. Marton Szogradi, Dr. Konsta Särkimäki

Activities: Silicon photonics and sensor development
Members: Dr. Timo Aalto, MSc. Katherine Bryant, MSc. Mikko Harjanne, Dr. Ari Hokkanen, MSc. Markku Kapulainen, MSc. Dura Shahwar, Dr. Fei Sun, Mr. Ben Wälchli

Activities: Materials modelling
Members: MSc. Jukka Aho, MSc. Timo Avikainen, MSc. Aymara Baumann Duran, Dr. Andris Freimanis, Dr. Sneha Goel, MSc. Aloshious Lambai, Dr. Anssi Laukkanen, MSc. Lassi Linnala, Dr. Sami Majaniemi, Dr. Olli Pakarinen, MSc. Rami Pohja, Dr. Sicong Ren, MSc. Tomi Suhonen

Activities: Hot cell analyses and experimental materials research
Members: MSc. Jouni Alhainen, MSc. Pentti Arffman, MSc. Brahim Dif, Dr. Janne Heikinheimo, Mr. Mika Jokipii, MSc. Petteri Lappalainen, Mrs. Taru Lehtikuusi, Mr. Jussi Leporanta, Mr. Jukka Maunumäki, Dr. Pekka Moilanen, Mrs. Asta Nurmela, Mr. Seppo Peltonen, MSc. Juhani Rantala, Mr. Kimmo Rämö, Mr. Jarmo Saarinen, Mr. Pekka Sinkkonen, Mrs. Madelen Ulfves

Activities: Probabilistic risk assessment
Members: MSc. Atte Helminen, MSc. Essi Immonen, Dr. Tero Tyrväinen, MSc. Kaupo Viitanen

Activities: Nuclear waste assessment
Members: MSc. Daniel Kaartinen, MSc. Tiina Lavonen, Dr. Anumaija Leskinen

Activities: Fire safety
Members: Dr. Tuula Hakkarainen, Dr. Timo Korhonen, MSc. Nikhil Verma

Activities: Ecosystem research

Members: Dr. Tiina Apilo, MSc. Juuli Huuhanmäki, Dr. Jorge Martins, MSc.Tapani Ryynänen, MSc. Jyri Rökman, MSc. Olli Soppela, Dr. Arto Wallin

Activities: Remote maintenance

Members: MSc. Markku Alamäki, MSc. Jarmo Alanen, Dr. William Brace, MSc. Jouko Heikkilä, Mr. Timo Hietavalkama, MSc. Tero Jokinen, MSc. Petri Kaarmila, MSc. Pekka Kilpeläinen, MSc. Petteri Kokkonen, Dr. Marja Liinasuo, MSc. Janne Lyytinen, MSc. Timo Malm, MSc. Hannu Martikainen, MSc. Riku Pennala, MSc. Kari Rainio, MSc. Hannu Saarinen, MSc. Qais Saifi, MSc. Tuisku-Tuuli Salonen, MSc. Janne Sarsama, MSc. Janne Saukkoriipi, MSc. Teemu Sipola, MSc. Mika Siren, Lic.Tech. Mikko Siuko, MSc. Esko Strömmer, MSc. Mikko Tahkola, MSc. Bastian Tammentie, MSc. Antti Tanskanen, MSc. Jussi Tenhunen, MSc. Petri Tikka, Msc. Van Dung Truong, Mr. Miika Uusi-Illikainen, Msc. Tapio Vaarala, MSc.Tero Välisalo, MSc. Arto Ylisaukko-oja, MSc. Akhtar Zeb

Aalto University (AU)
School of Engineering, Department of Mechanical Engineering

Activities: Physics

Members: Dr. Eero Hirvijoki

School of Science, Department of Applied Physics

Activities: Physics

Members: Prof. Mathias Groth (Group Leader), MSc. Francis Albert, Dr. Ray Chandra, MSc. Riccardo Iorio, Dr. Timo Kiviniemi, MSc. Henri Kumpulainen, Dr. Taina Kurki-Suonio, MSc. Roni Mäenpää, MSc. Patrik Ollus, MSc. David Rees, Dr. Lucia Sanchis, Dr. Seppo Sipilä, Dr. Antti Snicker, Dr. Konsta Särkimäki, MSc. Filippo Zonta, Suvi Niemelä (admin. support)

Students: Otso Hyvärinen, Luukas Myllynen, Vesa-Pekka Rikala, Heru Reksoprodjo, Joona Sissonen, Pyry Virtanen

Activities: Materials physics

Members: Sara Bouarich (admin support), Dr. Antoine Clement, MSc. Ludovico Caveglia Curtil, Dr. Tetiana Malykhina, MSc. Nima Fakhrayi Mofrad, Msc. Evgeniia Ponomareva, MSc. Rafael Nuñez, MSc. Iisa Saunamäki, Prof. Andrea Sand (Group Leader)

Students: Students: Akseli Aro, Ilja Stanovohh

CSC IT Center for Science Ltd

Activities: Computation
Members: Dr. Janne Ignatius, Dr. Jan Åström

Lappeenranta-Lahti University of Technology (LUT), Lab. of Intelligent Machines

Activities: Robotics in fusion applications
Members: MSc. Qingfei Han, Prof. Heikki Handroos, Dr. Amin Hekmatmanesh, Dr. Changyang Li, Msc. Dongyi Li, Dr. Ming Li, MSc. Nikola Petikov, Dr. Guodong Qing, Dr. Anna Unt, MSc. Qi Wang, Docent Huapeng Wu (Project manager), Msc.Qiwei Xue, MSc. Zhixing Yao, MSc. Ruochen Yin

Tampere University (TUNI)

Activities: Remote handling, DTP2
Members: Prof. Atanas Gotchev, MSc. Lionel Hulttinen, Prof. Jouni Mattila (Project Manager), MSc. Pauli Mustalahti, MSc. Laura Gonçalves Ribeiro, MSc. Olli Suominen

University of Helsinki (UH)

Activities: Physics, materials (Accelerator Laboratory)
Members: Dr. Tommy Ahlgren, MSc. Pejk Amoroso, MSc. Xudong An, Dr. Jesper Byggmästar, MSc. Zhehao Chen, Prof. Flyura Djurabekova, Dr. Fredric Granberg, Dr. Kalle Heinola, Dr. Pasi Jalkanen, MSc. Faith Kporha, Dr. Antti Kuronen, MSc. Aki Lahtinen, MSc. Victor Lindblad, MSc. Anna Liski, Dr. Eryang Lu, Dr. Ilja Makkonen, Dr. Kenichiro Mizohata, Prof. Kai Nordlund (Project Manager), MSc. Igor Prozheev, Prof. Jyrki Räisänen (Project Manager), Prof. Filip Tuomisto (Project Manager), MSc. Tomi Vuoriheimo, M.Sc. Jintong Wu, Dr. Leonid Zakharov, MSc. Iuliia Zhelezova

Activities: Advanced computing hub (ACH)
Members: Mr. Emil Amnell, MSc. Bruno Cattelan, Dr. Laurent Chôné, Dr. Fredric Granberg, Prof. Keijo Heljanko, MSc. Fran Jurinec, MSc. Oskar Lappi, Prof. Kai Nordlund, Prof. Jukka Nurminen

1.4 FinnFusion Advisory Board

FinnFusion Advisory Board steers the strategy and planning of the national research effort, promotes collaboration and information exchange between research laboratories and industry and sets priorities for the Finnish activities in the EU Fusion Programme. The Board consists of the FinnFusion member parties (Steering Group) and other important Finnish actors in Finnish fusion energy research.

Chair	Janne Ignatius, CSC
Members	Henrik Immonen, Abilitas
	Anssi Paalanen, Business Finland
	Veikko Puumala, Comatec
	Pilvi Ylander, EOS Electro-Optical Systems Finland
	Megumi Asano-Ulmonen, FinNuclear
	Harri Sairiala, Fluiconnecto
	Eero Vesaoja, Fortum
	Arto Timperi, IM Intelligent Machines
	Olli Naukkarinen, Luvata
	Olli Suominen, Operview Oy
	Rahul Nagaraja, QuanScient
	Sami Kiviluoto, Platom
	Juha-Matti Liukkonen, Reaktor
	Anna Kalliomäki, Research Council of Finland
	Mika Korhonen, Suisto Engineering
	Timo Haapalehto, MEAE
	Jarmo Lehtonen, Tevolokomo
	Karoliina Salminen, VTT
FinnFusion	*Mathias Groth, Aalto*
Steering Group	*Janne Ignatius, CSC*
	Eero Vesaoja, Fortum
	Filip Tuomisto, UH
	Heikki Handroos, LUT
	Jouni Mattila, TUNI
	Tommi Nyman, VTT
	Jan Westerholm, ÅA
Co-ordinator	Tuomas Tala, VTT
Secretary	Markus Airila, VTT
	Antti Snicker, VTT

The FinnFusion advisory board had two meetings in 2023, April 20th at VTT Centre for Nuclear Safety, Espoo and December 11th at VTT Centre for Nuclear Safety, Espoo.

1.5 Finnish members in the European Fusion Committees

1.5.1 Euratom Programme Committee, Fusion configuration

- Timo Haapalehto, MEAE

1.5.2 EUROfusion General Assembly

- Tuomas Tala, VTT

1.5.3 EUROfusion Scientific and Technical Advisory Committee

- Kai Nordlund, UH

1.5.4 EUROfusion HPC Allocation Committee

- Andrea Sand, AU

1.5.5 EUROFUSION HPC OPERATIONS COMMITTEE

- Fredric Granberg, UH

1.5.6 EUROfusion Project Boards

- Fusion Technology Department: Leena Aho-Mantila, VTT (Tuomas Tala acting)
- Fusion Science Department: Markus Airila, VTT

1.5.7 Governing Board for the Joint European Undertaking for ITER and the Development of Fusion Energy, "Fusion for Energy" (F4E GB)

- Timo Haapalehto, MEAE
- Tuomas Tala, VTT

1.5.8 Other international duties and Finnish representatives in the following fusion committees and expert groups in 2023

- Markus Airila and Aaro Järvinen are the VTT representatives in EUROfusion Communications Network (FuseCOM).
- Megumi Asano-Ulmonen is an Industrial Liaison Officer (ILO) for F4E.

- Flyura Djurabekova is the secretary of the REI (Radiation Effects in Solids) international committee, member of the ICACS (International Conference on Atomic Collisions in Solids), SHIM (Swift Heavy Ions in Matter) conferences, and PISC (Permanent International Scientific Committee) of ISDEIV (International Symposia on Discharges and Electrical Insulation in Vacuum) as well as one of the key members of the international committee of the Mechanisms of Vacuum Arcs (MeVArc) workshop series.
- Antti Hakola is a member of the programme committee for the EPS Conference on Plasma Physics 2023 and a member of the ITPA expert group on divertor and scrape-off layer.
- Kai Nordlund is a member of the international committee of the COSIRES (Computer Simulation of Radiation Effects in Solids) and IBMM (Ion Beam Modification of Materials) conferences.
- Andrea Sand is a member of the High Scientific Council of the European Nuclear Society, and the Finnish delegate (observer) to the DONES Steering Committee
- Antti Snicker is a member of the ITPA expert group on energetic particles.
- Tuomas Tala is a member of the ITPA expert group on transport and confinement.
- Mathias Groth is a member of the ITPA expert group on divertor and scrape-off layer physics.
- Arto Timperi is a member of the Fusion Industry Innovation Forum Management Board (FIIF MB) and the DEMO stakeholders' group.

2. Fusion Science Workprogramme 2023

2.1 WP AC: Code development for integrated modelling

Research scientists: E. Amnell, B. Cattelan, L. Chôné, F. Granberg, K. Heljanko, F. Jurinec, O. Lappi, I. Maarala, K. Nordlund, J. Nurminen, U. Simola, UH
J. Åström, CSC
A. Järvinen, VTT

In 2023, we continued to work on Bayesian Inference and Optimization, which was successfully used within 2 different codes, and can in practice be easily adopted into new codes. This methodology is a data/CPU-power efficient manner to obtain uncertain parameters. The work on Artificial Intelligence and Machine Learning continued, and was used to predict the defect binding energies. The model was also extended to identify most of the uncertain points, within the workflow, without any extra input from the user. The developed framework is general enough that it can almost directly be used to tackle many other similar problems in materials science. The use of image recognition showed that this method could be used to detect anomalies in the simulation (see Figure 2.1), and the workflow can be extended to automatically terminate simulations once this happens, to notify the user that something went wrong and to save computing power. This technique is also applicable to most plasma (and other) codes, not only the one it was utilized on. Development of best practices for domain composition and load balancing for EIRENE, with the EIRON code, has continued. The model is extended to meet the needs to ultimately serve as the basis for restructuring this huge code. Several codes were optimized during the year, parallelized and/or ported onto GPUs, to make use of HPC and the new pre exa-scale computer clusters, mainly based on GPUs as the main workhorse. Other work during 2023 focused on understanding the needs for Machine Learning data platforms and developing a framework to access the huge amount of data needed for such applications. A framework based solely on open-source applications was developed and successfully deployed at the national supercomputing center, as a proof-of-concept.

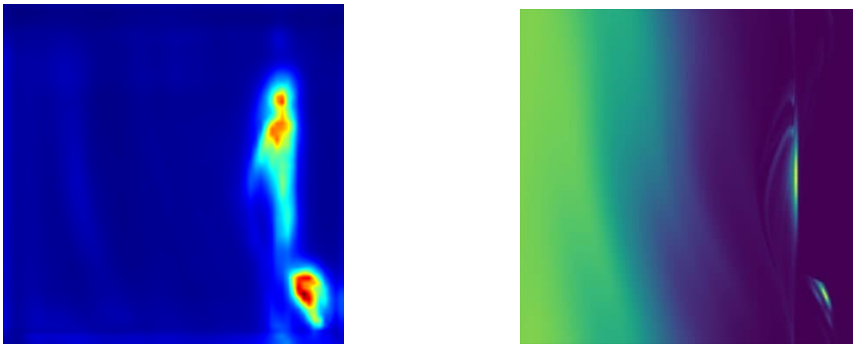


Figure 2.1. Anomaly detection in Gysela. The left figure is the anomaly detection results, which show where the anomaly is happening in warm colours. The right figure is the simulation data, where an anomaly clearly happens on the right side of the figure.

2.2 WP TSVV: Theory-Simulation-Verification-Validation

2.2.1 TSVV Task 4: Plasma Particle/Heat Exhaust: Gyrokinetic/Kinetic Edge Codes

Research scientists: L. Chôné, UH

Development of the full-orbit PIC code SymPiFE is continuing as part of TSVV-4. Significant refactoring of the code was done to improve separation of concerns, allow greater flexibility, and promote memory safety. Miniapps testing isolated features using manufactured solutions have been added to SymPiFE. A Doxygen documentation was also added to the repository.

A checkpointing and restarting feature was added, to save the state of the simulation using HDF5 binary output and allow continuation from such a snapshot. Developments to upgrade the explicit symplectic pusher on a curvilinear orthogonal mesh are ongoing. In addition to 1-3D rectilinear geometries, 2D cylindrical, 3D cylindrical, 3D cylindrical torus, and 3D spherical curvilinear coordinate systems are supported.

Reflecting and absorbing boundary conditions were implemented. See Figure 2.2, which demonstrates the formation of a sheath electric field and sonic ion outflow resulting self-consistently from the absorbing boundary condition.

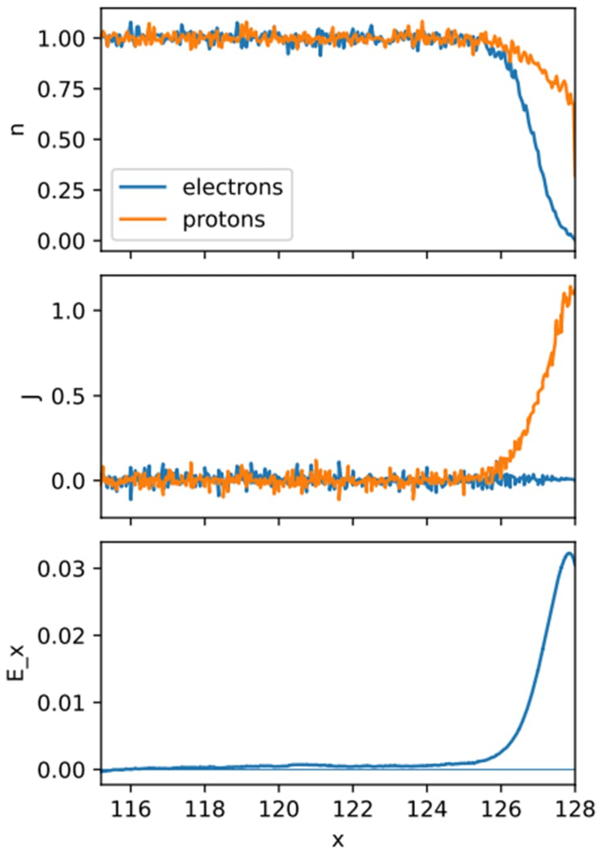


Figure 2.2: 1D1V Vlasov-Ampère simulation demonstrating the implementation of the absorbing boundary condition in SymPiFE and sheath formation. Top: particle density, middle: current, bottom: electric field. Normalised units are used. In particular, J/n corresponds to the normalised flow velocity in units of c_s (sound speed). The outflow of protons is found to be supersonic at the boundary, in accordance with the Bohm criterion.

2.2.2 TSVV Task 5 Neutral Gas Dynamics in the Edge

Research scientists: M. Groth, R. Chandra, AU

The radiation transport model in EIRENE is restored to assess line radiation opacity effects in high-density divertor plasma regimes. Ly-α and Ly-β re-absorption in particular can effectively modify the volume recombination and ionization balance, which in turn affects the required separatrix density to achieve plasma detachment. Radiation trapping in divertor plasmas was studied in the past by extending the EIRENE neutral particle transport code to include line photons as test-particles. We restore this approach in the more modern plasma edge code SOLPS-ITER and investigate opacity effects in high-density divertor plasmas observed in JET as the first application. The sources of the Lyman lines used here, namely the population of excited hydrogen (at n = 2 and 3 for Ly-α and Ly-β emission, respectively), are calculated using a collisional-radiative model within EIRENE. New effective plasma ionization, recombination, and electron energy rates are obtained with photon re-absorption effects included. The re-absorption of Ly-a and Ly-b has a moderate impact on the total ionization rate, up to 20% in detached regimes, as shown in Figure 2.3.

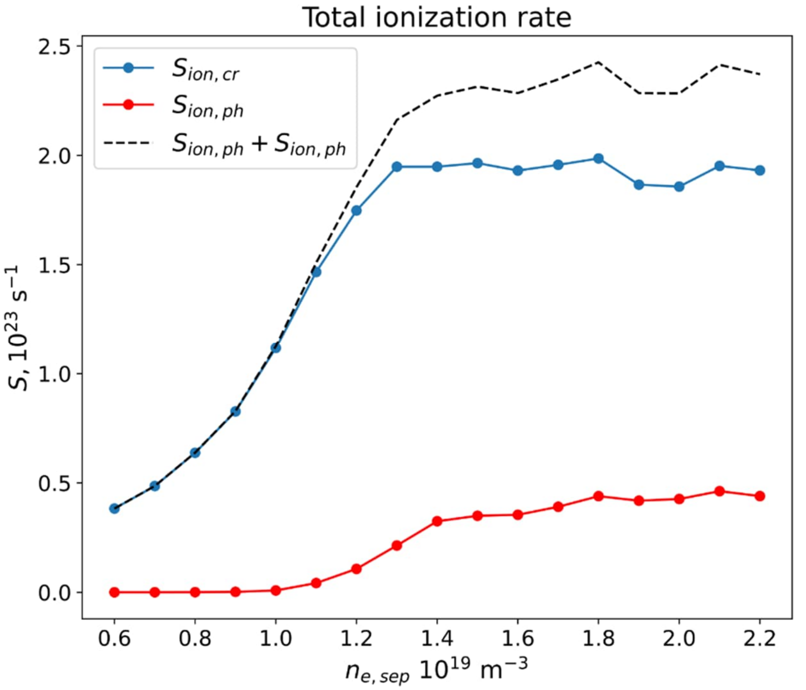


Figure 2.3. Total ionization rate separated by contributions from electron impact from electron impact, $S_{ion,cr}$ (blue), and Ly-a and Ly-b re-absorption, $S_{ion,ph}$ (red). The re-absorption of Ly-a and Ly-b has moderate impact on the total ionization rate at $n_{e,sep} \geq 1.4 \times 10^{19}$ m^{-3} (vertical dashed line).

2.2.3 TSVV Task 6 Impurity Sources, Transport, and Screening

Research scientists: M. Groth, H. Kumpulainen, R. Mäenpää, AU

A novel simulation workflow utilizing ERO2.0 and JINTRAC was developed and validated for improved prediction accuracy of W erosion and transport in the edge and core plasma. The predicted W density profiles in all studied L-mode and ELM H-mode scenarios reproduce the experiment within a factor of 2 to 3, consistent with the estimated modelling uncertainty.

Carefully adjusting the plasma conditions to measurements is critical to the W prediction accuracy. To predict the W density in unexplored plasma scenarios or future devices without available plasma measurements, accurate and reliable predictive capabilities of the plasma conditions are also necessary. With a sufficiently valid treatment of W erosion and transport, the main limiting factors for W prediction accuracy are measurement and/or modelling uncertainties of the background plasma, as opposed to simplifications in the transport model.

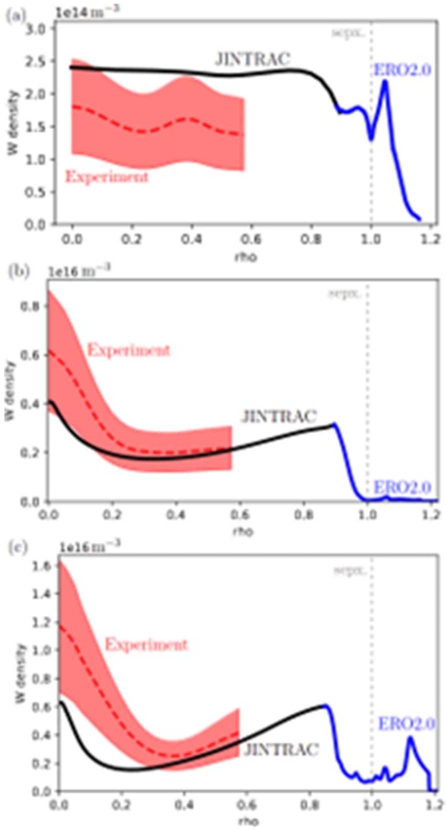


Figure 2.4. ELM- and flux-surface-averaged W density profiles predicted by ERO2.0 (blue lines) and JINTRAC (black lines) compared to the experimentally inferred W density (red dashed lines with red shaded confidence intervals) as a function of the normalised minor radius in JET a) L-mode #81472 at 9 s, b) ELMy H-mode #94606 at 10 s, and c) hybrid ELMy H-mode #97781 at 9 s.

2.2.4 TSVV Task 7 Plasma-Wall Interaction in DEMO

Research scientists: T. Ahlgren, J. Byggmästar, F. Granberg, F. Kporha, A. Kuronen, K. Nordlund, UH

The work carried out in 2023 was focused on how deuterium is affecting the sputtering of tungsten surfaces. It is known that deuterium will be implanted in the wall material and also decorate or supersaturate the surfaces, however, its effect on sputtering is still not well understood. We have carried out simulations utilizing several interatomic potentials, energies, incoming angles, deuterium decoration level, and surface orientations for argon sputtering. The results show many consistent trends between the two potentials and with previous work, where possible to compare. All of these results can be used in large-scale models to account accurately how incoming ions will sputter tungsten and also the deuterium decorating the surface. There was, however, one significant difference between the used potentials, and that was how tungsten sputtering is affected by deuterium decoration level. The deuterium sputtering was similar in both potentials. In one of the used potentials the deuterium reduced tungsten sputtering whereas in the other deuterium increase the tungsten sputtering. By deep analysis we found that there is a difference in how the potentials are predicting the binding energies for the W-D bond, and how a nearby deuterium atom is affecting the W-W bonds at the surface. This difference led to a difference in the seen trend.

2.2.5 TSVV Task 12 Stellarator optimization

Research scientists: S. Äkäslompolo, AU

ASCOT5 IMASifying is progressing with new supported input IDS added, and work on the first output IDSs has commenced. ASCOT5 is effectively a python code with a C-library. The default wrappers do not support python actors and thus a manually implemented iWrap/MUSCLE3 conforming wrapper is being tested in collaboration with ACH. MUSCLE 3 wrapper will allow coupling ASCOT5 to the several integrated workflows also beyond TSVV-12 (like HFPS and ETS). ASCOT5 was also open sourced and an EUROfusion ASCOT5 code camp was organized to increase the user base.

In 2023, the latest version of ASCOT5 was freshly ported to GPUs with major support from ACH. This time, an "event-based" approach was used, which yields high performance on GPUs in all the benchmarks performed so far. Only a subset of ASCOT5 features have been ported, however further features are currently being ported.

2.3 WP ENR: Enabling Research

FinnFusion participated in six Enabling Research projects in 2023:

- ENR-MAT.01.JSI: Detection of defects and hydrogen by ion beam analysis in channelling mode for fusion
- ENR-MAT.01.VR: Electronic interactions of slow ions and their influence on defect formation & sputter yields for plasma-facing components
- ENR-MOD.01.FZJ: Development of machine learning methods and integration of surrogate model predictor schemes for plasma-exhaust and PWI in fusion / Development of machine learning algorithms for data-driven pedestal models
- ENR-TEC.01.MPG: Novel methods for fast-ion tomographic reconstructions: Fast-ion tomography in 5D
- ENR-TEC.04.VTT: Silicon photonics steady state magnetic field sensor

2.3.1 Detection of defects and hydrogen by ion-beam analysis in channelling mode for fusion

Research scientists: T. Ahlgren, F. Djurabekova, X. Jin, I. Makkonen, K. Mizohata, F. Tuomisto, UH

In this project, we compared simulations and experiments of Rutherford backscattering spectrometry in channeling mode (RBS/c) to analyze radiation defects in tungsten samples with low (0.02 dpa) and high (0.2 dpa) damage doses. Simulated RBS/c signals were generated from realistic atomic structures, in which radiation defects were created by overlapping collision cascades using molecular dynamic (MD) simulations. Figure 2.5 a shows an example of comparison of experimental (dots) and simulated (lines) RBS/c spectra for 3 MeV probe He ions on <111>-oriented W samples. An excellent agreement for the case of low damage level indicates that nature of defects, namely dislocation loops of various shape, predicted by MD simulations is very similar to those developed in experimental samples. The discrepancies for the high damage case are explained by greater difference in nature of dominant defects in both samples.

We developed a simulation program for generating signals of nuclear reaction analysis in channeling mode (NRA/c) from arbitrary atomic structures. We proposed a methodology to predict how deuterium atoms are trapped in tungsten, based on angular scans of NRA/c which are sensitive to deuterium locations in different lattice positions. We demonstrated that this methodology can be used to predict the filling level of deuterium atoms in mono-vacancies, and to predict if there are other impurity atoms, such as, helium atoms, in a mono-vacancy. Figure 2.5 b shows comparison of simulated (lines) RBS/c and NRA/c angular scans to experiments, in which tungsten samples were implanted with 30 keV deuterium atoms.

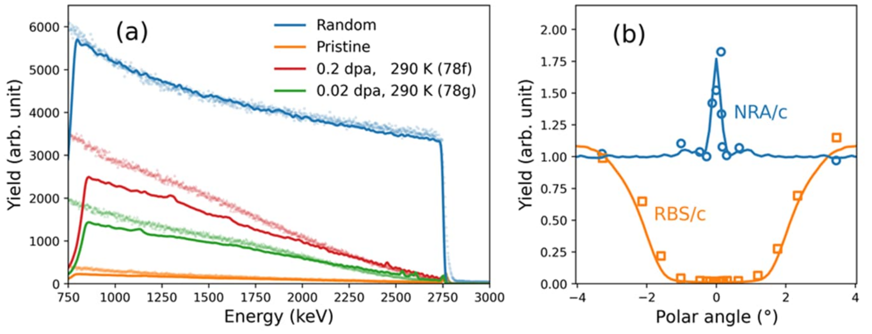


Figure 2.5: Analysis of radiation defects and trapping of deuterium in tungsten by ion channeling methods: (a) Simulated (lines) and experimental (dots) RBS/c spectra generated by using 3 MeV He ions on <111>-oriented tungsten samples and (b) Simulated (lines) and experimental (dots) RBS/c and NRA/c angular scans through the <001> axis of tungsten samples containing deuterium atoms.

2.3.2 Electronic interactions of slow ions and their influence on defect formation & sputter yields for plasma-facing components

Research scientists: L. Caveglia Curtil, E. Ponomareva, A. Aro, T. Malykhina, A. Sand, AU

Together with researchers from Uppsala University and TU Wien, we have investigated the energy deposition of slow light ions traveling through Fe and W, and the impact of these effects on predictions of sputtering yields. To develop a model of local electronic energy losses that can be implemented in large-scale molecular dynamics (MD) simulations, we have carried out real-time time-dependent density functional theory (rt-TDDFT) calculations of electronic stopping for both channeling, off-channeling and random trajectories. Energy losses were found to be substantially higher for trajectories that pass close to the cores of atoms, as compared to channeling trajectories (see Figure 2.6). These results indicate that the single value for the electronic stopping power used in current state-of-the-art MD simulations may be inadequate to capture the effects of energy losses in specific local geometries.

We calculated sputtering yields of light ions on Fe and W with MD simulations for several different surface orientations, finding a clear dependence of the crystal orientation. Experimentally, a minimum in the sputtering yield was observed for 30 degrees incidence angle by our collaborators at TU Wien. Our modelling results demonstrated that stronger channeling occurs at 30 degrees incidence angle if (and only if) the irradiated (bcc) surface has a <011> crystal orientation, which turned out to be in good agreement with the results of EBSD maps of the experimental samples, which showed a strongly <011>-dominated surface structure. We are now developing a dissipation model based on our TDDFT data to be incorporated into MD simulations.

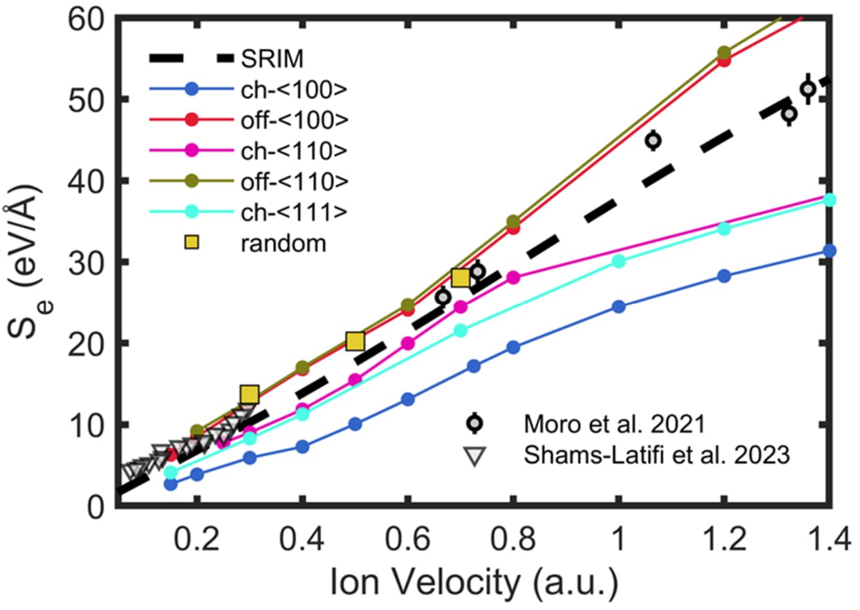


Figure 2.6: Electronic stopping of helium ions in tungsten computed with rt-TDDFT for different trajectories, compared to experimental measurements and the prediction from SRIM.

2.3.3 Development of machine learning methods and integration of surrogate model predictor schemes for plasma-exhaust and PWI in fusion / Development of machine learning algorithms for data-driven pedestal models

Research scientists: A. Kit, UH
A.E. Järvinen, VTT

In 2023, the focus on this work has been on state representation learning (SRL) algorithm applications for JET and AUG electron density and temperature plasma profiles. An SRL algorithm aims to learn a low-dimensional representation that evolves in time and is influenced by actions of an agent. These types of algorithms were investigated for predicting the dynamical evolution of ASDEX Upgrade plasma profiles, given a machine parameter control sequence. By training a representation learning model, based on Variational Autoencoders (VAE), together with a forward model that evolves the latent representation in time, the algorithm learns to qualitatively predict dynamical evolution of standard AUG scenarios (see Figure 2.7). However, since the model does not consider differences in various heating sources or impurity contamination of the plasmas, the model does not yet accurately predict all scenario trajectories, such as impurity accumulation events.

Another study investigated the capability of these models to learn features that are independent or scale with the device size. When training a VAE-based representation learning model for a database of JET and AUG pedestal profiles and attaching an auxiliary regression objective for machine control parameters and device size, the algorithm clearly encodes a Greenwald like density scaling in the latent representation. It was observed that allocating a dedicated latent space for the device size scaling was necessary to avoid the device size scaling information becoming entangled with information related to changes of the machine control parameters.

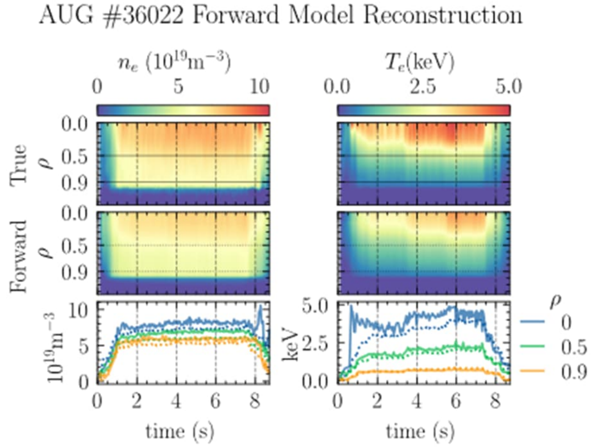


Figure 2.7: Observed and predicted time evolution of electron density and temperature profiles in an ASDEX Upgrade plasma.

2.3.4 Novel methods for fast-ion tomographic reconstructions: Fast-ion tomography in 5D

Research scientists: A. Snicker, VTT

Measuring fast ions fusion reactor relevant plasmas is challenging due to limited amount of diagnostic coverage and large phase-space volume that fast ions cover. To this end, tomographic reconstruction schemes are developed to combine the individual diagnostic data to infer the most likely fast ion distribution function that results in these measurements. While developing such models, a prior information has a pivotal role as typical scenario is a lack of enough measurement data. To this end, ASCOT simulations have been used to form a set of slowing-down functions that are used as expansion functions for the tomographic reconstruction. In particular, large number of ASCOT simulations have been carried out for JET tokamak slicing the active beam line into cylinders along the beam path to form a set of expansion functions. This work will continue in 2024, under a new ENR project with even more emphasis on the ASCOT calculations.

2.3.5 Silicon photonics steady state magnetic field sensor

Research scientists: A. Salmi, T. Aalto, K. Bryant, S. Dura, A. Hokkanen, M. Kapulainen, C. Matteo, F. Sun, T. Tala, B. Wälchli, VTT
T. Jensen, M. Jessen, S. Kragh Nielsen, J. Rasmussen, DTU

Our research on the Faraday effect in silicon-on-insulator (SOI) based waveguides has uncovered significant challenges in developing a sensitive magnetic field sensor using this technology. These challenges include 3D manufacturing tolerances, temperature control, purity in light coupling, and strong dispersion of birefringence in 3 µm silicon waveguides. Instead of the planned sensor integration with optimised components we needed take a step back and focus on a detailed understanding of birefringence properties. We designed and manufactured two types of complementary test structures: arrayed waveguide gratings (AWG) of variable widths and folded waveguide series of variable widths. These were essential for accurately gauging effective index birefringence.

We then compared these measurements together with group index measurements obtained using simpler, conventional methods like Fixed Analyser and Fabry-Perot techniques (no need for special test structures for measurement) against COMSOL simulations. The simulations were crucial in enhancing our understanding of both geometrical and stress-induced birefringence effects within the waveguides.

To ensure realistic birefringence calculations, we carefully accounted for the cross-sectional geometry and assessed the stresses in the waveguide, the cladding, and the buried oxide. This assessment included bow measurements and computations of room temperature thermal stresses in the waveguide via simulating the cooling from the fabrication process temperature (approximately 900°C).

The simulations closely aligned with our experimental data (see Figure 2.8), increasing our confidence in both the measurements and the modelling. While these results represent a modest step towards realizing the planned sensor, they provide new insights into the effective index birefringence of 3 µm SOI waveguides and will be published in the Journal of Lightwave Technology. Although the ENR project has concluded, it may still benefit from progress made in related ongoing research projects at VTT and further advancements in SOI technologies.

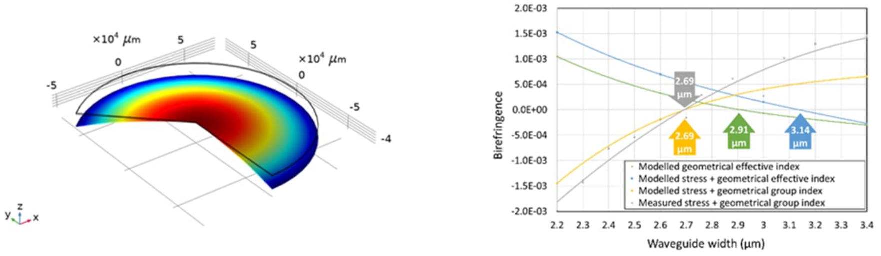


Figure 2.8 (left) COMSOL modelling of the wafer bow measurement for BOX stress evaluation. (right) COMSOL modelling of effective index and group index birefringence versus Fabry-Perot measurement showing good agreement.

2.4 WP PWIE: Preparation of efficient PFC operation for ITER and DEMO

2.4.1 Overview

The 2023 scientific programme of WPPWIE continued promoting the same key research topics that have been on the agenda since the advent of the present EUROfusion structure in 2021, namely erosion, deposition, fuel retention, and surface modifications of plasma-facing components (PFCs). A completely new activity was the design and development of a LIBS (Laser-Induced Breakdown Spectroscopy) system for studying the tritium inventories on the inner wall structures of JET in its decommissioning phase, as part of a large European Consortium. Special emphasis was paid on surface analyses of tokamak (JET, ASDEX Upgrade (AUG), WEST), stellarator (W7-X), and laboratory samples, numerical modelling of different plasma-wall-interaction and scrape-off-layer (SOL) phenomena based on experiments carried out on AUG and JET, and assessing retention and erosion characteristics of Be- and W-based plasma-facing components.

2.4.2 Plasma-edge and plasma-wall interaction modelling

Research scientists: M. Groth, H. Kumpulainen, R. Mäenpää, AU

JET-ILW H, D, T, and 40%-60% D-T L-mode plasmas showed that the onset of detachment was achieved at approximately the same electron density across the edge of the core plasma. Furthermore, the density limit was observed 30% lower in T than in H plasmas. The onset of detachment was achieved when the electron temperature at the low-field side plate reached 2 eV. Both the electron density and pressure peaked when the electron temperature reached 0.7-1.0 eV. Upon further increasing the edge density, the peak electron density and pressure at the plate decreased uniformly across the divertor plate, and the peak regions moved off the target plate toward the low-field side divertor X-point in nearly bifurcated fashion. The onset of detachment below 2 eV correlates with the increase in the molecular and atomic densities, and the related plasma-molecule and plasma atom interaction. The formation of the high-density/pressure region in the low-field side divertor was observed to be independent of the molecular gas pressure in the sub-divertor, and thus the fuelling and pumping rates of the experimental setup. Hence, plasma recycling at the divertor and main chamber determined the scrape-off layer and core plasma conditions, refuting the hypothesis proposed that the lower conductance and gas flows of T versus H and D molecules through the pumping slots in the JET divertor lead to the observed difference in the divertor conditions. For partially detached divertor plasma conditions these studies showed, statistically significant, 30% stronger broadening of the SOL electron density at the LFS midplane and a factor of 2 stronger reduction of the ion current to the LFS target plate for T versus H plasmas. For both attached and detached conditions, 30-50% higher electron densities in the LFS divertor were observed for T than for H plasmas.

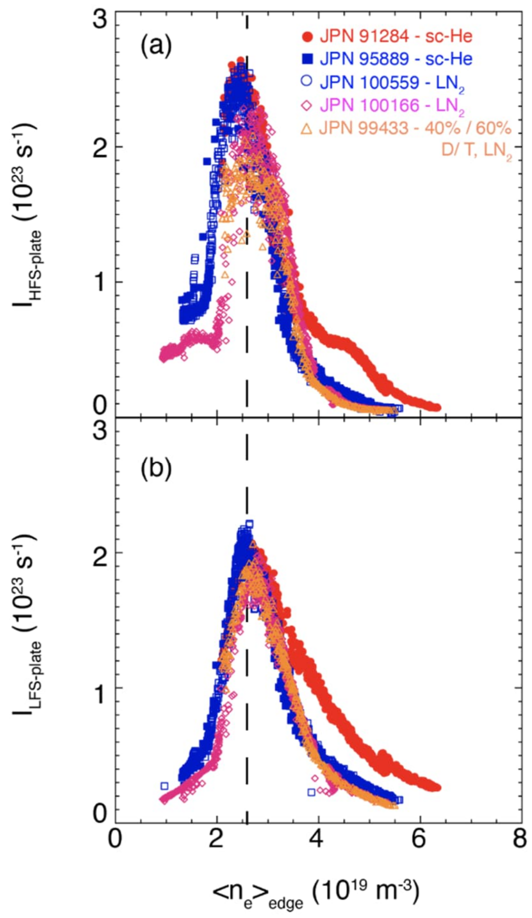


Figure. 2.9 Total ion current to the HFS (a) and LFS (b) target plate as function of line-averaged density at the LFS edge of the core plasma for protium (red, JPN 91284), deuterium (blue, JPNs 95889 and 100559), tritium (magenta, JPN 100166) and deuterium-tritium (gold, JPN 99433). Discharges with the divertor cryogenic pump at sc-He and LN2 are indicated by the solid and open symbols, respectively. The black dashed vertical line indicates the assumed detachment onset density.

2.4.3 PWI with Be, T and neutrons: focus on JET analysis and its interpretation

Research scientists: T. Ahlgren, K. Mizohata, F. Tuomisto, T. Vuoriheimo, UH
A. Hakola, J. Likonen, VTT

The main aim in 2023 was to continue erosion/deposition and fuel retention studies on divertor, wall tiles and in-vessel erosion-deposition probes (EDP) exposed either in 2013-2016 or in 2011-2016, and removed during the 2016-2017 shutdown. In addition, comparison with individual campaigns will be made to confirm linear/non-linear erosion/deposition. VTT used Secondary Ion Mass Spectrometry (SIMS), Time of Flight Elastic Recoil Detection Analysis (TOF-ERDA) and Thermal Desorption Spectrometry (TDS) for the analysis of divertor and wall components.

During the shutdown in 2009–2011, all the carbon-based plasma facing components (PFC) were replaced with the ITER-like wall (JET-ILW). The divertor tiles of JET-ILW are made of tungsten-coated carbon fibre composites (CFC), except the load bearing tiles at the divertor base, which are made of solid tungsten. For each of the three JET ILW campaigns a few special marker tiles have been placed in the divertor. Amongst the W-coated CFC tiles are tiles coated with a ~ 3 μm layer of Mo with a ~ 4 μm topcoat of W to monitor W erosion and tiles with just a ~ 4 μm layer of Mo. Limiters in the main chamber are manufactured from solid beryllium. JET has now completed three operating periods, ILW-1 (2011-2012), ILW-2 (2013-2014) and ILW-3 (2015-2016), giving an opportunity to make comparisons between tiles exposed for different operating periods.

In addition to fuel retention studies, transport to and from one of the Mo only markers (tile 14ING3B - a tile3 from the lower part of the inner divertor wall) to tile 14BNG4D (an innermost base tile4 with a standard Mo + W marker) has been extensively studied using SIMS and TOF-ERDA. Metallic elements are principally eroded by incident plasma ions as atoms or ions and most probably return to the surface a short distance further in the plasma field line direction where they may be eroded again: migration may thus occur by a series of “hops ”. During the first ILW campaign ILW1 one Mo-only marker tile was installed – a Tile 3 from the lower part of the inner divertor wall which was removed during the subsequent shutdown. This facilitated detection of W from surrounding tiles onto this tile and of Mo migration onto other tiles in the divertor, specifically to Tiles 14BNG4D and 2BNG4C (innermost base Tiles 4 with standard Mo + W markers) which were also removed for extensive study. About 7% of the Mo removed from the Tile 3 Mo marker was found on band 4 tiles, with almost identical amounts on tiles on opposite sides of the torus (see Figure 2.10). The majority of the Mo would have been re-deposited on other (W-coated) Tiles 3, and significant W was re-deposited on the Mo marker from the surrounding tiles, with a poloidal deposition pattern similar to the Mo erosion.

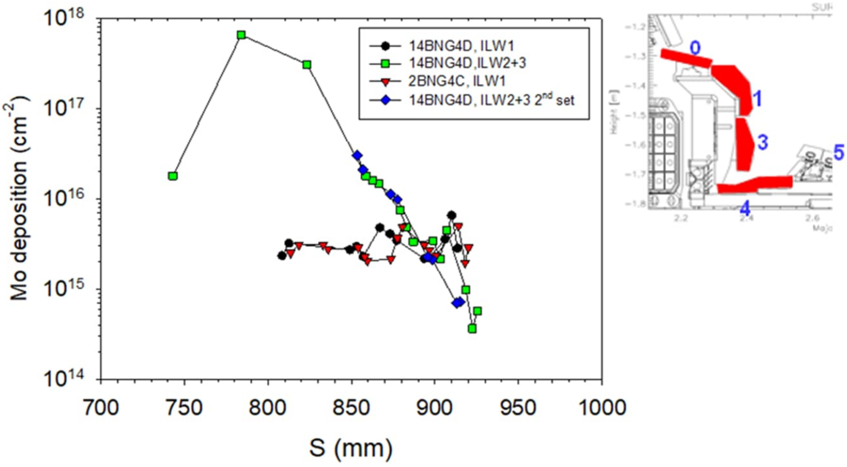


Figure 2.10. Amounts of Mo deposition measured by SIMS on Tile 4.

2.4.4 Development of LIBS for studying tritium inventories on JET PFCs

Research scientists: A. Hakola, J. Karhunen, J. Likonen, VTT

LIBS is one of the few techniques available for monitoring the tritium content of co-deposited layers during the maintenance breaks of fusion reactors. At VTT, together with collaborators from Italy, Estonia, Slovakia, Poland, Latvia, and the UK, we have developed LIBS to accurately assess the amount of deuterium and tritium on PFCs removed from JET. Based on this experience, we have designed a compact LIBS system for surveying the inner wall structures of JET, see Figure 2.11. The system will be mounted on the MASCOT remote-handling arm of JET and operated for a limited period in 2024 to obtain information on tritium retention in various parts of the vessel. In 2023, the design was completed and all the key components for the JET system were ordered such that the commissioning could take place in early 2024.

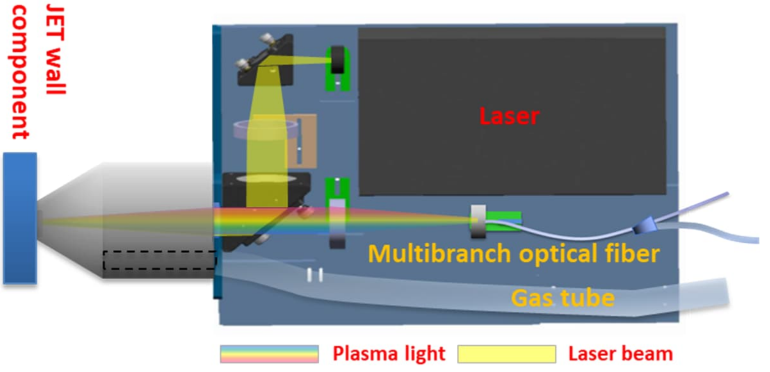


Figure 2.11. Schematic illustration of the LIBS system designed for JET. The system will be mounted on MASCOT to access different regions of the vessel.

2.4.5 Retention of plasma fuel in laboratory-made beryllium coatings

Research scientists: A. Hakola, J. Likonen, VTT

In 2023, the results collected from a variety of beryllium test samples over the last couple of years were put together to elucidate the role of different physical parameters in the retention process of plasma fuel (here D). Increasing surface temperature will drastically reduce retention while inclusion of sufficiently large amount of He and/or Ne in the deposit will enhance fuel accumulation; details can be consulted in Figure 2.12. These can be attributed to strong lattice modifications and alteration of defect concentrations in the layers, while growing temperature will also efficiently release stresses formed during the deposition phase. The composition of the reference layers is similar to those measured for JET co-deposits and annealing of the layers at constant temperatures will even make their structure closer to the experimental observations. In the future, the results will be generalized to the selected first-wall structures of ITER.

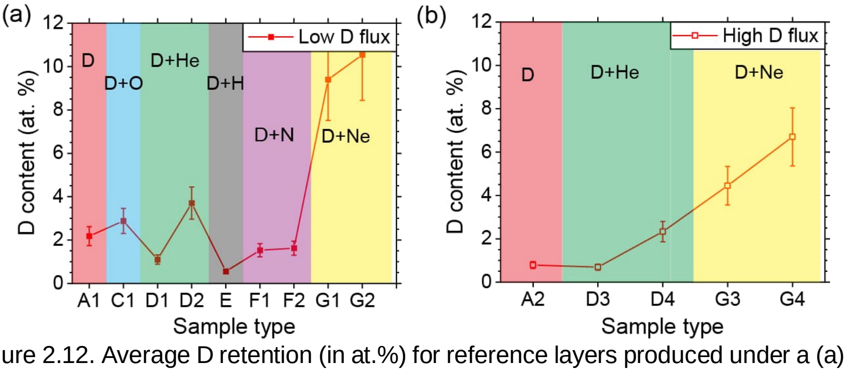


Figure 2.12. Average D retention (in at.%) for reference layers produced under a (a)

low and (b) high D flux during the deposition and in the presence of varying impurity gases.

2.5 WP SA-SE.CM. Scientific Exploitation - Code Management, Analysis tools and Simulation in support to JT-60SA experiments

Research scientists: S. Sipilä, A. Snicker, AU

ASCOT4 code development, management and support has been continued in 2023 under IMAS with an emphasis on making ASCOT4-RFOF, capable of modelling fast ion distributions in the presence of ICRH, available as an IMAS actor using available wave data from CYRANO. The work is ongoing. ASCOT4-RFOF will eventually be used in, e.g., the energetic particle (EP) stability workflow to study the stability of fast-ion driven modes in JT60-SA.

2.6 WP TE: Tokamak exploitation campaigns

2.6.1 Overview

Within the WPTE Task Force, work was performed on four devices in 2023: JET, TCV, MAST-U, and WEST. On JET, the main highlights were executing the third DT campaign (DTE3) in September-October 2023 as well as fully commissioning and exploiting two key systems foreseen to be used in ITER: a LID-QMS (Laser-Induced Desorption, Quadrupole Mass Spectrometry) diagnostics for monitoring the tritium content on selected wall components and an upgraded SPI (Shattered Pellet Injection) setup for efficient disruption control. The JET operations came to their end in 18 December 2023, when the final plasma discharge ever was performed, with the target set to develop a negative-triangularity scenario. On WEST, for its part, a large fraction of the experimental time was dedicated to a high-fluence campaign where overall ~450 discharges were run cumulating up to ~3 hours of plasma time while keeping all the discharge parameters fixed. The areas where the Finnish contribution was the most noticeable were modelling of fast ions using the ASCOT code (TCV and MAST-U), investigating particle and momentum transport (JET, TCV, and MAST-U), and studying detachment characteristics of the plasmas (JET).

2.6.2 Helium campaigns on AUG and JET

Research scientists: A. Hakola, J. Karhunen, A. Kirjasuo, J. Likonen, A. Salmi, T. Tala, VTT
F. Albert Devasagayam, M. Groth, S. Leerink, D. Rees, AU

The results obtained from the 2022 helium campaigns on AUG and JET were summarized and reported in the IAEA Fusion Energy Conference in London in October 2023. The campaigns aimed at providing ITER with feedback if their initial plasma experiments should be performed in hydrogen or helium – or even directly switch to deuterium. For this reason, the AUG and JET helium campaigns put particular emphasis on obtaining ELMy H-mode operation and detailed investigations of plasma-wall interaction processes as well as comparison to H or D plasmas. Both in pure He and mixed He+H plasmas, H-mode operation could be reached but more effort was needed to obtain a stable plasma scenario than in H or D, see Figure 2.13 for details. Suppression of ELMs by resonant magnetic perturbations was studied on AUG but was only possible in plasmas with a He content below 19%; the reason for this unexpected behaviour remains still unclear and various theoretical approaches are being pursued to properly understand the physics behind ELM suppression. Concerning plasma detachment, recycling at the divertor was smaller in He than in D and higher densities were needed for the onset of detachment. This was attributed to the lack of molecular channels to assist detachment in He plasmas. In the field of plasma-wall interactions, the erosion rates of tungsten (W) plasma-facing components (PFCs) were an order of magnitude larger than what has been reported in hydrogenic plasmas, potentially because of the prominent role of He^{2+} ions in the plasma. In addition, for the first time, the formation of nanoscale structures (W fuzz) was unambiguously demonstrated in H-mode He plasmas on AUG. However, no direct evidence of fuzz creation on JET was obtained despite the main conditions for its occurrence being met. The reason could be a delicate balance between W erosion by ELMs, competition between the growth and annealing of the fuzz, and coverage of the surface with co-deposits. Finally, reaching the desired purity of He plasmas was noticed to be relatively straightforward whereas subsequent H or D campaigns after the He one required special cleaning efforts and engineering solutions to ensure efficient pumping of the released compounds.

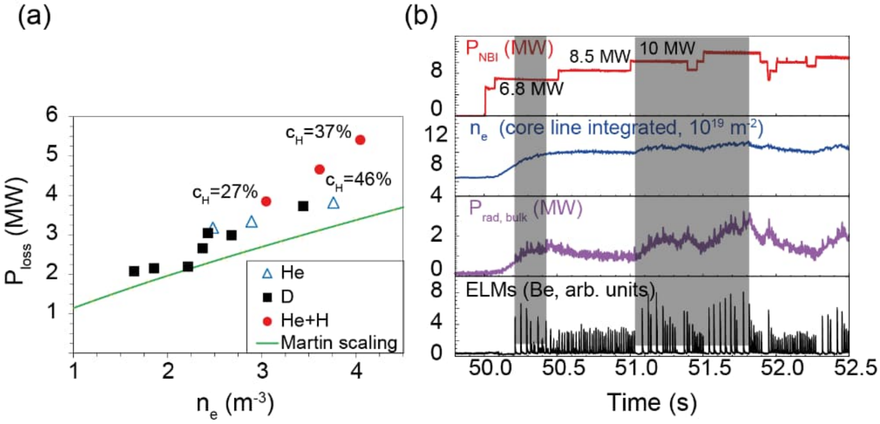


Figure 2.13. (a) Threshold power for the LH transition as a function of line-averaged

density in selected plasmas at JET together with the theoretical prediction (Martin scaling). The H concentrations of the mixed H+He plasmas are marked in the plot next to the corresponding red circles. (b) Examples of time traces for the heating power, line-integrated density, bulk radiation, and ELM activity (in terms of Be emission) for the JET pulse 101445 (1.3 MA/1.3 T). Type-I ELM activity is denoted by gray rectangles, and stable type-I ELMs are obtained above 10 MW (>51 s).

2.6.3 Isotope mass scaling between D and T in JET plasmas

Research scientists: A.E. Järvinen, A. Kirjasuo, A. Salmi, T. Tala, VTT
Francis Devasagayam, AU

The results obtained from the 2021 JET DT campaign on isotope scaling in L-mode plasmas were summarized and reported in the IAEA Fusion Energy Conference in London in October 2023 and in the Nuclear Fusion Special Issue on JET DT campaign. The dimensionless isotope mass scaling experiment between pure Deuterium and pure Tritium plasmas with matched ρ^*, ν^*, β_n, q and T_e/T_i has been achieved in JET L-mode with dominant electron heating (NBI+ohmic) conditions. 28% higher scaled energy confinement time $B_t\tau_{E,th}/A$ is found in favour of the Tritium plasma. This can be cast in the form of the dimensionless energy confinement scaling law as $\Omega_i\tau_{E,th} \sim A^{0.48\pm0.16}$. This significant isotope mass scaling is consequently seen in the scaled one-fluid heat diffusion coefficient $A\chi_{eff}/B_t$ which is around 50% lower in the Tritium plasma throughout the whole plasma radius. The isotope mass dependence in the particle transport channel is negligible, supported also by the perturbative particle transport analysis with gas puff modulation. The comparison of the edge particle fuelling or ionisation profiles from the EDGE2D-EIRENE simulations show that the absolute density differences that are necessary for the dimensionless match in the confined plasma dominate over any isotope mass dependencies of particle fuelling and ionization profiles t the plasma edge. Local GENE simulation results indicate a mild anti-gyroBohm effect at $\rho_{tor} = 0.6$ and thereby a small isotope mass dependence in favour of Tritium on heat transport and a negligible effect on particle transport. A significant fraction of the isotope scaling and reduced heat transport observed in the Tritium plasma is not captured in the GENE and ASTRA-TGLFSAT2 simulations by simply changing the isotope mass for the same input profiles.

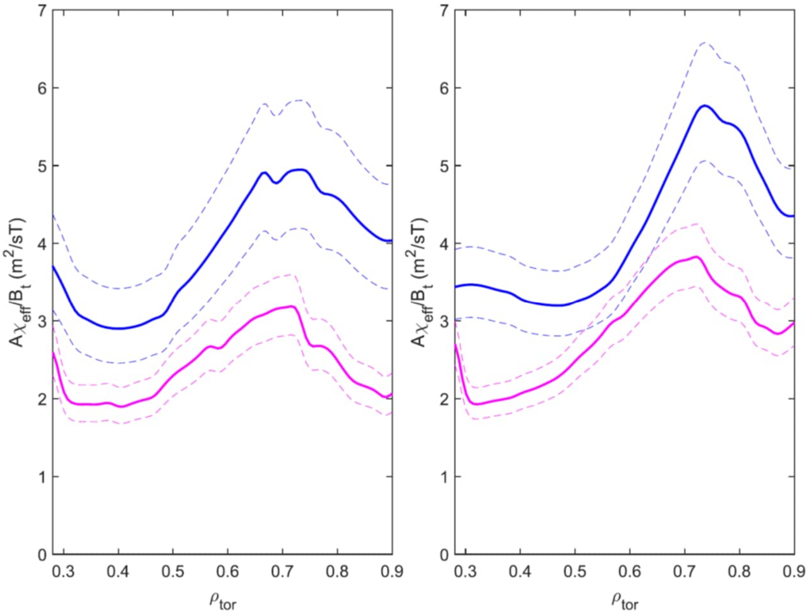


Figure 2.14: Scaled one-fluid effective diffusion coefficients for the Deuterium ischarge (blue) and the Tritium discharge (magenta) at two different NBI power levels, P_{nbi} = 0.8/1.4 MW (left panel) and P_{nbi} = 1.8/3.4 MW (right panel), with the larger NBI power level referring to the Tritium pulse and smaller one to the Deuterium pulse. The dashed lines indicate the error bars.

2.6.4 Addressing the impact of Lyman opacity in inference of divertor plasma conditions with 2D spectroscopic camera analysis of Balmer emission during detachment in JET L-mode plasmas

Research scientists: J. Karhunen, VTT

The impact of re-absorption of the deuterium Lyman series emission was addressed in a previously presented experimental method for inferring divertor plasma conditions from Balmer series emission with 2D spectroscopic camera analysis during detachment in JET L-mode plasmas. The methodology was amended by modifying the standard photon emission coefficients and ionization/recombination rate coefficients of the ADAS database to consider the re-population of excited states due to Lyman opacity. Consequently, the accuracy of the analysis was found to improve, particularly for estimating the atomic divertor density at the onset of detachment, as confirmed by synthetic analysis based on EDGE2D-EIRENE simulations.

2.6.5 Impact of charge exchange on beam-ion confinement in MAST Upgrade

Research scientists: P. Ollus, AU

Due to its compact size and weak outboard magnetic field, the spherical tokamak MAST Upgrade is susceptible to losses of fast ions due to charge-exchange reactions with edge neutrals. The fast-ion orbit-following code ASCOT was used to investigate the impact of charge exchange on beam-ion confinement. As experimental evidence of beam-ion losses, measurements of FIDA light, neutron emission and more have been analyzed. Direct measurements do suggest charge-exchange losses of beam ions. However, the presence of other effects, e.g. magnetohydrodynamic instabilities, makes it difficult to isolate the impact of charge exchange. Detailed analysis of fast charge-exchange neutrals hitting the bolometer diagnostic is underway using ASCOT, with the aim of quantifying beam-ion charge-exchange losses. The neutral density is reconstructed based on measurements of the neutral-gas pressure.

2.6.6 Particle transport and sources in perturbation experiment (JET)

Research scientists: A. Kirjasuo, A. Salmi, T. Tala, VTT

Gas puff modulation data from JET isotope experiments (D-T) were analyzed with an optimization scheme where time evolving electron density were matched against experimental measurements. This required accurate density profiles across the whole radius with high time resolution to ensure good statistics and thus small error bars. Thanks to the advances in the profile reflectometry diagnostics this data was available. Additionally, to limit the amount of freedom in the fitting procedure we utilized Da constrained EDGE2D-EIRENE simulations to estimate the flux surface averaged absolute ionization source rate, and electron temperature measurements to estimate the time evolution of the transport. With these constraints the fitting yielded transport coefficients that simultaneously reproduced both the steady state density and its time evolving perturbation. The resulting transport coefficients from the fitting are shown in Figure 2.15.

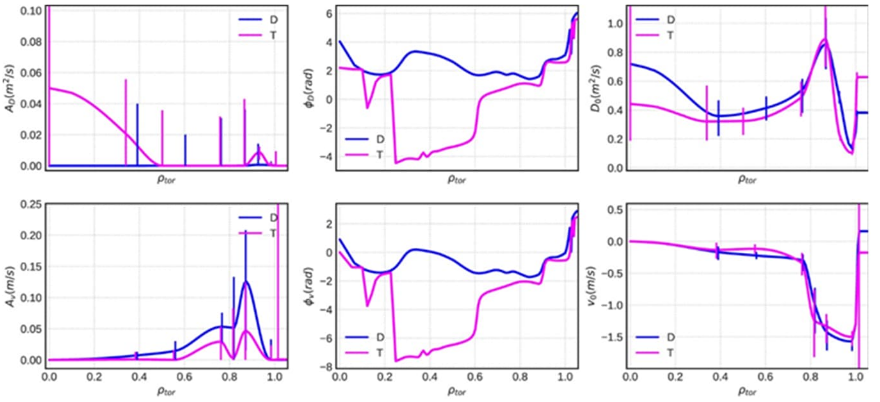


Figure 2.15: Comparison of the optimised diffusive and convective transport coefficients and their temporal behaviour between the isotopes. Deuterium case is at 3.00 Hz gas modulation and Tritium at 1.28 Hz. Note that the values are absolute and that they depend on the absolute magnitude of the fuelling sources.

We can see that modulation amplitude of both transport channels is small (unlike is e.g. sweeping modulation experiment) and especially for diffusion it could be non-existing. For convection the modulation is higher, but it is still not possible to make strong conclusions about this isotope scaling. The same applies to phase, naturally. Neglecting the modulated component results in worse fitting but statistically it is only moderately meaningful even with our good measurement data. The main conclusion we can make is that the particle transport is likely quite similar between the isotopes and that inward particle pinch near the edge is present (right panels).

2.6.7 Intrinsic torque experiment in TCV

Research scientists: A. Kirjasuo, A. Salmi, T. Tala, VTT

Initial experiments were conducted on the TCV tokamak to study the intrinsic torque in minimally rotating plasmas. The small rotation was achieved by utilizing TCV neutral beam (NB) injection system's new capabilities by injecting a mixture of co- and counter-current NB that balance the plasma's intrinsic rotation. The development of the analysis technique is ongoing and is aimed at providing information about the intrinsic torque via fitting simulated data against measured rotation. The learnings from this initial set of data will mostly be used to optimize the follow-up experiments with physics scans.

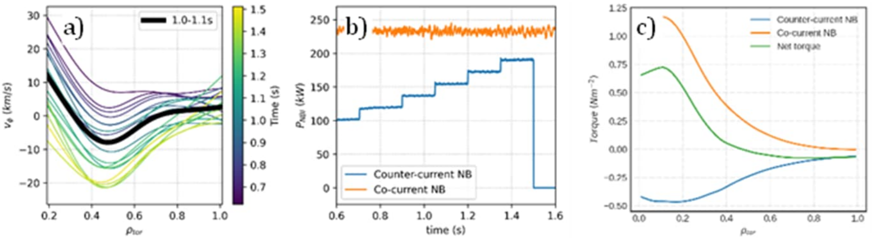


Figure 2.16: Toroidal rotation evolution for #78931 with counter-current NB ramp and TRANSP calculated torque profiles.

2.6.8 Fast ion studies in AUG

Research scientists: S. Sipilä, A. Snicker, AU

ASCOT4-RFOF simulations of ICRH on 5% H population and NBI D with and without MHD (TAE) were made for ASDEX Upgrade discharge 39573 in order to determine the physical mechanism behind the reduction of AE induced losses in FILD. To analyze the effect in more detail, parameter scans of plasma n&T as well as TAE amplitude were made. The results have been submitted for further analysis with the FILDSIM code.

Further ASCOT4 simulations were made for ASDEX Upgrade discharges 38814 and 40688 to study the effect of NBI deuterium slowing-down on high frequency Alfvén eigenmode (GAE) growth rate in the core region. The derivatives of the simulated 4D fast ion distribution $f(R,z,\xi,E)$ were used in an analytic representation of the growth rate. The results were presented at the 29th IAEA Fusion Energy Conference, and a manuscript was prepared for submission to Nuclear Fusion. Work was also initiated on another manuscript including the ICRH results.

2.6.9 Task force Leadership activities

Research scientists: A. Hakola, VTT

In 2023, Antti Hakola continued his duties as one of the Deputy Task Force Leaders (TFL) for WPTE, as part of the team of nine TFLs. His main responsibility areas were (i) material erosion, migration, and fuel retention; (ii) characterization of runaway electrons and taming disruptions, and (iii) plasma operations in alternative divertor configurations. Related experiments or analyses/modelling activities were carried out on all the operating devices (JET, TCV, MAST-U, and WEST). Besides coordinating research activities, the deputy TFL duties included reporting of the scientific outcomes and preparing new campaigns. Particular focus points in 2023 at JET were executing the DTE3 campaign, as well as the subsequent cleaning campaign, and carrying out extensive SPI investigations. On TCV, much effort was put on benign termination of runaway electron beams while research on alternative divertor configurations proceeded on TCV and MAST-U. On WEST, the previously mentioned high-fluence campaign was the clear highlight of the activities.

2.7 WP W7X: Isotope effect in W-7X stellarator

Research scientists: J. Kontula, T. Kiviniemi, T. Kurki-Suonio, L. Sanchis, S. Äkäslompolo, AU

The ASCOT code was used to analyse the impact of different species in the beam-ion losses in W7-X. Future W7-X campaigns will include H, D and He as both the NBI-injection and target plasmas but, so far, only H injection and target plasmas have been extensively analyzed. Experiments using helium as injection and target plasmas are planned for the upcoming OP2 campaign. This data will be used to validate our simulations, which indicate higher power loss when changing from hydrogenic to helium target plasma, and facilitate reliable predictive simulations for future operation in D. Simulation results indicate twice as high fast-ion losses in the (D,D) than in (H,H). The main contribution to the wall loads comes from ripple-trapped particles, with the maximum values from 1 MW/m2 to 3 MW/m2 for the (H,H) and (D,He) case, respectively. When comparing different configurations, the low-mirror has the highest losses, but no power lands on vulnerable PFCs.

2.8 WP PrIO: Preparation of ITER first experimental campaigns

Research scientists: O. Hyvärinen, L. Sanchis, A. Snicker, AU

Under the work package WPPrIO, ASCOT calculations have been carried out to support the ITER FILD project. The development of the fast ion loss detector (FILD) culminated in 2023 to preparation of documentation and simulation data to support the conceptual design review (CDR) of the diagnostics. To this end, large number of ASCOT simulations were carried out to study the sensitivity of the fast ion (mainly fusion born alphas) signal versus the insertion dept of the probe head (see Figure 2.17). Moreover, significant effort was made to improve the reliability of the simulated fast ion flux to the probe head. These improvements include inclusion of the plasma response to the imposed resonant magnetic perturbation due to ELM correction coils (ECCs), local estimation of the flux at the probe head, estimation of the beam-thermal signal vs. the thermonuclear signal, and combination of the NBI flux to the alpha flux. Moreover, these ASCOT results were used to model the synthetic velocity-space FILD signal in baseline H-mode ITER scenario as illustrated in Figure 2.18.

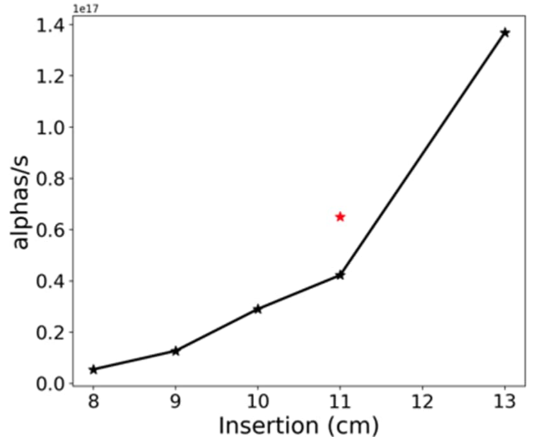


Figure 2.17. Estimated alpha particle flux at the probe head as a function of the insertion depth of the FILD probe head. The red dot represents estimate from 2016 and the black curve the calculations from 2020-2023.

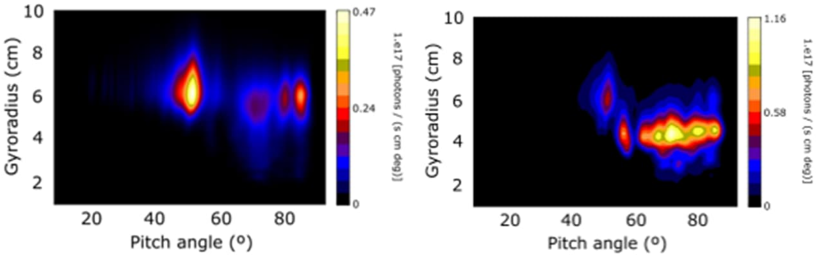


Figure 2.18: The synthetic velocity space patterns of lost alphas (left) and lost alphas+NBI ions (right) in ITER H-mode baseline scenario.

3. Fusion Technology Work Programme 2023

3.1 WP BB: Breeding blanket

3.1.1 Neutron and gamma-ray simulations with Serpent2 for the tungsten shield mock-up, BB-S-05.02-T002-D034

Research scientists: T. Kurki-Suonio, L. Sanchis, AU
A. Snicker, VTT

As part of the testing/validation of the shielding performance of advanced shield configurations considered for DEMO, our task was to carry out quantitative comparison of the measurements in the W-shield mock-up experiments at FNG to predictions by Serpent2. In 2023, the mock-up model with the updated geometry, including the activation foils and material composition of the W shield experiment, was implemented in Serpent2. The neutron fluxes and 3 reaction rates were calculated at 8 locations for two experimental configurations: 1) including indium activation foils, 2) Including Nb and W activation foils.

Serpent2 simulations revealed an absorption peak in the neutron flux at 20 keV due to (n,g) reaction at distances 22.55 cm and 34.25 cm from the FNG for all three activation foils. The reaction rates for neutron scattering in indium (n,n'), and neutron multiplier reaction Nb(n,2n) were steadily dropping as a function of distance from FNG, while the reaction rate for gamma-producing reactions in tungsten. W(n,g), displayed significant drops at the distances 22.55 cm and 34.25 cm. Unfortunately, the comparison to experimental data could not be accomplished before the key person, Dr. Sanchis, left the group for a new position in Spain.

3.1.2 Serpent2 neutronics simulations for the DEMO WCLL tritium-breeding mock-up

Research scientists: T. Kurki-Suonio, L. Sanchis, AU

A model of the "Water Cooled Lithium Lead (WCLL)" breeding blanket mock-up was implemented in Serpent. This mock-up, built at the Frascati Neutron Generator (FNG), represents the European DEMO design of the WCLL concept. The model has been implemented according to the latest WCLL mock-up geometry and material composition, together with the specifications of the FNG neutron source. Serpent was used to estimate the neutron transport and 4 reaction rates at 7 detectors locations. Benchmarks against the MCNP code gave discrepancies beloww 10% for most of the energy range. Once a good agreement was found between the codes, the reaction rates of Nb(n,2n), In(n,n'), N(n,p) and Al(n,a) were compared with the experimental data. The comparison showed a satisfactory agreement with C/E values between 0.8-0.98 in the majority of the cases.

3.2 WP BOP: Heat transfer, balance-of-plant and site

Research scientists: S. Norrman, M. Szogradi, VTT

As the maturation of the conceptual Indirect Coupling Designs (ICDs) proceeded, both Water-Cooled Lithium-Lead (WCLL) and Helium-Cooled Pebble-Bed (HCPB) thermal-hydraulic Apros models had been updated. In former case the primary circuit piping was completely rebuilt, following a new topology provided by the DEMO Central Team. The new configuration envisages two separate cooling loops, enveloping the Breeding Blanket (BB) with 2x2 identical Once-Through Steam Generators (OTSGs). Consequently, new OTSG models were built in Apros, utilizing the previous years' experience, moreover, the Primary Heat Transfer System (PHTS) and the primary side of the divertor cooling loops were all equipped with dedicated pressure control systems. Corresponding logics were also designed, implemented and tested in order to obtain an acceptable steady state for the WCLL ICD model.

Concerning the HCPB candidate, 2023 activities focused on the Intermediate Heat Transfer System (IHTS) where a new design was implemented, provided by Kraftanlagen Heidelberg GmbH (KAH). This system utilizes quasi-atmospheric molten salt reservoirs, posing significant challenges in terms of pressure and thermal-hydraulic modelling. Benchmarking activities had been carried out in co-operation with Karlsruhe Institute of Technology (KIT) and University of Palermo (UNIPA), comparing the transient behaviour of a down-scaled IHTS model using Apros and TRACE. The results highlighted that lumped-parameter codes in general struggle at low-load (low flow velocities) conditions as the validity ranges of popular heat transfer correlations do not extend into the laminar region. These issues were more prominent on the gas-side of the helical coil heat exchangers of the IHTS, promoting the necessity of additional experimental work. Figure 3.1 depicts the Apros model of the charge loop along with the transient helium and molten salt temperature profiles of the IHX and charge loop hot leg, respectively.

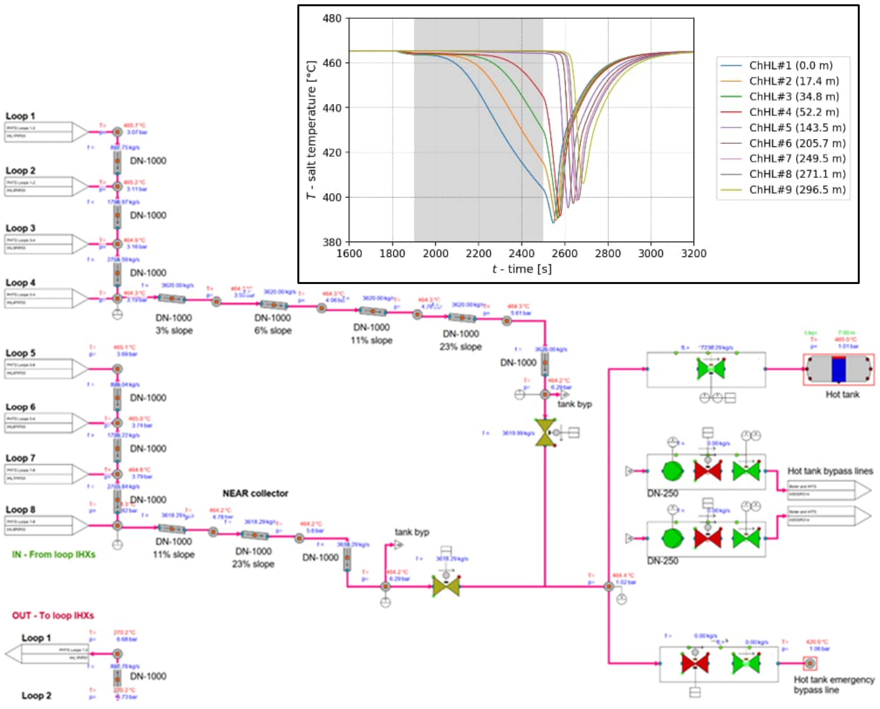


Figure 3.1. Apros IHTS charge loop model with IHX tube-side axial temperature profile (left-bottom) and thermocline propagation via the charge loop hot leg (top).

3.3 WP ENS: Early Neutron Source definition and design

3.3.1 PROJECT LEVEL ANALYSES

Research scientists: A. Helminen, E. Immonen, T. Tyrväinen, K. Viitanen, VTT

International Fusion Material Irradiation Facility - DEMO Oriented Neutron Energy Source (IFMIF-DONES) is designed for the validation of structural materials of DEMO. The definition and design of IFMIF-DONES is carried out in Work Package Early Neutron Source (WP ENS).

VTT has participated in WP ENS providing probabilistic risk assessments (PRA) for IFMIF-DONES. The aim of PRA is to give insights to the strengths and weaknesses of the design and operation of IFMIF-DONES.

In 2023, VTT work concentrated on the development of IFMIF-DONES internal events, design phase PRA model. The current design phase PRA model consists of 11 event trees on systems' transients and potential lithium leakages.

In addition to the traditional PRA modelling, a literature review on the integration of PRA with organizational factors/safety culture assessment was conducted. The integration may open a novel way of applying the PRA model to improve the organizational factors/safety culture of IFMIF-DONES. The mapping of PRA elements on the iceberg model of safety culture is shown in Figure 3.2.

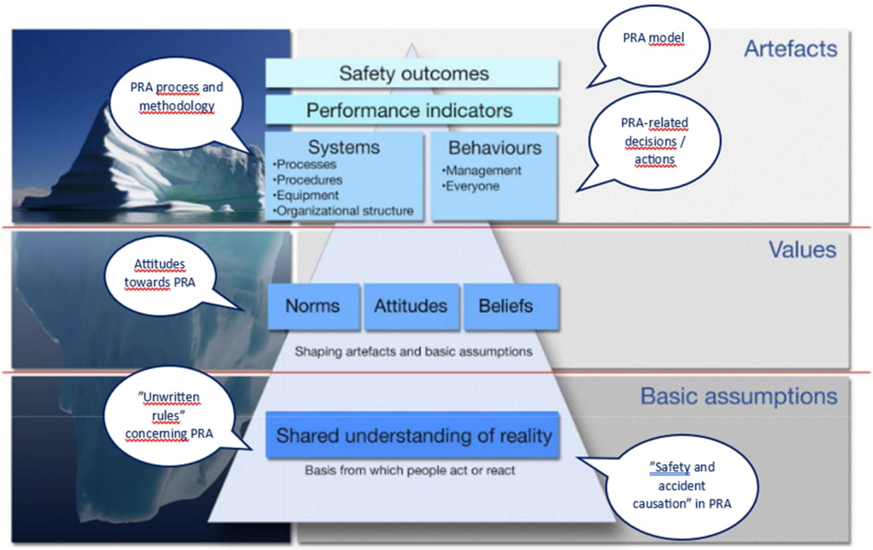


Figure. 3.2. The mapping of PRA elements on the iceberg model of safety culture.

3.3.2 Design of a radiation-resistant monitoring camera system for IFMIF-DONES remote operations

Research scientists: K. Rainio, M. Siuko, VTT

The content of this subtask (END-3.5.5.6-T008-01) has been specified as follows: Remote Handling (RH) Maintenance of systems and components of DONES is planned to be executed in dedicated maintenance areas. In DONES there are four independent maintenance areas each one equipped with its RHS and with a dedicated Viewing System (VS). The VS is one of the subsystems of the RHS of DONES. The work to be developed in the ambit of this task includes the following topics:

- Identification of design requirements for the VS of the RHS of DONES
- Proposal for the viewing system architecture of the RHS and its integration in the RH control system
- Potential location of cameras inside each maintenance area
- Preliminary list of interfaces between VS and other systems
- Market survey on camera systems

The work has concentrated on topic 5 (Market survey on camera systems), whereas for topics 1 - 4 very rough worst-case scenarios have been used. Topic 5 was considered the most important topic, because without knowing what kind of radiation tolerant camera systems are currently available, the design tasks of other topics are impossible.

3.4 WP MAG: Magnet conductor/ insulator research

Research scientists: T. Avikainen, A. Laukkanen, T. Suhonen, VTT

The performance of fusion magnets is strongly relying on the dielectric strength given by the electrical and mechanical robustness of the magnets insulation system which must be maintained over the whole plant lifetime in a gamma and fast neutron radiation environment. The dielectric and mechanical durability of the electrical insulation is in the focus of the WPMAG project related to the high voltage superconductive coils. The manufacturing process step is wanted to be changed with the implementation of the insulation solution taking place before the challenging heat – treatment and vacuum process cycle required by the Nb3Sn based superconductive cables.

The insulation solutions deserve a dedicated study to understand the potential failures. The possible use of available commercial insulation materials suggests complicated tests and numerical modeling to investigate the fundamental understanding of the complicated composite materials and structural designs. During 2023 demonstration modeling was implemented at VTT to assess the properties and performance of some common identified use cases. The FEM modelling analysis were implemented to both the high voltage electrical and the mechanical testing.

VTT's role in the project was to chart potential insulation solutions to be implemented in the practical demonstration system. Target was to find a suitable subcontracting partner that could take a role in practical manufacturing of the demos, choosing the most promising material components and finally implement the electrical and mechanical reliability tests. During the 2023 after discussions with the potential candidates it proved that the allocated subcontracting must be divided to the smaller parts like manufacturing of mock-ups and testing to the different subcontracting parts. First one would include the collection of the chosen insulation materials in co-operation with the material suppliers and the testing partner would be in responsible of both the electrical and material tests. This might make it possible to collect the most potential insulation materials from different suppliers. By assuming to keep in only one subcontracting partner being responsible of the whole chain including the materials, assembling, heat-treatment processing and finally challenging tests, probably drop out most of the potential material suppliers. Many of the required tests should be implemented in the cryonic temperatures (77K) which means the very challenging testing tasks.

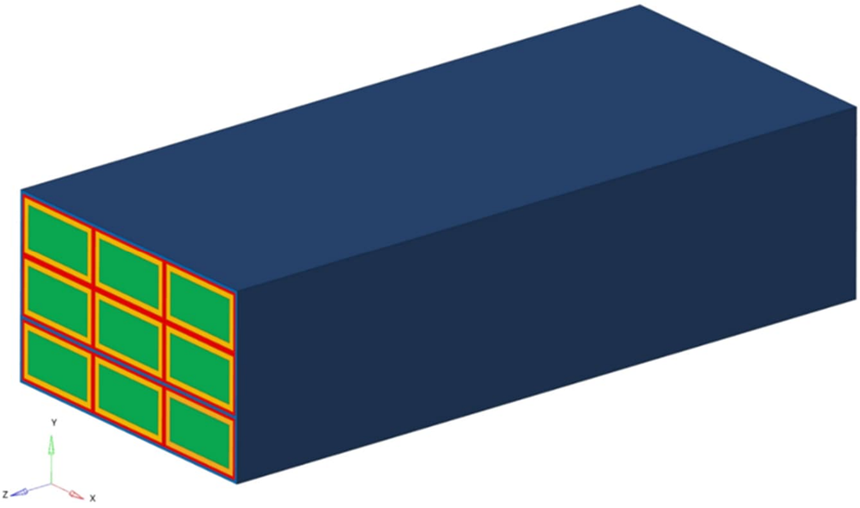


Figure 3.3. Visualization of the 3D design of the mock – up including 9 conductors and insulation layers.

3.5 WP MAT: Materials

3.5.1 WP MAT Hot cells

Research scientists: P. Arffman, M. Jokipii, P. Lappalainen, J. Leporanta, J. Lukin, M. Paasila, K. Rämö, J. Saarinen, P. Sinkkonen, M. Ulfves, VTT

The Materials Work Package (WPMAT) aims to develop and qualify materials for use in various components in fusion reactors. The EUROfusion WPMAT task specification PIE of LOT-II outlines the required mechanical testing (fracture toughness, tensile test, and Low Cycle Fatigue) for irradiated CuCrZr alloy specimens up to 1 dpa.

The new dynamic servo-hydraulic test rig required for mechanical tests was delivered to VTT in December 2022, and a new Hydraulic Power Unit (HPU) with increased capacity was delivered in late February 2023. Additionally, the delivery of the chiller required for cooling the hydraulic grips of the test rig was made in May 2023. The factory acceptance tests of the new dynamic servo-hydraulic rig were performed in June 2023.

The actual installation work of the dynamic servo-hydraulic test rig inside the hot cell began in June 2023 with the installation of the base stands required for the test rig, and the transfer of the test rig inside the hot cell was completed in August 2023. The installation of the hydraulic pipeline, as well as leak and pressure tests, were carried out in September 2023. Following the installation of the hydraulic pipeline, vibration measurements were conducted to ensure that simultaneous operation of two different material test rigs does not cause vibration interference at different operating frequencies. Before commissioning the test rig for testing purposes, it was factory-calibrated in December 2023.

Additionally, the nuclearization process for the test rig was initiated. This process involves the fabrication of auxiliary tools required for specimen mounting, installation of cameras, modifications to tables and rear liner, creation of hydraulic and cooling water feedthroughs, and installation of thermocouples for temperature measurement. At the end of 2023, the test rig enabling fatigue tests on irradiated material has been commissioned, and actual tests can be conducted in 2024.

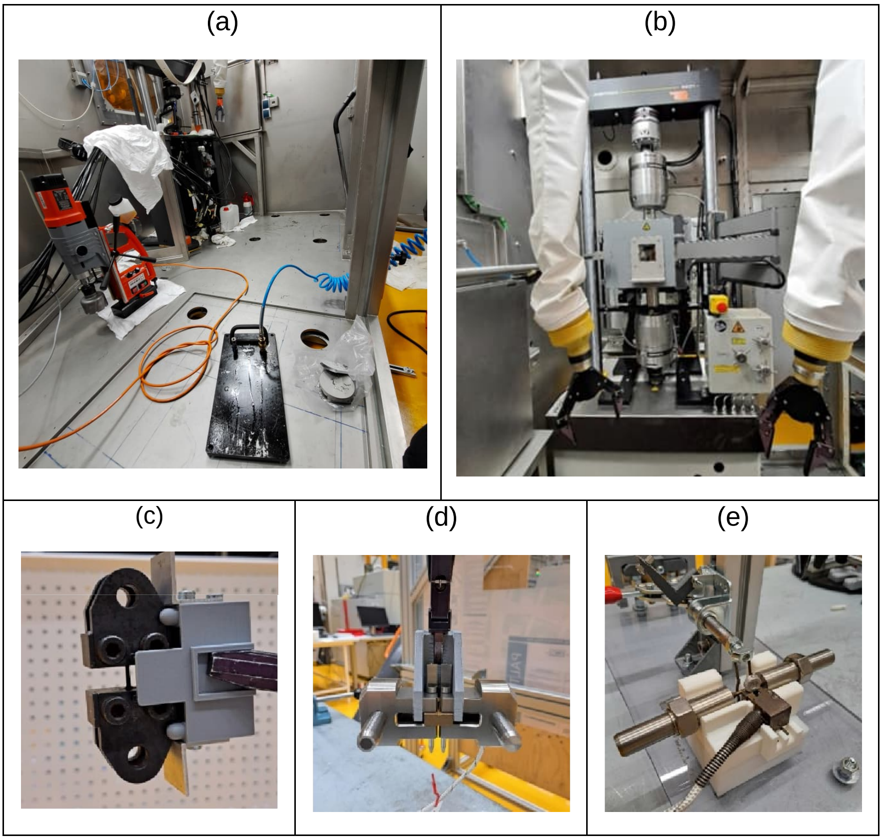


Figure 3.4. The installation of the base stands for the test rigs (a), as well as the test rig installed inside the hot cell (b), the tool designed for a tensile test specimen (c), the tool designed for a fracture toughness test specimen (d) and the tool designed for a low cycle fatigue test specimen (e).

3.5.2 IREMEV activities

Research scientists: T. Ahlgren, J. Byggmästar, F. Granberg, A. Kuronen, V. Lindblad, K. Nordlund, UH
A. Clement, I. Stanovohh, A. Sand, I. Saunamäki, AU

At UH, the work focused on the effects of deuterium on the defect production in tungsten. Experimentally there are different defect evolutions seen, depending on if deuterium is present during ion irradiation or not, however, the mechanisms are not clear. We have with molecular dynamics simulations carried out simulations of different setups, to represent the experimental conditions. We found that we can reproduce the seen trends and found the mechanisms leading to the seen behaviour. Differences in defect mobility and recombination as well as increase defect production under some conditions were seen to be reason for the experimentally observed trends. Also, the work on defects binding to screw dislocations were continued and the results are used as input for Machine learning models, to be able to fast predict the results, without the need for full simulations.

At Aalto, the effects of external strain on the primary radiation damage was studied with molecular dynamics simulations. Under operating conditions, the build-up of radiation damage will give rise to stresses and strains in reactor structural components, which may affect the further accumulation of damage. Applied strain was observed to affect the eigenstrain of the cascade-induced defects through the orientation of the self-interstitial crowdions, which under tensile strain in a <111>-direction were found to align along the strained axis, while avoiding that direction and lying along one of the other three <111>-orientations under compressive strain. The crowdion orientation is random under no strain. This preferred orientation of crowdions under strain will affect their migration, leading to a restoring effect of the point defects, which explains earlier observations from cumulative cascade simulations.

3.5.3 MIcroStructural characterization, in-situ micromechanical testing and multiscale materials modeling

Research scientists: T. Andersson, A. Laukkanen, T. Suhonen, VTT

Research as well as industrial collaboration continued in 2023 about Cu- and CuCrZr-alloys. Modeling framework concerning manufacturing and processing of CuCrZr was developed in collaboration with Luvata. The framework included all crucial manufacturing steps like casting, drawing, cold working and precipitation annealing. ITER-garade CuCrZr extruded plate, which has been subject to thermal treatment (annealing at 580°C for 2 h) to simulate the Hot Radial Pressing (HRP) joining technique “SAcwA+HRP” and pipe sample from ENEA were also received and characterized (SEM-EDS-EBSD). Based on the characterization results crystal plasticity models were created with three slightly different approaches (crystalline damage, porous damage and phase field damage). Similar approach was taken with OFP copper and extended into creep modeling framework. This work was presented and published at ECCC 2023 conference and the extended version in Materials at High Temperatures -journal.

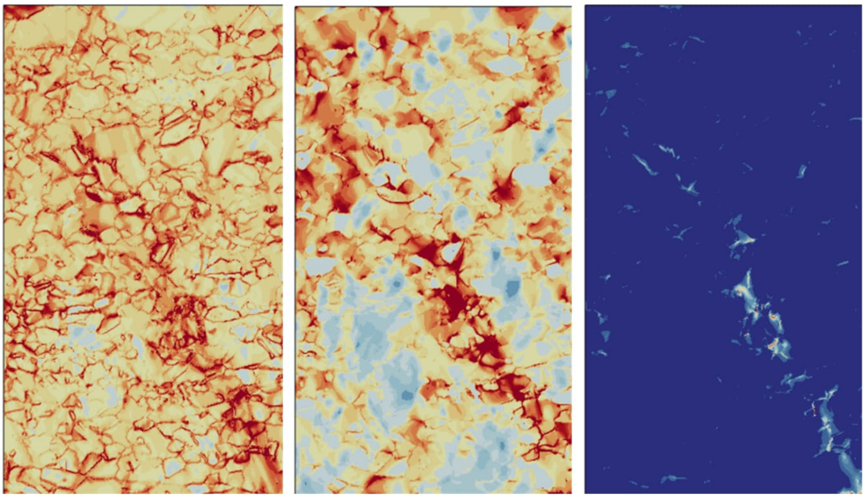


Figure 3.5. Example of CrCrZr-micro structure behavior under mechanical load with a size-dependent ductile fracture model, left) V.Mises stress, middle) dislocation density and right) porosity fraction (ductile damage model – crystal plasticity).

3.6 WP PRD: Prospective R&D

3.6.1 HHFM High heat flux materials

Research scientists: T. Andersson, M. Haapalehto, A. Laukkanen, T. Pinomaa, T. Suhonen, VTT

Research in collaboration with three EUROfusion partners, IPP MPG, IJS and KIT continued in 2023 about W- and W-based novel plasma facing alloys. VTT´s task for 2023 mainly focused on the development of computational framework which was particularly based on phase field crystal (PFC) and molecular dynamics (MD) to support additive manufacturing processes such as powder bead fusion (PBF) and electron beam melting (EBM) activities, supporting the experimental activities of:

- Laser beam melting of tungsten and beam shaping for improving printability and subsequent part properties (in collaboration with IPP MPG)
- Laser powder bed fusion of tungsten-W2C (in collaboration with IJS)
- Electron beam melting (EBM) of tungsten (in collaboration with KIT)

The work resulted: In "beam shaping trials of laser beam melting of tungsten", implementation and computational trials completed, the work will continue with parametric studies and comparisons to experimental findings. In "laser powder bed fusion of W-W2C" initial primarily thermodynamical work was carried out and development work performed on a full field microstructural simulator. The thermodynamical work will first be completed and comparisons to experimental and characterisation results then pursued, followed by parametric studies. In “electron beam melting of tungsten”, the work will continue with studies of process parameter effects and model validation.

3.6.2 Serpent2 neutron model for HELIAS stellarator

Research scientists: T. Lyytinen, A. Snicker, VTT, Joonas Virtanen, AU

Serpent2 neutronics modeling of the HELIAS stellarator concentrated on the non-planar field coils. To analyze the poloidal flux distribution, the CAD-based model of the coils was divided into poloidal segments. We observed a non-trivial helical flux shape, deviating from the flux patterns in the first wall and blanket. Additionally, the fast flux consistently exceeded the technological limit across the coils using the inboard blanket thickness configuration of a dual-coolant lithium lead (DCLL) composition (see Figure 3.6). Moreover, the maximum blanket thickness configuration was predicted to surpass the flux limit based on the average flux calculations and peaking factors obtained from the inboard blanket thickness calculation.

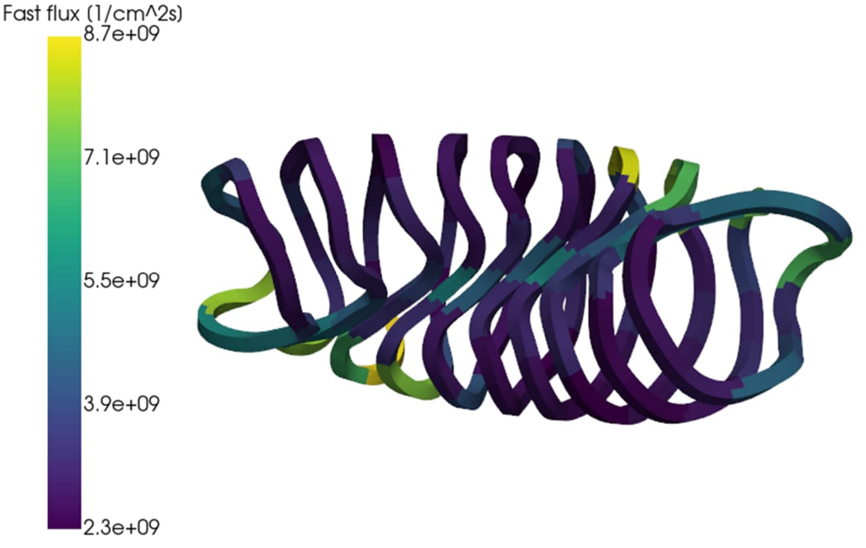


Figure 3.6. Fast flux (E > 0.1 MeV) in coil winding packs using DCLL composition and inboard blanket thickness (breeding zone = 50 cm, back-support structure = 12.5 cm), where flux limit of 1E9 1/cm^{2}s is exceeded.

3.7 WP RM: DEMO Remote maintenance

Research scientists: J. Alanen, W. Brace, J. Heikkilä, T. Jokinen, P. Kaarmila, D. Kaartinen, P. Kilpeläinen, P. Kokkonen, J. Koskinen, M. Liinasuo, J. Lyytinen, T. Malm, H. Martikainen, S. Qais, T. Salonen, J. Sarsama, T. Sipola, M. Siuko, E. Strömmer, M. Tahkola, B. Tammentie, A. Tanskanen, V. Truong, T. Vaarala, T. Välisalo, A. Ylisaukko-oja, VTT

L. Changyang, A. Hekmatmanesh, W. Huapeng, L. Ming, H. Qingfei, LUT

K. Kund, S. Muhlig-Hofmann, V. Puumala, Comatec

3.7.1 Overview

The DEMO Remote Maintenance Work Package (WPRM) is a collaborative effort that covers the development of maintenance processes, controls, strategies, and equipment within the Tokamak Fusion Power Plant (T-FPP). The Finland Research Group (Finn RM-Group) activities are a key part of this, comprising developments within the In-Vessel, In-Bioshield, Upper Port, Lower Port, and Equatorial Port maintenance areas. This collaborative approach spans multiple tasks within the DEMO RM work package, demonstrating the collective effort involved. The Finn RM-Group is comprised of research institutes VTT and LUT, as well as industry participants, including Comatec, Qualifin, Fulvisol, and Coresbond. The EUROfusion Framework Programme 9 (FP9) deliverable for WPRM is tasked with the parallel delivery of the System Design activities, technology R&D activities, and testing and validation of specific design concepts and technologies. The emphasis on proof-of-principle testing and validation is evident in the commencement of the design and construction of a Remote Maintenance Test Platform (RMTP) comprising several test rigs as an integral part of the existing Divertor Test Platform (DTP2). VTT is leading the RMTP task with full participation from industry partner Coresbond. LUT is also building satellite test rigs in its facility. Regular information transfer and close collaboration are vital to the success of WP RM tasks; therefore, the research activities involve applying ontologies and PLM with support from Fulvisol. WPRM work and the Finn RM-Group's activities are categorised under three programmes: Remote Maintenance System Design (RM-S), Remote Maintenance Technology Research & Development (RM-T), and Design, Construction, and Operation of RMTP.

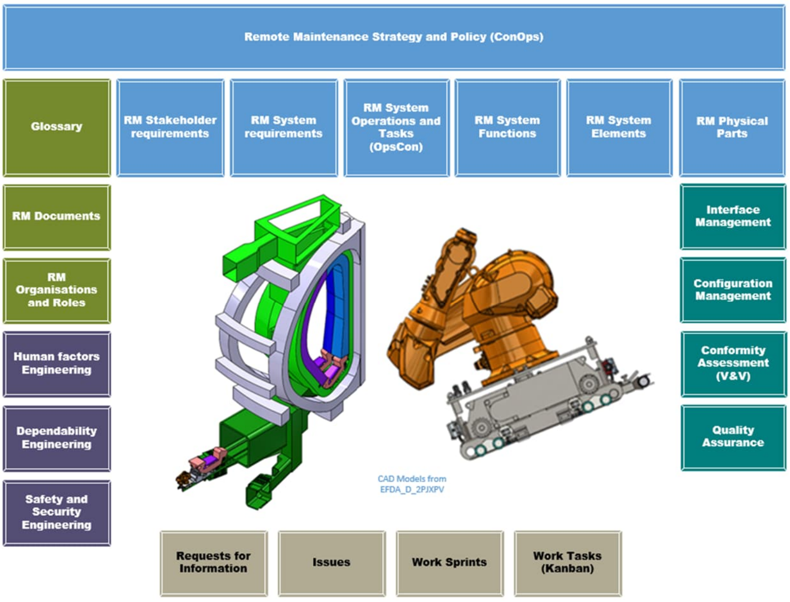


Figure 3.7. Regular information transfer and close collaboration through PLM

3.7.2 RM System Design

The RM System Design work focuses on equipment design and assessments that can help inform DEMO's architecture. It is concerned with satisfying high-level functions (safety, operability, human factors, reliability, and risk mitigation) as part of the maintenance strategy. RM equipment design comprises specialised autonomous and robotic designs for maintenance activities within the T-FPP. The design activities include research on existing robotics and autonomous systems with defined TRL and redesigning to a higher Concept Readiness Level (CRL) to be compatible with the technical challenges for application in extreme conditions. VTT and LUT, with industry partner Comatec, are also developing novel RM equipment for replacing the in-vessel components, comprising heavy elements like the breeder blanket, divertor cassettes, and limiters. Due to the emphasis on proof-of-principle testing, reliability assessment, dynamic modelling, and simulation are highly prioritised. There are activities in the RM system design to investigate and define processes from design to virtual model/digital twin capable of supporting the RM. There are activities for research and developing methodologies for updating and refining inaccurate dynamic systems using a stochastic modelling process and research on enabling high-performance Entity System framework to run a digital twin. Further, much emphasis is placed on RAMI analysis, rescue, and recovery studies, as well as analysis to identify vulnerabilities in the system design that could represent an unacceptable risk to the reliable operation of RM equipment. Rescue and recovery studies strive to include all possible retrieval of RM equipment with minimum human intervention, thus focusing more on autonomous systems.

3.7.3 RM Technology R&D

RM Technology R&D's focus has shifted to technology-led development, advocating a product-driven design (PDD) approach. This paradigm shift is based on the design mission statement, “to use a bottom-up approach and define equipment with appropriate TRL” for subsequent application in the RM System Design phase. Subsequently, there is a drive to use commercial-off-the-shelf (COTS) components in the design of FPP since these parts have higher TRL. However, the use of COTS components has an inherent risk because of the lack of confidence in the traceability and the long-term performance of these parts. Therefore, the researched technologies are diverse. Finn RM-Group involvement includes research on human factors and twin condition monitoring, integrated monitoring of the RM equipment, control operations, and human operator involvement. In addition, a stringent methodology for product assessment, selection, procurement, and testing (screening and qualification) is followed to make COTS feasible or available for the intended application. Identified COTS shall be redesigned and retrofitted for RM activities, linking various industry partners in fusion technology R&D and system design. The main goal of the retrofit is to make nominated COTS suitable and adaptive as an RMS in the FPP environment. Much emphasis is placed on Technology Maturation & Risk Reduction (TMRR) to reduce technology risk, engineering integration, and life-cycle cost risk and to determine the appropriate set of technologies to be integrated into a full system. The TMRR phase comprises conducting competitive prototyping of COTS elements from various industries and applying the RMTP for testing and validation.

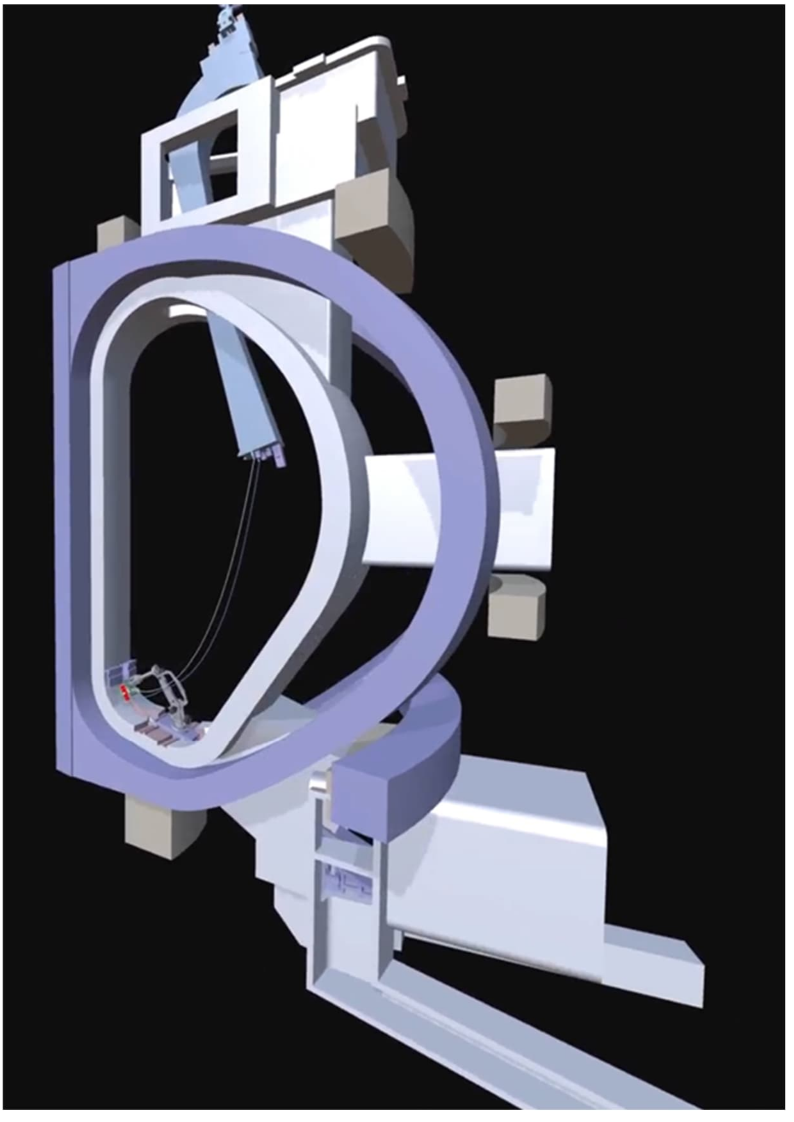


Figure 3.8. Proof-of-concept of RM equipment for In-Vessel Maintenance operation

3.7.4 Remote Maintenance at LUT

Research scientists: L. Changyang, Q. Han, W. Huapeng, L. Ming, Y. Ruochen, Q. Guodong, H. Amin, A. Unt, Qiwei Xue, Q. Wang, D. Li, Z. Yao, LUT

In 2023 LUT participated in the WP RM with 4 majoy areas: Plant Architecture Assessments WP2&3 (Bluemira modelling), condition monitoring, Stochastic modelling, Port Closure Plate (PCP) and support to Port Plant Systems, and AWP23 - In-Vessel Remote Maintenance Development WP2 of Multi-Purpose Deployer (MPD).

1) In In-vessel maintenance system, we have carried out literature reviewing and development of RM system for Plasma Facing conponents (PFC), development of in-vessel manintance-MPD and study 3D additive manufacturing for on-site maintenance.

2) In Condition monitoring AI algorithms (Data driven methods) are studied: we focus on the methods of human condition monitoring in man-in-loop remote handling system; the study aims to pioneer the integration of artificial intelligence algorithms with physiological signal processing to estimate the condition of an operator. The algorithm specifically focuses on sensor information fusion from Photoplethysmography (PPG), Electroencephalography (EEG) signal, and Remote Photoplethysmography (RPPG) technology.

3) In the stochactics modelling the study investigates the effects of the deviations of the robotic dynamic parameters on the performance of the robotic control system, in terms of control system stability, position tracking accuracy and the feasibility of the actuators.

4) Plant Architecture Assessments, this work studies Plasma physics Bluemira modelling, and optimization of architecture considers remote maintenance boundary conditions.

5) Port Closure Plate and support to Port Plant Systems, study the remote maintenance methods for closure plate, Neutron Shields (NS) and Electron Cyclotron (NC).

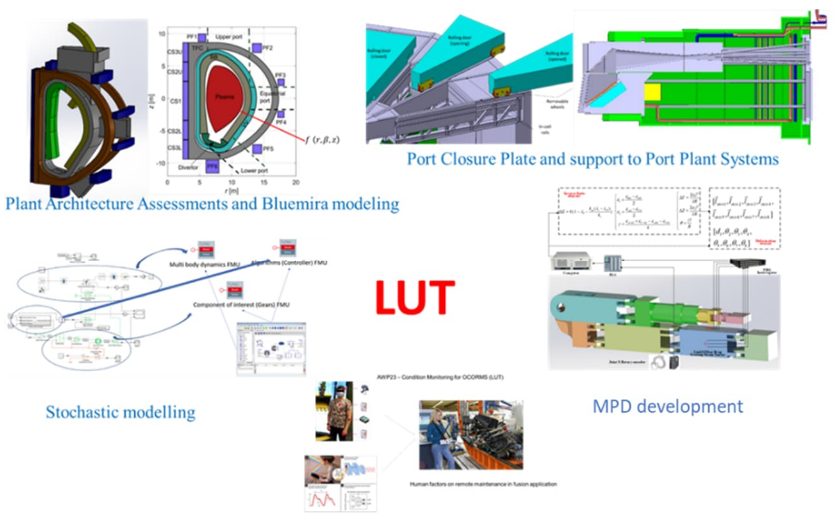


Figure 3.9. LUT university activities on DEMO.

3.8 WP SAE

3.8.1 Liquid operational waste expected from current DEMO design

Research scientists: M. Airila, A. Leskinen, T. Lavonen, VTT

The generation of radioactive waste, in terms of volume, radioactivity content, and frequency of batches generated, must be considered before the construction of a facility. In 2023, VTT investigated liquid radioactive waste streams from the DEMO design so that the Generic Site Safety Report (GSSR) can be developed further. We identified and classified the most important waste streams and listed process options identified so far, including a processing technology readiness estimate. Examples of liquid waste streams include waste waters from the process systems and ion-exchange resins, lithium-lead related waste, contaminated lubricants, laboratory waste, as well as several types of secondary waste. Most liquid wastes produced are similar to ones in fission power plants, which have plenty of industry experience in handling radioactive wastes. In DEMO design, the same waste management procedures should be primarily considered.

3.8.2 Fire accident analyses

Research scientists: T. Hakkarainen, T. Korhonen, N. Verma, VTT

The fire risk analysis of the DEMO power plant includes fire hazard identification and fire consequence assessment. Foremost, the fire safety analysis should show that any releases will remain within the plant limits and no conditions for cliff-edge effects will occur.

In 2023, the work in Fire accident analyses task concentrated on defining fire zoning principles for the future demonstration fusion power plant DEMO. Analyses were performed utilizing computational fluid dynamics (CFD) simulations with Fire Dynamics Simulator (FDS) software, as well as zone fire models and analytical calculation methods. Failure risks of fire sector partitions depending on room dimensions and fire load densities were mapped, and tables and graphs for design were produced. The applicability of different tools with varying levels of complexity for different use cases was also assessed.

3.8.3 DIAGNOSTICS FOR TRITIUM MEASUREMENTS LOCATED INSIDE DEMO VACUUM VESSEL

Research scientist: J. Likonen, VTT

In this task VTT assessed in-VV tritium inventory diagnostics monitoring systems for DEMO reactor. As a licensed nuclear facility, ITER and future power plants such as DEMO must limit the in-vessel tritium (T) retention to reduce the risks of potential release during normal and off-normal operation including accidents conditions. Due to radiological and explosion risks pointed out by safety evaluation studies, the accumulation of dust and tritium in the VV could significantly impact the operation of ITER and future fusion reactors. Therefore, the In-VV tritium inventory monitoring is relevant both for safety analysis as well as for demonstrating the compliance with safety limits stated in the licensed domain of plant operation. In view of DEMO licensing and operation, there is a need to improve the knowledge and to develop and assess techniques allowing the monitoring of dust and tritium inventories in the VV and also mitigation techniques allowing detritiation, dust removal and explosion mitigation.

A laser based system is foreseen to probe the deposited layers at ITER, especially on the inner and if possible also the outer divertor baffle. The diagnostic methods for in-VV tritium investigations include Laser Induced Desorption Spectroscopy (LIDS), Laser Induced Ablation Spectroscopy (LIAS), Laser Induced Breakdown Spectroscopy (LIBS) and Laser Induced Desorption combined with Quadrupole Mass Spectrometry (LID-QMS). The first two methods need plasma whereas the latter two methods do not. The results of the literature survey were reported in WP SAE.T-02.02-T001-D001/D002/D003 report.

4. Communications

4.1 FinnFusion Annual seminar

The FinnFusion Annual Seminar was organised by Chalmers University of Technology, Sweden, and held at Lindholmen conference centre, as a 4th joint Nordic seminar with the Danish and Swedish Research Units on 12–13 June 2023. Invited speakers were Ian Chapman, UKAEA, United Kingdom, Joelle Mailloux, UKAEA, United Kingdom, Volker Naulin, Eurofusion, Peter Roos, Novatron Fusion, Sweden, Patrik Carlsson, BiSS, Sweden and Odd Erik Garcia, The Arctic university of Norway. The seminar attracted around 100 participants. The Annual Report, *FinnFusion Yearbook 2022*, VTT Technology 419 (2023) 107 p., was released during the meeting.

4.2 Articles and public relations

During 2023, Finnish media published several articles and interviews on the fusion research activities in Finland:

- Taina Kurki-Suonio: Tieteiden yö (The night of science) with the theme "How science saves the world" 12.1.2023
- Tuomas Tala: Hyvästit ydinkatastrofeille! Fuusiosähköä voidaan saada verkkoon 2030-luvulla, mutta ensin on ratkaistava monta ongelmaa https://www.helsinki.fi/fi/uutiset/energia/hyvastit-ydinkatastrofeille-fuusiosahkoa-voidaan-saada-verkkoon-2030-luvulla-mutta-ensin-ratkaistava-monta-ongelmaa, 2/2023. Yliopistolehti 1/2023.
- Tuomas Tala: Tutkijat uskovat: enää noin 20 vuotta fuusiovoimalaan, Tiedeykkönen, Yle Areena 17.3.2023. https://areena.yle.fi/podcastit/1-64970280
- Tuomas Tala: The juxtaposition between fusion and fission is pointless" – Europe is at the forefront of fusion energy research, DNA Business 14.12.2023. https://www.dna.fi/dnabusiness/blogi/-/blogs/the-juxtaposition-between-fusion-and-fission-is-pointless-europe-is-at-the-forefront-of-fusion-energy-research
- Taina Kurki-Suonio: Kosmista Mustangia kesyttämässä, osat 1 ja 2, Dimensiolehti 12.12.2023, 19.12.2023 Kosmista Mustangia kesyttämässä, osa 1/2 - Dimensiolehti Kosmista Mustangia kesyttämässä, osa 2/2 - Dimensiolehti

4.3 Courses on fusion studies

Lecture courses at Aalto University, School of Science:

- *Fusion Energy Technology (M. Groth, T. Kiviniemi, spring 2023).*
- *Introduction to plasma physics for fusion and space applications (T. Kurki-Suonio, autumn 2023).*
- *Radiation Damage in Materials (A. Sand, spring 2023)*

5. Education and training

5.1 WP EDU: FinnFusion student projects

5.1.1 Overview

FinnFusion has adopted EUROfusion's procedure of student reporting to get a shared overview on the education activities. The students register on a central web form, including their profile and progress information. In FinnFusion, every PhD student whose topic has relevance to the EUROfusion programme is encouraged to register. The number of student projects in the FinnFusion programme is remarkably high, which reflects the fact that the FinnFusion programme is broadly aligned with the priorities of the European programme and sets a high priority to excellence in education activities.

During 2023, six Doctoral dissertations, four Master's thesis and one Bachelor's theses were completed (see Section 10.4).

5.1.2 Doctoral students

Student:	Tommi Lyytinen (VTT)
Supervisor:	Andrea Sand (AU)
Instructor:	Antti Snicker (VTT)
Topic:	*Using Monte Carlo methods to simulate transport of fusion-born neutrons in complicated reactor geometries*
Report:	During 2023 research focused on determining the poloidal neutron flux and tritium breeding ratio (TBR) distributions for a parametric HELIAS stellarator model. The flux calculations using Serpent2 code extended from first wall up to non-planar field coils. In reactor layers close to the plasma, the flux distribution correlated with the distance to the plasma, producing a helical shape. The correlation vanished in the outer layers, such as the coils, making the flux distribution non-trivial. Moreover, a technological fast flux limit of 1E9 1/cm^{2}s was exceeded throughout the coils with the low blanket thickness configuration (inboard side). The flux limit was also predicted to exceed the maximum thickness configuration using calculated peaking factors. This work combined with previous parametric studies resulted in a conference paper and a journal article (submitted).

Student:	Tomi Vuoriheimo (UH)
Supervisor:	Filip Tuomisto (UH)
Instructor:	Kalle Heinola (IAEA), Tommy Ahlgren (UH)
Topic:	*Irradiation-induced defects and hydrogen retention in fusion reactor plasma-facing materials*

Report: Research focused on understanding hydrogen isotope trap site formation on irradiated W and deuterium trapping mechanisms. Work during 2023 included writing a paper on self-irradiated W with gradually filled deuterium by gas loading at elevated temperatures. Experimental findings using PAS and TDS results showed a distribution of different-sized vacancies in the samples. Vacancy clusters dominated the surface layers and mono-vacancies were found deeper in the material. In addition, work included writing and finalizing PhD thesis for its submission.

Student: Francis Albert Devasagayam (AU)
Supervisor: Mathias Groth (AU)
Instructor: Timo Kiviniemi (AU), Susan Leerink (AU)
Topic: *GENE simulations of GAM-Turbulence interaction in the FT-2 tokamak*
Report: In a recent experiment in the FT-2 tokamak, intermittencies in GAM and turbulence intensities throughout 13 ms were observed while the changes in the density and temperature profiles are insignificant. The intensity of turbulence fluctuations measured by two reflectometers recorded a 21% suppression during the GAM period in the radial region r/a = 0.4 to 0.8. In this paper, several linear simulations and one global non-linear simulation using the gyrokinetic code GENE covering ρtor from 0.17 to 0.83 are carried out. Linear simulations are carried out to find the dominant instability and the growth rate of the dominant instability at different radial locations between r/a = 0.3 and 0.7. Non-linear simulation results are analyzed to study the interplay between GAM and turbulence in the FT-2 tokamak to better understand the mechanisms behind the energy transfer between GAMs and turbulence and damping of GAMs. Global simulation shows intermittency in GAM activity. Non-linear coupling between GAMs and turbulence is calculated via the cross-bicoherence between poloidal flow and density fluctuations in the frequency space to study the energy transfer between turbulent fluctuations and GAM flows at different time points and radial locations.

Student: Riccardo Nicolo Iorio (AU)
Supervisor: Mathias Groth (AU)
Instructor: Timo Kiviniemi (AU), Eero Hirvijoki (AU)
Topic: *Collisional bracket for the guiding-center Vlasov-Maxwell-Landau model*
Report: As part of a PhD thesis, submitted in September 2023, ELMFIRE gyrokinetic simulations were carried out to assess the implementation of a discrete Landau collision integral aimed at preserving energy and momentum. The adoption of a specific binary collision model, tailored to satisfy the conservation laws, has yielded premiere numerical insights, particularly concerning the impact of variations in impurity density arising from steep gradients in density and temperature profiles. This analysis entails a comparative evaluation, aligning the Landreman-Fülop-Guszejnov

model's analytic theory with the neoclassical predictions of Hazeltine-Hinton and the numerical data generated by the ELMFIRE code. The thesis research presents a novel numerical analysis, exploring the correlation between turbulent transport and the radial electric field. Notably, when employing a Lower Hybrid (LH) heating operator at off-axis and on-axis radial positions for a FT-2 tokamak, heightened turbulence influence has been observed at r/a = 0.55 during a simulation duration of 70μs. In both off/on-axis cases, the influence of turbulence led to more noticeable local fluctuations in the Er profile. However, while in the former the turbulent mode manifested a strong high-shearing flow, with the neoclassical mode exhibiting a more modest contribution, in the latter the magnitude of Er was primarily governed by the neoclassical component, displaying notable deviations from its analytical estimate. These results align with prior research while suggesting the emergence of a robust shearing phenomenon, ultimately leading to the reinstatement of transport to its neoclassical equilibrium.

Student: Henri Kumpulainen (AU)
Supervisor: Mathias Groth (AU)
Instructor: Mathias Groth (AU)
Topic: *Impurity transport in tokamak edge plasmas*
Report: As part of a PhD thesis, completed in June 2023, the validity and options for improvement of simulation codes in predicting tungsten erosion and transport in tokamaks, by code-code comparisons and validation against measurements from JET experiments were carried. The simulations studied in this thesis predict the sputtering of W atoms from plasma-facing components, their ionization in the scrape-off layer, and the transport of W ions parallel and perpendicular to the magnetic field in the scrape-off layer, pedestal, and core plasma regions. The predicted W erosion rate at the JET divertor targets is found to have a negligible impact on the W density in the main plasma due to efficient divertor screening. According to EDGE2D-EIRENE, DIVIMP, and ERO2.0 predictions, the W influx to the main plasma is predominately due to W sputtering near the low-field side divertor entrance due to energetic D atoms created by charge-exchange. Integrated core-edge JINTRAC predictions agree with measurements of the main plasma W density in L-mode, indicating that both the DIVIMP and EDGE2D-EIRENE predictions are consistent with the experimentally inferred W density within a factor of 2. Simulations of high-power type-I ELMy H-mode plasmas, using ERO2.0 for W erosion and transport in the edge plasma and JINTRAC with NEO for core W transport, predict the 2D poloidal W density profile in agreement with the inferred W density within the modelling uncertainties.

Student: Roni Mäenpää (AU)
Supervisor: Mathias Groth (AU)
Instructor: Mathias Groth (AU)
Topic: *Nitrogen transport and chemistry in divertor plasmas*
Report: SOLPS-ITER simulations of nitrogen seeded, low-confinement mode Joint European Torus (JET) plasmas predict that the electron temperature along the low-field side (LFS) divertor leg is reduced by up to a factor of ten when nitrogen is assumed to recycle as molecules (N2) instead of atoms using a fixed nitrogen injection rate. The LFS divertor temperature reduction under the molecular recycling assumption occurs due to a three-step mechanism: 1) the plasma penetration of nitrogen atoms is increased due to the strong triple bond of the N2 molecule and the kinetic energy release in the dissociation event, both mechanisms contributing equally. 2) The abundance of multiply charged nitrogen ions in the divertor is increased. 3) The electron temperature is reduced due to the increase in radiation (by up to a factor of 3) from multiply charged nitrogen ions. ERO2.0 simulations of nitrogen seeding on static background plasma solutions from EDGE2D-EIRENE (previously presented in [1], revised here to include fast reflections) predict that N II, N III and N IV line emission is increased by 40% to 75% when nitrogen is assumed to recycle as molecules, demonstrating the importance of considering the effect of molecular dissociation reactions on the divertor plasma in a self-consistent manner.

Student: Rafael Nuñez (AU)
Supervisor: Andrea Sand (AU)
Instructor: Andrea Sand (AU)
Topic: *Accurate predictions for electronic stopping calculations in radiation-exposed materials.*
Report: Precise estimates of the electronic stopping are important for the radiation damage process, which is of particular interest for fusion materials. The energy losses to the electronic system can be accurately calculated using the rt-TDDFT approach. It enables us to explore the non-adiabatic states of the radiation damage process in real-time and to reveal the role of the different electron orbitals involved in the process. Due to the computational cost of these calculations, it is critical to develop a model that captures electronic losses with rt-TDFFT precision, to be implemented in large-scale simulations.

Student: Patrik Ollus (AU)
Supervisor: Mathias Groth (AU)
Instructors: Antti Snicker (AU, VTT)
Topic: *Modelling fast ions in current and future fusion devices under the effect of charge exchange reactions*
Report: Dedicated experiments were performed in the second physics campaign of MAST Upgrade to investigate beam-ion charge-exchange losses. The neutral density at the outboard plasma edge

was varied by switching the plasma fuelling from the high-field side to the low-field side mid-experiment. Direct measurements show a strong increase in neutral pressure and suggest a degradation of the beam-ion confinement, as expected due to increased charge-exchange losses. However, the presence of other effects, e.g. a sudden decrease in the plasma rotation, makes it difficult to isolate the impact of charge exchange. Detailed analysis of fast charge-exchange neutrals hitting the bolometer diagnostic is underway using the fast-ion orbit-following code ASCOT, with the aim of verifying and quantifying the suspected beam-ion charge-exchange losses. The neutral density is reconstructed based on measurements of the neutral-gas pressure.

Student: Evgeniia Ponomareva (AU)
Supervisor: Andrea Sand (AU)
Instructor: Andrea Sand (AU)
Topic: *Local electronic excitations by slow light ions in tungsten*
Report: Electronic energy losses of hydrogen and helium ions were calculated via rt-TDDFT framework in tungsten. Specifically, the low-energy ion propagation regime was addressed, where the electronic stopping data was lacking. A pre-sampling algorithm was utilized to optimize random trajectory selection, resulting in close agreement between simulated and experimental stopping data. A linear dependence of electronic stopping on ion velocity was observed for close approach trajectories, with distinct slopes for center-channeling ions attributed to activation thresholds of semicore states. The number of explicit electrons considered for tungsten atoms significantly impacted the energy loss data, particularly for helium ions. The ab initio data, benchmarked with experiment, was then translated into a functional form via an implemented fitting algorithm, enabling the study of coupled energy dissipation processes within electronic and atomic subsystems in molecular dynamics simulations.

Student: David Rees (AU)
Supervisor: Mathias Groth (AU)
Instructors: Mathias Groth (AU)
Topic: *The impact of main ion species on divertor plasma detachment in tokamaks*
Report: Experiments in JET ITER-like wall neutral beam injection (NBI) heated, low-confinement mode plasmas found that the current to the divertor targets in helium (He) plasmas was up to 70% lower on the low-field side (LFS) than in otherwise identical deuterium (D) plasmas. The edge plasma density at which the rollover of the divertor current occurred i.e. the onset of detachment, was 10% higher in He plasmas on both the LFS and high-field side (HFS). The total radiated power was similar in He and D plasmas for densities below rollover density. At densities above the rollover

density, the total radiated power and power from within the separatrix are higher in He, reducing the power across the separatrix and subsequently the current to the target. In He plasmas, the peak radiated power was observed in the confined region above the X-point in tomographic reconstructions from bolometry.

The hydrogenic two-point model (H-2PM), an analytical model for the scrape-off layer that predicts a common electron and ion temperature and density along a flux tube from a target temperature and density, was adapted to a single-species He model. Across a range of densities and heating powers, predicted Te was within 20 eV of upstream measurements by high resolution Thomson scattering. For high-recycling conditions, He-2PM predictions of n_e were within 10% of the Li-beam diagnostic measurements, excluding the near-SOL, when assuming Z_{eff} = 1, suggesting the divertor SOL was not fully ionised in the JET-ILW He plasmas.

Student: Filippo Zonta (AU)
Supervisor: Mathias Groth (AU)
Instructor: Eero Hirvijoki (AU)
Topic: *Study of action principles and metriplectic dynamics in plasma physics and their discretization*
Report: As part of the PhD thesis, completed in June 2023, an energy and momentum preserving multi-species particle discretization of the Landau operator was presented. The code was validated against different test cases, including a relaxation example, for two species with mass-ratio 200, and a thermalization example for electron-deuteron species with a real mass-ratio. The numerical results are in excellent agreement with the theoretical estimates. However, while the total momentum is always conserved to machine precision, sporadic jumps in the energy error were observed. A new Monte Carlo integrator, known as the Backward Monte Carlo (BMC) permits integrating the probability to reach a certain target domain, for example, a Fast-Ion Loss Detector (FILD), backward in time, taking into account deterministically the statistical spread of the Monte Carlo collision operator. In such way, the BMC scheme has proven to improve substantially the simulated hit rates of fast ions, and hence their statistics, in a ASDEX Upgrade (AUG) test case with a Neutral Beam Injector (NBI) source. The code for the BMC scheme was developed inside the orbit following code suite ASCOT5, therefore providing an easy, production-ready, and parallelized code that can be used with the existing tool chain in use by the research community.

Student: Qingfei Han (LUT)
Supervisor: Heikki Handroos (LUT)
Instructor: Huapeng Wu (LUT)
Topic: *Multilevel kinematic modulations of geckos running on inclined surfaces*

Report: Gekko gecko demonstrates adept navigation through intricate terrains, facilitated by their hierarchically structured digits adorned with setae. Nevertheless, the dynamic nature of the terrain necessitates modulation of the adhesive apparatus to accommodate gravitational variations. Despite the considerable focus on their adhesive microstructures (setae), uncertainties persist regarding adjustments at the level of digits and feet. To explore the modulation mechanisms employed by geckos, we conducted a kinematic analysis involving five Gekko gecko navigating an inclined racetrack with adjustable angles (0°, 45°, 90°). At 0° and 45°, each limb showcases analogous kinematic adjustments, while diverging at 90°, providing evidence that geckos can manipulate adhesive forces through adjustments in their body apparatus. A gecko-inspired multi-digit device, incorporating adhesive materials, was fabricated to serve as a model system emulating digit orientation. The experimental findings reveal that the gecko-inspired multi-digit device, replicating the interdigital angle during ascent on a 90° slope, manifests increased normal force during vertical dragging and enhanced shear force during tangential pulling. The importance of multi-level kinematic adjustments lies in their potential to provide valuable insights for the development of legged climbing robots and the enhancement of high-performance gaits.

Student: Dongyi Li (LUT)
Supervisor: Huapeng Wu (LUT)
Instructor: Huapeng Wu (LUT)
Topic: *Motion Control of Blanket Remote Maintenance Robot Based on Model Predictive Control Algorithm*
Report: This research studies the motion control of the blanket remote maintenance robot (Mover) of the China Fusion Engineering Test Reactor (CFETR). Firstly, the mathematical model of the Mover Driving Unit (MDU) was established by using physics-based method. Secondly, due to the compact structure of the Mover and the states derivative noise, a state error feedback-based state observer was established in this work. Then, as the inconsistency between the forward and backward mathematical models, the system control is a challenge and therefore a controller based on model predictive control (MPC) is designed. To improve the calculation efficiency and the stability of the actual operation, the control matrix was solved based on the primal-dual method and Hildreth iterative method. Finally, for comparison between the MPC controller and the original PI controller, the simulation and experiments were conducted.

Student: Qi Wang (LUT)
Supervisor: Huapeng Wu (LUT)
Instructor: Huapeng Wu (LUT)
Topic: *The study of the safety methods for the robot working inside the fusion vacuum vessel*
Report: Joint torque sensory feedback is an effective technique for achieving high-performance robot force and motion control. However, most robots are not equipped with joint torque sensors, and it is difficult to add them without changing the joint's mechanical structure. A method for estimating joint torque that exploits the existing structural elasticity of robotic joints with harmonic drive transmission is proposed in this work. In the presented joint torque estimation method, motor-side and link-side position measurements along with a proposed harmonic drive compliance model, are used to realize stiff and sensitive joint torque estimation, without the need for adding an additional elastic body and using strain gauges to measure the joint torque. The proposed method has been experimentally studied and its performance is compared with measurements of a commercial torque sensor. The results have attested the effectiveness of the proposed torque estimation method.

Student: Qiwei Xue (LUT)
Supervisor: Huapeng Wu (LUT)
Instructor: Huapeng Wu (LUT)
Topic: *Study human factor on remoted robotic system based on Machine Learning Method for fusion energy applications*
Report: The target of this research is to detect the brain's movement patterns based on EEG signal processing techniques and machine learning. The key points for EEG signal processing are computing signal features and accurate classifications and extracting features from EEG signals to build automatic mental fatigue measurement and monitoring system. In the future work, the experiment will feed a flow of the EEG signals to the detection algorithm, extract the features, and become invaluable in the prevention of mental-fatigue related accidents. In addition, detecting mental stress by using Photoplethysmography (PPG) is one another way, and detecting PPG signals using machine vision involves a camera to capture subtle changes in skin color caused by variations in blood volume. This study will also work on machine vision to detect stress using machine leaning algorithm.

Student: Zhixin Yao (LUT)
Supervisor: Huapeng Wu (LUT)
Instructor: Huapeng Wu (LUT)

Topic: *Equatorial Port Remote Maintenance Systems Development - MPD*

Report: The research studies the equatorial port remote maintenance system – MPD. Firstly, the new structure design has been developed, and two versions of MPD: the short version 7 DOF, and the long version 9 DOF have been designed. Secondly, the workspace of those two versions of MPD has been analyzed. Thirdly, the structural analysis has been carried out including the structural deformation analysis, modal analysis, and earthquake load analysis. Fourthly, the dynamic of the MPD has been modelled, and the dynamic performance error is analyzed. Finally, the wrist joint which suffers from the maximum bending moment and torsional load has been designed in detail, and the wrist joint test platform has been built up to provide the essential basis for the detailed design of the entire MPD.

Student: Ruochen Yin (LUT)
Supervisor: Huapeng Wu (LUT)
Instructor: Huapeng Wu (LUT)
Topic: *Learning based peg-in-hole Assembly Task for Fusion Application*
Report: This research focuses on peg-in-hole assembly based on a two-phase scheme and force/torque sensor (F/T sensor) for a compliant dual-arm robot, the Baxter robot. The coordinated operations of human beings in assembly applications are applied to the behaviors of the robot. A two-phase assembly scheme is proposed to overcome the inaccurate positioning of the compliant dual-arm robot. The position and orientation of assembly pieces are adjusted respectively in an active compliant manner according to the forces and torques derived by a six degrees-of-freedom (6-DOF) F/T sensor. Experiments are conducted to verify the effectiveness and efficiency of the proposed assembly scheme. The performances of the dual-arm robot are consistent with those of human beings in the peg-in-hole assembly process. The peg and hole with 0.5 mm clearance for round pieces and square pieces can be assembled successfully.

Student: Laura Maria Goncalves Ribeiro (TUNI)
Supervisor: Atanas Gotchev (TUNI)
Instructor: Atanas Gotchev (TUNI)
Topic: *Target Tracking Using Optical Markers for Remote Handling in ITER*
Report: In the year 2023 the work has been complete. The dissertation was subjected to public examination and passed with distinction. The work focused on the development of methodologies to extract the six-degree of freedom pose of operational targets at ITER. More

specifically, the work focused on the development of retro reflective optical markers that can be easily detected in images and withstand the challenging environment conditions in ITER's divertor; the development of a robust, interpretable algorithm for marker detection and identification. The developed strategies were extensively tested on realistic test setups of relevant use cases and can estimate pose of targets reliably, with an end-to-end positional error in the range of a few millimeters.

Student: Lionel Hulttinen (TUNI)
Supervisor: Jouni Mattila (TUNI)
Instructor: Jouni Mattila (TUNI)
Topic: *Parameter Identification and Compensation for Actuator Nonlinearities for Remote Handling Manipulator Control*
Report: In the ITER vacuum vessel, precise motion and force control of the slave devices are a necessity to telemanipulate divertor cassettes weighing up to several tonnes. For successful remote handling tasks, the slave devices should be aware of their own actuation capabilities, which calls for data-driven system identification. However, traditional learning and adaptation techniques do not account for the underlying physical feasibility conditions, which could help identifying the system dynamics more robustly using limited available data. This PhD study focuses on developing feasibility-aware identification and adaptation methods for serial manipulators with arbitrary topology, easing commissioning of nonlinear model-based controllers for such systems.

Student: Pauli Mustalahti (TUNI)
Supervisor: Jouni Mattila (TUNI)
Instructor: Jouni Mattila (TUNI)
Topic: *Bilateral force reflecting master-slave control system development for heavy-duty RH manipulators subject to high-gear ratios and static nonlinearities*
Report: In ITER Remote Handling (RH) manipulator operations in vacuum vessel are subject to heavy loads in a limited space. These operations require RH devices with high mechanical gear ratios with a high-precision force/motion control. However, the dynamic behavior of manipulators with gears nonlinearities makes control design and their stability analysis an extremely challenging task. This study focuses on developing model-based control methods for heavy-duty RH manipulators subject to high-gear ratios and associated static nonlinearities.

Student: Pejk Amoroso (UH)
Supervisor: Filip Tuomisto (UH)

Instructors: Jonatan Slotte (UH)
Topic: *Characterization of Novel Ge-based Materials for Advanced Radiation Sensors*
Report: Ge-based materials are used for a wide range of radiation detection and sensor applications. Doping germanium with other elements enables control of the photonic and electronic properties of the material. The objective of the project is to characterize point defects in novel types of doped Ge and Ge-based compound semiconductors, and thus obtain a better understanding in how to obtain desirable properties for materials for advanced radiation sensors. My current research focuses on Ga-doped Ge, GeSi and GeSn, for all of which interesting and unexpected results have been obtained. The main experimental method used for defect characterization is Positron Annihilation Spectroscopy (PAS), while Ion Beam Analysis techniques (IBA) have been used for elemental concentration analysis and depth profiling.

Student: Zhehao Chen (UH)
Supervisor: Filip Tuomisto (UH)
Instructors: Filip Tuomisto (UH)
Topic: *Irradiation damage on high entropy alloys*
Report: In 2023, we investigated the evolution and migration of helium bubbles in 3D-printed and arc-melted High-Entropy Alloys (HEAs), and 304 Stainless Steel using a transmission electron microscope (TEM). To understand the migration and growth patterns of helium bubbles, and their implications for materials deployed in radiation environments, HEAs are subjected to nickel and helium irradiation as well as subsequent annealing conditions. After irradiation at room temperature, all samples initially displayed similar helium bubble sizes. Annealing up to 673K had a minimal impact on bubble size. However, annealing at 873K led to significant bubble growth. The larger average bubble size was observed in the HEA compared to 304 Stainless Steel, while a higher proportion of small bubbles was found in the 304 Stainless Steel. This indicates that Ostwald Ripening (OR) is more prevalent in 304 Stainless Steel, which is further confirmed by in-situ TEM annealing observations. Depth distribution analysis revealed distinct damage belts after annealing in the samples; from the narrowest in 3D printed HEA to the broadest belts in 304 Stainless Steel. These results indicate that the helium concentration at the peak of irradiation damage decreases in the same order. This phenomenon suggests limited long-term migration of helium atoms in both the Cantor and 3D-printed Cantor HEAs, potentially due to the complex and random diffusion paths of helium atoms.

Student: Aslak Fellman (UH)
Supervisor: Kai Nordlund (UH)
Instructors: Fluyra Djuberokova (UH)
Topic: *Machine learning potentials for FCC high-entropy alloys*
Report: Developing machine learning (ML) interatomic potentials for fusion relevant high-entropy alloys. The ML models are based on gaussian process regression and are trained on density functional theory data. The potentials were designed for radiation damage simulation applications, including explicit short-range repulsion. Using the developed potentials we have studied radiation damage in FCC high-entropy alloys. Work on FCC HEA ML potentials was presented with a poster at the 21st international conference on fusion reactor materials (October 22-27, 2023, Granada, Spain) with the title of "Machine learning interatomic potentials for FCC high-entropy alloys".

Student: Faith Kporha (UH)
Supervisor: Kai Nordlund (UH)
Instructors: Fredric Granberg (UH)
Topic: *Sputtering of Deuterium Decorated Tungsten Surfaces*
Report: Last year, we studied W and D sputtering from deuterium-decorated tungsten surfaces at 100 eV and 200 eV argon irradiation, using Molecular Dynamics. We analysed sputtering yield dependencies on surface orientations, incident angles, deuterium decoration levels, and ion energies with two different interatomic potentials. Our studies showed that all parameters affected sputtering yields, consistent with other simulations and experiments. We also observed contrasting W sputtering results between the two potentials employed. Further research aims to determine the most appropriate potential for describing the sputtering process.

Student: Oskar Lappi (UH)
Supervisor: Keijo Heljanko (UH)
Instructor: Jan Åström (CSC)
Topic: *Software quality and performance in large-scale HPC*
Report: I have worked on the Eiron project to achieve scalable and reproducible simulations using domain decomposition and asynchronous communication for neutral particle transport.
The Eiron project is nearing a first release. Eiron produces deterministic outputs regardless of how it has been parallelized, this is achieved by using one RNG stream per particle. OpenMP parallelization and a pipelined MPI solution are implemented. A full domain decomposed simulation is still in progress, but the communication design has been completed and verified. A domain

decomposed solution would scale to multiple nodes and remove the artificial memory limit holding back the resolution of EIRENE simulations, allowing more accurate simulations for ITER simulations.

Once finished, the performance and design work done in Eiron can be applied to the development of EIRENE. If Eiron as a tool proves to fit the needs of the fusion community, work can also begin to port more features

Student: Victor Lindblad (UH)
Supervisor: Kai Nordlund (UH)
Instructors: Fredric Granberg (UH)
Topic: *Studying kink formations on screw dislocation lines, using MD*
Report: Future fusion reactors will be subjected to various forms of irradiation, such as neutron and ion irradiation. This will inevitably lead to damage accumulation in the structural components of the reactors. Understanding to which extent this damage accumulation occurs and how this changes the integrity of the components is of utmost importance. Both from a safety perspective as well as from an operational point of view. Our task is to study irradiation effects in materials proposed to be used in the ITER reactor. Due to its high melting temperature, heat shields are planned to use Tungsten (W). We are therefore performing various irradiation simulation schemes in pure W and W with embedded impurities to understand the underlying mechanisms for damage accumulation and the retention of central impurities such as Deuterium (D) and Tritium (T). Since T is radioactive, the amount of expected retention needs to be determined and eventually monitored closely.

Student: Anna Liski (UH)
Supervisor: Filip Tuomisto (UH)
Instructors: Filip Tuomisto (UH), Tommy Ahlgren (UH)
Topic: Refractory high-entropy alloys as plasma-facing wall materials
Report: Refractory high-entropy alloys are class of metals composed of 5 or more components in equal proportions. These alloys demonstrate extreme durability in high temperatures and are promising materials for extreme environment applications, such as fusion first-wall. As a plasma facing material the interactions with hydrogen become important for consideration and understanding the parameters influencing hydrogen retention into high-entropy alloy need to be considered before any applications. We employ W beam to pre-damage the lattice in a controllable amount and introduce deuterium with low-energy ion-implanter. The remained amounts of deuterium are analyzed with ion beam analysis tools and thermal desorption spectrometry. Additionally, first-principles

calculations were crucial for relating the effect of microstructure with retention properites. The microstructure was characterized by scanning electron microscopy.

Student: Bruno Oliveira Cattelan (UH)
Supervisor: Fredric Granberg (UH)
Instructors: Fredric Granberg (UH)
Topic: *A Machine Learning Approach for Binding Energy Estimation in Dislocations*
Report: In this project we aim at showing the benefits of surrogate models for dislocation binding energy simulations when atom vacancies are present. We use neural networks with distribution estimation to predict both the energy and prediction quality. From our experiments we saw that 25% of the points have low certainty and can be automatically identified and removed. These can be rerun using traditional methods. The work was presented as a poster in FCAI AI Day 2023. A paper is currently being written.

Student: Emil Amnell (UH)
Supervisor: Fredric Granberg (UH)
Instructors: Aaro Järvinen (VTT)
Topic: *Determining optimal parameters values for LHCD reduced model using Bayesian Optimization*
Report: The Lower Hybrid Current Drive, LHCD, reduced model is orders of magnitude faster than standard LH modelling methods but introduces a hyperparameter that needs to be chosen by the user. We employed Bayesian optimization to match model results to experiments in a database of hundreds of shots and times from discharges from WEST. We constructed the posterior distribution for the optimal parameter value for each entry in the database using MCMC to quantify the uncertainty in our results. This way, we identified the range of overall good parameter values to use in practice.

Student: Igor Prozheev (UH)
Supervisor: Filip Tuomisto (UH)
Instructors: Filip Tuomisto (UH)
Topic: *Electrical compensation and acceptor-type carrier traps in nitride semiconductors and interfaces*
Report: Work during 2023 included conducting an experiment that directly indicate that the formation of acceptor-type defects or the presence of acceptor impurities are inefficient for the compensation of Si donors in GaN and AlGaN. The key finding showed that the compensation seems spatially correlated or dependent on the Si doping level, which raises a complicated question of the local

environment vs. the Fermi level phenomenon. Experimental findings were supported by theoretical calculations based on density functional theory for obtaining electrical configuration of studied defects in nitride lattices. Further investigation and enhanced electronic structure calculations continues in 2024

Student: Jintong Wu (UH)
Supervisor: Fredric Granberg (UH)
Instructors: Fredric Granberg (UH)
Topic: *High dose irradiation simulation of tungsten*
Report: Work during 2023 included investigating the micro-structural evolution, based on a totally novel approach. The idea is based on extracting the local strain field, to characterize the elasto-plastic deformation during high dose irradiation for tungsten. Also, the study on how to do a realistic dose rate micro-scale irradiation simulation, by combing Objective Kinetic Monte Carlo, with classical Molecular dynamics, is still undergoing. Further analysis continues in 2024.

Student: Iuliia Zhelezova (UH)
Supervisor: Filip Tuomisto (UH)
Instructors: Filip Tuomisto (UH)
Topic: *Point defect and radiation hardness of beta-Ga_2O_3 semiconductor crystal*
Report: We have applied positron annihilation spectroscopy to study the vacancy-type defects in β-Ga2O3 single crystals. The three different types of crystals were prepared by Czochralski and edge-defined film-fed growth, and doped with Fe, Mg and Sn for semi-insulating and n-type characteristics. The crystals were also subjected to 6-MeV proton irradiation for controlled introduction of mono-vacancy defects. Positron lifetime and the details of the anisotropy of the Doppler broadening signals were measured as a function of temperature, and the results compared with the annihilation signals predicted by theoretical calculations. We find Ga vacancies in all three basic split Ga vacancy configurations to dominate the positron data in the as-grown crystals. In contrast, unrelaxed Ga vacancies are found as the main defect introduced by the irradiation.

Student: Nikola Petkov (UKAEA)
Supervisor: Huapeng Wu (LUT)
Instructor: Roger Powell (UKAEA)
Topic: *Condition monitoring of Remote handling system for DEMO*

Report: The design of the remote maintenance system (RMS) is a crucial variable in the design of future fusion reactors and can also become a bottleneck in the entire design process. The concept design of the RMS is also very time-consuming and requires the exploration of multiple possible solutions to select the most optimal one. The potential for overlooking better solutions due to concerns about remaining on schedule and not delaying the entire design process is a risk that must be considered. Our goal is to create a machine learning system that suggests concept solutions for long-reach robots that are both streamlined and efficient, and to increase the speed of the concept design process by at least 50%. The method proposes a solution in two ways: direct prediction, which is relatively fast but may not be as accurate, and enhanced prediction, which uses a physics simulator and trajectory MCTS to calculate the configuration value function.

Student: Tom Andersson (VTT)
Supervisor: Hannu Hänninen (AU)
Instructors: Anssi Laukkanen (VTT), Matti Lindroos (VTT)
Topic: *Thermomechanical crystal plasticity model for predicting copper deformation damage mechanisms.*
Report: The aim of the work is to formulate a physics-based model for predicting precipitate hardened copper behaviour as a function of temperature. Cr and Zr precipitates in the copper grades are taken into account either explicitly in the model geometry, representative volume element RVE, or as a hardening term in the material model depending on the size of the precipitate. The evolution of the precipitates during the manufacturing of the material (component) and during the operation is investigated with electron microscopy methods. The project's first years focused on studying the basics of deformation mechanisms of the material, surveying literature for available data and characterizing the microstructural features affecting the deformation mechanisms and developing crystal-plasticity material model that could adequately describe material behaviour at wide temperature range.

Student: Anu Kirjasuo (VTT)
Supervisor: Filip Tuomisto (UH)
Instructors: Antti Salmi (VTT), Tuoma Tala (VTT)
Topic: *Intrinsic torque in JET ohmic plasmas of different hydrogenic isotopes*
Report: Intrinsic torque has been studied in JET ohmic plasmas on hydrogen, deuterium, and tritium. These plasmas exhibit intrinsic rotation and two intrinsic rotation reversals with changing density, but at slightly different density for each of the isotopes (ref.

F.M.Nave NF 2023). In this research, intrinsic torque is estimated based on intrinsic rotation measured, and assumptions on Prantdl number and pinch, and an isotope dependence is found in the intrinsic torque required for the experimentally measured intrinsic rotation.

Student: Saifi Qais (VTT)
Supervisor: Huapeng Wu (LUT)
Instructor: Brace William (VTT), Ming Li (LUT)
Topic: *Advancing Stochastic Simulations for Nonlinear Problems: Leveraging the Transformation Law of Probability Density*
Report: In engineering, uncertainties pervade product lifecycles, presenting significant challenges to design reliability and safety, particularly in safety-sensitive industries such as nuclear. Stochastic simulations, leveraging Monte Carlo Sampling, machine learning, and parallel computing, are indispensable for addressing these uncertainties. However, they often overlook the direct influence of prediction models on predicted probability distributions, compromising both efficiency and accuracy. This work thoroughly investigates the impact of prediction models on predicted probability distributions, presenting a novel mathematical framework to establish the transformation law of probability density. Additionally, we develop the Finite Cell Weight Variation method based on this transformation law. The proposed method seamlessly integrates prediction models into state probability predictions, enhancing reliability assessments while preserving high levels of accuracy and computational efficiency. We illustrate the method's effectiveness with practical examples and validation using Latin Hypercube Sampling (LHS), where several input variables are statistically determined. Our estimation of the probability of the predicted state closely aligns with results obtained using LHS. Furthermore, we explore the implications of our findings and outline future directions in stochastic simulations aimed at strengthening reliability assessments.

5.2 WP TRA: EUROfusion Researcher and Engineering Grants

5.2.1 A methodology for cracks tolerance assessment in irradiation embrittled EUROFER Reduced Activation Ferritic Martensitic (RAFM) Steel

Research scientist: A. Freimanis, VTT

Radiation damage leads to material hardening and embrittlement. Moreover, radiation damage in fusion reactors is expected to be by a magnitude larger than in the current fission reactors. Therefore, novel material and fracture modelling techniques are required to assess the safety of reactor designs made from EUROFER97 structural steel. We have developed and implemented a new crystal plasticity material model for irradiation hardening, gathered a large data set with EUROFER97 material properties, and done the preliminary work on the fracture model. The next steps are to implement the fracture behaviour in our computational code and focus on fracture toughness assessment in EUROFER97 steel. Currently, one paper is in its final writing stage and two more are planned.

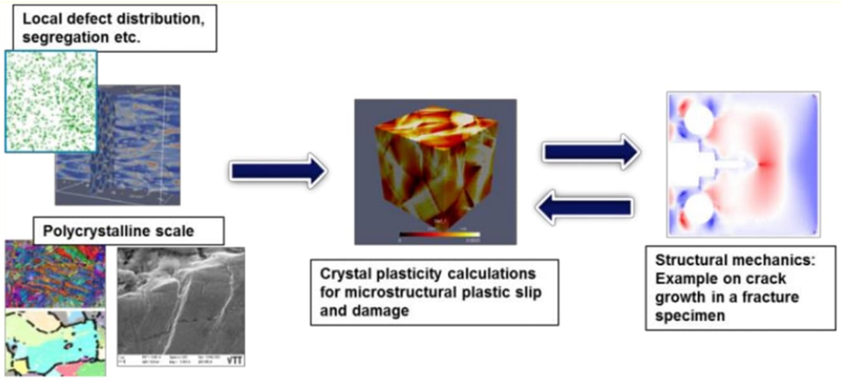


Figure 5.1: Assessment of fracture toughness through multiscale modelling.

5.2.2 Fast-particle modelling in fusion plasmas and surrounding materials

Research scientist: L. Sanchis, AU

The recently developed AFSI-Serpent toolchain allows calculating the transport of fusion neutrons in a geometry that can be as complex as a CAD model allows. After successful tests with an AUG-like toy model, it was applied to a JET model. The full 3D geometry of the JET vessel was implemented in Serpent to calculate the neutron flux through the different components. The neutron reaction rates for thermonuclear and beam-target DT reactions were calculated by AFSI using realistic plasma parameters, and the reaction-rate matrices were converted to neutron sources in json format, to serve as an input for Serpent transport calculations. As a result, a neutron flux spectrum was calculated at the Fission-Chamber detectors, which will be validated by the experimental data from DT/DT2 campaigns.

Further development of the Backward Monte Carlo (BMC) method for addressing wall loads was stopped due to limitations in including the 3D geometry of the wall.

The evaluation of the wall collisions of the particles, necessary for calculating accurate distribution of power loads, increased the running times of the simulation largely above our initial estimations.

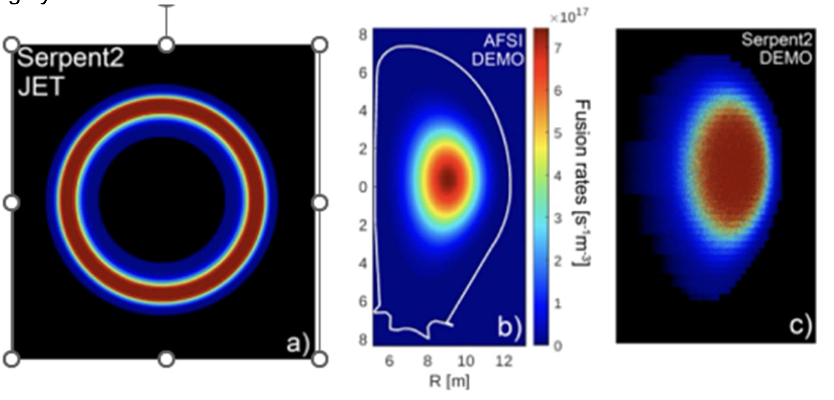


Figure 5.2 a) Top view of the n source calculated from AFSI reaction rates and implemented in Serpent. b) Neutron rate from the thermonuclear DD and DT reactions. c) Neutron source read by Serpent

6. International collaborations

6.1 DIII-D tokamak

6.1.1 Comparisons of electron temperature, density, and pressure profiles in DIII-D Discharges with EDGE2D-EIRENE predictions

Research scientists: M. Groth, AU

EIRENE predictions of atomic and molecular emission in DIII-D low-confinement mode high-recycling and partially detached plasmas are within 50% of spectroscopic measurements of the Lyman and Balmer series, and Fulcher molecular band emission when constrained by 2D Divertor Thomson Scattering (DTS) and Langmuir probe (LP) measurements. Hence, for measured recycling flux and (electron) plasma conditions, and in the absence of ELMs and other transients, the combination of plasma recycling models, the applied AMJUEL atomic and molecular rates, and the neutral transport model in EIRENE reproduces the deuterium emission within the uncertainty of the measurements and code setup. These studies isolate the issue of EDGE2D-EIRENE underestimating atomic and molecular emission to accurately predicting the 2D plasma distributions.

For high-recycling divertor plasma conditions, at the onset of divertor detachment, substituting the EDGE2D-EIRENE predicted plasma conditions with the DTS electron temperature and densities, and the predicted target ion fluxes with the LP-measured ion fluxes, results in a <20% decrease in the Lyman and Balmer alpha emission, but a fivefold reduction in the Fulcher and Lyman-Werner band emission. In these conditions, the measured electron temperature (T_e) and densities (n_e) at the target plate were of the order 2-3 eV and 3-4x10^{20} m^{-3}. The reduction in the predicted molecular emission for the DTS/LP case versus the EDGE2D-EIRENE background plasma case is driven by the reduction of the molecular density in the plasma region directly adjacent to the divertor target plate. Significantly larger discrepancies between the atomic and molecular emission for the EDGE2D-EIRENE predicted and DTS/LP imposed plasma background are observed for partially detached divertor conditions, $T_{e,plate}$ approx. 0.5 eV, $n_{e,plate}$ approx. 2.5 x10^{20} m^{-3}. For these conditions, EDGE2D-EIRENE critically predicts n_e to peak at the target plate, while the DTS-measured n_e was observed to peak halfway between the target plate and the divertor X-point.

6.2 CFETR tokamak

Research scientists: H. Handroos, H. Wu, LUT

The welding/cutting robot machine developed by LUT is tested in CFETR VV assembly. The robot machine can fully fulfit the assembly task and reach the required performance.

Figure 6.1. Robotic machine carring out machning inside of the VV.

6.3 KSTAR tokamak

Research scientists: A. Kirjasuo, A. Salmi, T. Tala, VTT

Extrapolating results from current day experiments to larger future fusion devises poses a challenge. One approach is overcome this is by utilising dimensionless quantities in experimental analysis. The 4-point ρ* scan experiment for momentum transport with NBI modulation was conducted in 2022. The aim of the experiment was to gain further insights of momentum transport coefficients and intrinsic torque as a function of ρ* at KSTAR as part of the ITPA TC-9 group on Intrinsic rotation and torque for ITER rotation prediction in L- and H-modes. The initial analysis results show that there is an average of 1.7x difference in ρ* when the q profile is very nicely matched and both υ* and β* have a max. average variation of less than 25% in the analysis interval of rho = 0.3-0.7. The modulation is very clearly visible across the whole radius, with clear amplitude and fairly flat phase profiles. Ion temperature and electron density profiles display modulation that is lower than the rotation modulation. Pulses form a good set for analysis with the new momentum transport coefficients determination methodology in 2024.

6.4 EAST tokamak

Research scientists: S Sipilä, AU

As the first simulation cases of collaboration with EAST tokamak, ASCOT4-RFOF simulations of ICRH on a 5% hydrogen population were made to evaluate the hot ion tail distribution of EAST discharges 110375 and 119576.

7. Fusion for Energy activities

7.1 Development and integration of 3D Machine Vision, HLCS modules and GENROBOT at DTP2

F4E grant: F4E-GRT-0901

Research scientists: J. Alanen, H. Saarinen, VTT
A. Gotchev, L. Gonçalves Ribeiro, O. Suominen, V. Vechtomov, TUNI

The new ITER Remote Handling Control System (RHCS) with the following system elements were integrated, tested, and demonstrated at Divertor Test Platform, DTP, VTT, Tampere:

- Command and Control (C&C), by GTD
- Virtual Reality (VR), by VTT, based on Unity VR engine
- Remote Diagnostics Application (RDA), by VTT
- Genrobot, by GTD
- Digital Valve (DigiValve), by Tamlink and Fluiconnecto
- 3DNode (a separate demo, not during the 2nd cassette operations), by Tampere University
- Low Level CIP (LLC) communications layer, by GTD.

The RHCS was demonstrated for Fusion for Energy, ITER Organisation, and ITER Domestic Agencies of Japan and Korea on 23rd and 24th of January 2024 by running the 2nd Divertor Cassette removal and installation operations. The operations were carried out twice, both successfully.

Figure 7.1. A view of the DTP2 operator room. The displays left to right; lower row: An Excel implementation of the Operations Management System, Command & Control operator user interface, and Remote Diagnostics Application; upper row: Virtual Reality, and camera view from the inner rail of the reactor towards the maintenance tunnel.

7.2 Digivalve tests on DTP2

F4E grant: F4E-GRT-0974

Research scientists: H. Sairiala, Fluiconnecto
J. Erkkilä, M. Paloniitty, L. Siivonen, Tamlink
J. Alanen, O. Rantanen, H. Saarinen, M. Siuko, VTT

DigiValve, the water hydraulic digital valve created by Tamlink and Fluiconnecto, was in use throughout the central cassette and 2nd cassette operations (carried out under GRT-0901, see Section 7.1), instead of traditional servo valves. DigiValve controlled, with half-millimetre precision, four joints of the Cassette Multifunctional Robot (CMM) and its second cassette end-effector: lift, tilt, cantilever rotation and hook plate rotation. DigiValve turned out to be very accurate and reliable in controlling the movements of the 10-ton divertor cassette. Even in case one of its on-off valve amplifiers failed, operations could be carried out well; only the accuracy was affected a bit. Also, no problems with the impurity of the water occurred. These are proof of DigiValve's resilience in difficult conditions.

Figure 7.2. DigiValve cantiever rotation and hookplate rotation valves.

8. Completentary research in Finnfusion

8.1 ECO-Fusion activities (VTT)

Research scientists: Tiina Apilo, Juuli Huuhanmäki, Sofi Kurki, Jorge Martins, Tapani Ryynänen, Olli Soppela, Antti-Jussi Tahvanainen, Arto Wallin, VTT

One of the primary focal points of the project revolves around fusion ecosystems and business models. Throughout 2023, efforts persisted in delving deeper into this realm, with the objective of comprehending the interconnection and potential synergy between international fusion projects and their implications for Finnish companies. Various research methodologies were employed not only to amass pertinent information but also to facilitate knowledge dissemination among companies, thereby enriching their understanding of the fusion industry.

In 2023, a Delphi research method was used to gather experts' views on the future of fusion technology. The goal was to engage experts in active discussions and thereby initiate new understandings and viewpoints for everyone. The Delphi study involved two rounds of inquiries and pre-understanding workshops, with the second round building upon the answers from the first round. Several organizations participated in the research, including research institutions, companies, and government organizations. These organizations represented multiple countries, such as Finland, Italy, Germany, the United States, Hungary, France, the Netherlands, and Estonia. The research results will be published in 2024.

In the area of modeling, work focused on to understand and identify leverage points to increase participation of Finnish companies on fusion related commercial projects. This was done by building systems-based views on fusion tenders. Three different approaches were used: systems thinking, modelling and agent-based modelling. Work was divided into three phases:

Phase 1: Systems mapping (qualitative modelling) – goal to provide common understanding about fusion energy related organizations, supply chain practices and tendering processes

Phase 2: System dynamic modelling – goal to understand system's behaviour on high level ("population level" cf. epidemiologic modelling of spread of disease in populations)

Phase 3: Simulation with agent-based model - goal to model behavior of individual agents (companies) who are faced with decisions to participate in fusion ecosystem, fusion tenders and projects.

Also interviews in Finland and abroad were conducted with focus on business potential through ambidexterity perspective. Based on this an academic article was published: "Insights into the buyer-supplier cooperative relations in big science", Jorge Martins, CInet, 2023.

8.2 ECO-Fusion activities (UH)

Research scientists: Fredric Granberg, Kai Nordlund, UH, Aaro Järvinen, VTT
Rahul Nagaraja, Quanscient Ltd

The ECO-Fusion project at UH is a collaboration between the ACH in Finland and Quanscient Ltd, with the goal to transition fusion simulation codes to the quantum era. The Sparselizard open-source C++ finite element library provides a framework for numerical implementation of multiphysics systems and domain-decomposition capabilities for high-performance computing. The collaboration aims to take advantage of these for numerical simulation of models describing the scrape-off layer (SOL) plasma. As a first step, the one-dimensional isothermal fluid approximation for SOL plasma was implemented and successfully validated with analytical solutions. Successively, an energy conservation equation was implemented so that the plasma temperature is determined in a self-consistent manner. This was verified against the two-point model. The code is extended to consider losses and collision processes. The results from Sparselizard simulations are being benchmarked against that of SD1D code for cases of uniform volumetric source and energy transfer due to either heat conduction or heat convection (see Figure 8.1) or both.

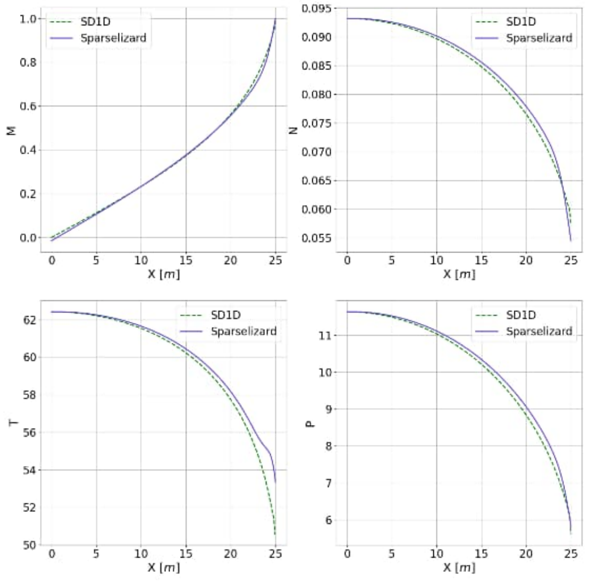


Figure 8.1: Comparison of SOL plasma profiles between Sparselizard and SD1D for uniform particle and heat source with convection as the sole heat transfer mechanism.

8.3 Partner activities

8.3.1 Comatec Oy, remote maintenance

Research scientists: V. Puumala, S. Muhlig-Hofmann, Comatec Oy

Comatec Group is an engineering company that provides and develops design, project management and expert services. The group employs more than 600 professionals in over 20 locations in 5 countries. Comatec is particularly known for its ability to carry out challenging assignments in the technology industry and the field of mechanical engineering. Comatec's solutions are always based on tried and tested up-to-date technology.

Comatec has participated in the development of remote maintenance equipment for the DEMO fusion reactor. The work has included detailed CAD design and analysis of main components, identification of the most important technical challenges and requirements, and visualization of maintenance activities with animations based on virtual reality. The work is linked to WP RM (section 3.8 WP RM: DEMO Remote maintenance).

8.3.2 Electro Optical Systems Finland Oy (EOS Finland Oy)¸ Novel AM materials for Energy Generation (NAMMEG)

Research scientists: A. Mutanen, J. Ottelin, J. Välikangas, P. Ylander, EOS Finland Oy

Electro Optical Systems Finland Oy (EOS) is a competence center for metal materials for additive manufacturing (AM), developing metal materials and process products for EOS Laser-based Powder-Bed Fusion (L-PBF) systems. In this project "Novel AM materials for Energy Generation (NAMMEG), we are developing materials of high interest for the energy generation industry. New materials are needed to elevate AM as an innovative production method providing new solutions and help take technological leaps in energy generation. EOS Finland Oy has now concentrated on AM process development of tungsten and zirconium materials. For tungsten, the target is to develop a high productivity process with optimal microstructure for selection of applications. For Zirconium, it was mandatory to modify our EOS laser printing machine for safe powder handling and processing as the material is highly flammable. Now we have successfully printed also real larger parts.

8.3.3 Luvata PORI Oy, Heat resistant coppers for fusion reactors

Research scientists: S. Hernesniemi, O. Naukkarinen, W. Rajala, T. Renfors, S. Terho, S. Palm, Luvata Pori Oy

Luvata Pori has completed this project and demonstrated that heat-resistant coppers can be manufactured utilizing the new extrusion press, hot rolling, and hot forging. The achieved material properties are now in line with the demanding customers' specifications. There is a lot of interest from fusion and high-energy physics applications and our commercial deliveries have started. The selection, procurement, installation, and startup of the new hot extruder was a huge undertaking, requiring also significant modifications to surrounding processes enabling now manufacturing of these heat-resistant coppers.

VTT also completed their material modelling starting from the billet casting, hot and cold deformations until the final heat treatment. The modelling has helped Luvata to optimize its manufacturing processes to achieve the required properties of the materials.

8.3.4 Platom Ltd, International Licensing Framework in Challenging Environments

Research scientists: K. Hassinen, S. Kiviluoto, T. Kivirinta, J. Maunula, M. Nordlund, S. Sihvola, Platom Oy

Platom is a company providing expert services in the nuclear field focusing on the main areas of safety, engineering, operability, and licensing, quality and project management.

Platom is part of the Business Finland co-innovation project ECO-Fusion with the aim to develop a licensing framework, which can be applied to fusion (as well as to other potential new technologies) internationally and in Finland. During the year 2023 this framework advanced on several fronts. Effort was put in gathering experiences from earlier projects and refining them into actionable items for improved quality of services. Requirement management saw development in order to be utilized effectively, and a related piloting work was completed. The so-called "licensing tool" was prepared for further development and a data set was tested for qualification and data management.

In addition to the co-innovation project, task planning was initiated for 2024 EUROfusion work.

8.4 STEP collaboration

8.4.1 Ongoing activation of cross-field drifts in SOLPS-ITER simulations of STEP with fully tracked Ar impurities

Research Scientists: J. Karhunen, A. Järvinen VTT

Following successful activation of the cross-field drifts in SOLPS-ITER simulations of STEP in simulations mimicking spatially constant Ar concentrations, an effort has been made to ramp up the drift contributions in simulations with fully tracked Ar impurities. Expectedly, further challenges have been met with the increased complexity of the simulation setup, yielding slower progress than with the fixed Ar fraction. Via further attention on the numerical aspects of the simulation setup, a previously unreached activation degree of 77% has been achieved while avoiding divergence of the simulations. However, work to complete the activation of the drift terms is still ongoing.

8.5 Code development in FinnFusion

8.5.1 Apros

Research Scientists: S. Norrman, M. Szogradi, VTT

Apros is a commercial software platform, owned by VTT and Fortum, for system-wide modelling and dynamic simulation of process, automation and electrical systems. The scope of applications varies from small computational experiments to full-scope training simulators of industrial plants, both in the conventional and nuclear fields. The thermal hydraulic (T/H) model library features different sets of governing equations for one dimensional water/steam/gas flow (homogeneous and 6-eq.) and for a wide range of other fluids (homogeneous). T/H models have been validated against a set of separate effect tests and integral tests. A simulation model is built and configured with a graphical user interface (see Figure 8.2). Within EUROfusion, several alternatives of Balance-of-Plant (BoP) configurations have been developed and investigated during the Pre-conceptual Design Phase of DEMO by means of dynamic simulations of normal operation of the plant. This work continues in the Conceptual Design Phase.

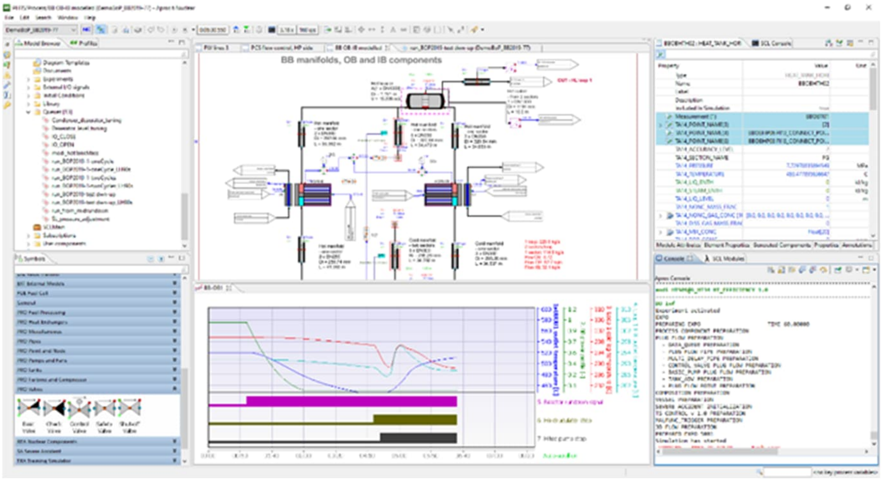


Figure 8.2. Apros user interface.

8.5.2 ASCOT5 – a state-of-the-art simulation environment for fast ions and beyond

Research Scientists: A. Snicker, K. Särkimäki, S. Äkäslompolo, T. Kurki-Suonio, P. Ollus, L. Sanchis, S. Sipilä, F. Zonta, G. Fourestey, AU

ASCOT5 was made open source and is now hosted on GitHub (see https://github.com/ascot4fusion/ascot5). Online documentation and tutorials were also made available. A second EuroFusion training camp was organized with around twenty participants including public and private sector researchers. GPU porting reached a milestone (Figure 8.3), where in principle collisionless simulations are production ready. Porting to IMAS is progressing (and described in Section 8.5.3).

New physics implemented in the code include collecting constants-of-motion distribution and modelling charge-exchange and beam ionization using ADAS. Code is actively used by various institutions across the globe. User support is handled via slack channel and GitHub issue tracker.

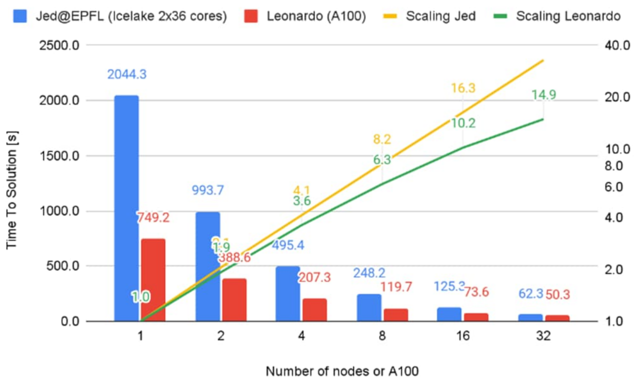


Figure 8.3. Comparison of a collisionless simulation with 1 million markers when ASCOT5 is run in CPUs (Icelake) or GPUs (A100). Courtesy of EPFL-ACH.

8.5.3 Orbit-following ICRH Monte Carlo code ASCOT4-RFOF

Research Scientists: Seppo Sipilä, AU

With the IMAS support and ICRH capability of ASCOT5 under development, support for ICRH simulation capable ASCOT4-RFOF, basic ASCOT4 and related actors in the IMAS environment was continued. Work was initiated to use ICRH wave data from the CYRANO wave code under IMAS.

8.5.4 Full-f gyrokinetic turbulence code ELMFIRE

Research scientists: T. Kiviniemi, F. Albert, E. Hirvijoki, R. Iorio, S. Leerink, F. Zonta, AU
L. Chôné, UH

Over the years, backbone of ELMFIRE work has been collaboration with experimental group in Ioffe Institute which is now in hold due to EU sanctions. Instead, during 2024 main effort with ELMFIRE code was numerical verification of Landreman-Fülop-Guszejnov (LFG) model running ELMFIRE in neoclassical mode in presence of impurities as a function of ordering parameter $\delta = \rho_p/L$ where ρ_p is the orbit width and L the gradient scale length, see Figure 8.4. ELMFIRE group has been also developing 6D Vlasov-Maxwell PIC code which is reported in section 2.2.1.

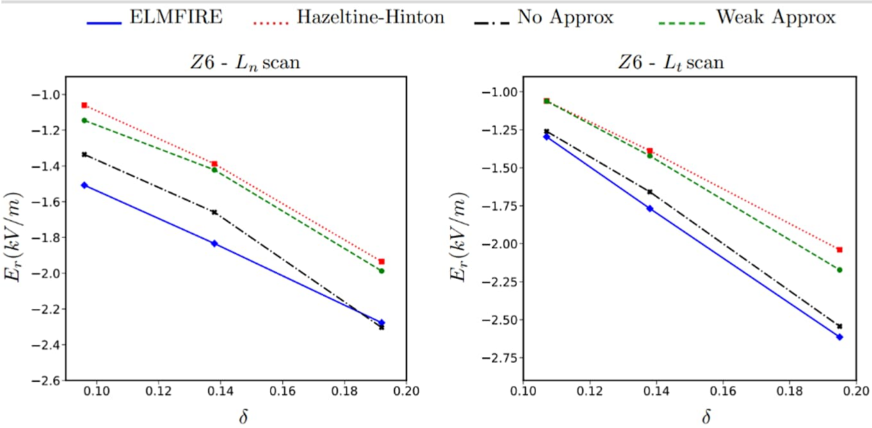


Figure 8.4. Radial averaged E_r over mid-radius for Z = 6 by varying a) density and b) temperature gradient length over values L = 10, 20 and 40 cm and keeping the other gradient length fixed at 20 cm. Results show good agreement between ELMFIRE result and LFG-model when weak approximation is not assumed ("no approx" -case in the figure).

8.5.5 Molecular Dynamics

Research Scientists: J. Byggmästar, F. Granberg, A. Kuronen, K. Nordlund, UH
J. Åström, CSC, V. Yli-Suutala, J. Westerholm, ÅA

The use of Machine Learning interatomic potentials has become more and more normal in the last years, however, at the expense of being much more CPU intensive. To remedy this, one of the used ML potential forms used in materials science was GPU enabled in 2023. The new development has been proven to work on huge systems with the very accurate ML potential. This now enables simulations not possible before at a reasonable time and CPU cost.

9. Other activities

9.1 Missions and secondments

Jari Likonen to IFERC facilities, Rokkasho, Japan, 16 – 20 January 2023 (International collaborations).

Antti Hakola and Jari Likonen to Forschungzentrum Jülich, Jülich, Germany, 5 – 10 February 2023 (WPPWIE)

Anu Kirjasuo to Max-Planck-Institut für Plasmaphysik (ASDEX Upgrade tokamak), Garching, Germany, 5 – 10 February 2023 (WPTE).

Jari Likonen to JET facilities, Culham, United Kingdom, 6 – 10 March 2023 (WP PWIE).

Juuso Karhunen to JET campaign participation, UKAEA, Culham, United Kingdom, 6 – 10 March 2023 (WPTE).

Antti Hakola to WEST facilities, CEA, Cadarache, France, 12 – 18 March 2023 (WPTE).

Timo Kiviniemi and Lucia Sanchis to W7-X, Greifswald, Germany, 13 – 17 March 2023 (WP W7X).

Anu Kirjasuo to JET facilities, Culham, United Kingdom, 23 March – 1 April 2023 (WPTE).

Antti Salmi to JET facilities, UKAEA, Culham, United Kingdom. 27 – 31 March.

William Brace to RACE Facility, UKAEA, Culham, United Kingdom, 26 March – 1 April 2023.

Antti Hakola to JET facilities, UKAEA, Culham, United Kingdom, 27 March – 1 April 2023 (WPTE).

Mathias Groth to DIII-D, General Atomics, San Diego, USA, 16 April – 12 May 2023 (WPTE, International Missions).

Antti Hakola to JET facilities, UKAEA, Culham, United Kingdom, 23 – 29 April 2023 (WPTE).

Jari Likonen to JET facilities, Culham, United Kingdom, 24 – 28 April 2023 (WPTE).

Antti Hakola to JET facilities, UKAEA, Culham, United Kingdom, 14 – 17 May 2023 (WPTE).

Arto Ylisaukko-oja, Marja Liinasuo and Bastian Tammentie to RACE Facility, UKAEA, Culham, United Kingdom, 13 – 15 June 2023.

Antti Hakola to JET facilities, UKAEA, Culham, United Kingdom, 18 – 21 June 2023 (WPTE).

Juuso Karhunen to JET campaign participation, UKAEA, Culham, United Kingdom, 26 June – 7 July 2023 (WPTE).

Jintong Wu attended University of Alicante, Alicante, Spain, 9 – 22 July 2023.

Juuso Karhunen to STEP modelling collaboration, UKAEA, Culham, United Kingdom, 17 – 28 July 2023 (WPTE).

Aaro Järvinen to Culham Centre for Fusion Energy, UKAEA, United Kingdrom, 24 – 27 July 2023.

Antti Salmi to JET facilities, UKAEA, Culham, United Kingdom, 4 – 8 August, (WPTE).

Mathias Groth to DIII-D, General Atomics, San Diego, USA, 25 August – 14 September 2023 (WPPWIE, International Missions).

Antti Hakola to JET facilities, UKAEA, Culham, United Kingdom, 3 – 9 September 2023 (WPTE).

Juuso Karhunen to JET campaign participation, UKAEA, Culham, United Kingdom, 4 – 15 September 2023 (WPTE).

Tomi Vuoriheimo to JT60-SA International Fusion School, Naka, Japan, 4 – 15 September 2023 (WPSA).

Anu Kirjasuo to JET facilities, Culham, United Kingdom, 24 – 29 September 2023 (WPTE).

Francis Albert Devasagayam to JET, Culham, UK, 25 – 29 September 2023 (WP EDU).

Antti Hakola to JET facilities, UKAEA, Culham, United Kingdom, 2 – 7 October 2023 (WPTE).

Anu Kirjasuo to JET and MAST-U facilities, Culham, United Kingdom, 8 – 14 October 2023 (WPTE).

Mathias Groth to Culham Science Centre/JET, Abingdon, UK, 23 – 26 October 2023 (WPTE).

Antti Hakola to JET facilities, UKAEA, Culham, United Kingdom, 6 – 15 November 2023 (WPTE).

William Brace to CEA and ITER facility, France, 7 – 11 November 2023.

Anu Kirjasuo to MAST-U facilities, Culham, United Kingdom, 20 – 25 November 2023 (WPTE).

Jari Likonen to JET facilities, UKAEA, Culham, United Kingdom, 20 – 25 November 2023 (WP PWIE).

Anu Kirjasuo to TCV facilities, EPFL, Lausanne, Switzerland, 27 November – 1 December 2023 (WPTE).

Juuso Karhunen to JET campaign participation, UKAEA, Culham, United Kingdom, 27 November – 8 December 2023 (WPTE).

Antti Salmi to TCV facilities, EPFL, Lausanne, Switzerland, 27 November – 2 December (WPTE).

Aaro Järvinen to ITER, Saint Paul lez Durance, France, 4 – 8 December 2023.

Antti Hakola to JET facilities, UKAEA, Culham, United Kingdom, 12 – 16 December 2023 (WPTE).

9.2 Conferences, seminars, workshops, and meetings

Antti Hakola participated in the European Fusion Programme Workshop in Les Diablerets, Switzerland, 1 – 3 February 2023.

Antti Hakola and Jari Likonen participated in the WP PWIE 2022 Reporting Meeting, Jülich, 6 – 10 February 2023.

Antti Hakola acted as an external examiner in a PhD committee for Elena Tonello in Milan, Italy, 16 February 2023.

Aslak Fellman participated in the Active Learning for Materials Science workshop, AL4MS Aalto University, 27 February – 3 March 2023.

Fredric Granberg and Aaro Järvinen participated in the TSVV11 and Advances in Integrated Modelling workshop, DIFFER, the Netherlands, 20 – 23 March 2023.

Antti Hakola joined the KFE remote handling team visit in Tampere, 21 March 2023.

Taina Kurki-Suonio participated in Physics Days 2023, Tampere, 29 – 31 March 2023.

Aaro Järvinen participated in the 4th International Conference on Data-Driven Plasma Science (ICDDPS-4), Okinawa, Japan, 17 – 21 April 2023.

David Rees, Jari Likonen and Tomi Vuoriheimo participated in the 19th International Conference on Plasma-Facing Materials and Components for Fusion Applications, Bonn, Germany, 22 – 26 May 2023.

Tomi Vuoriheimo participated in the 6th International Workshop on Models and Data for Plasma-Material Interaction in Fusion Devices, Aachen, Germany, 29 – 31 May 2023.

Tero Tyrväinen participated in WPENS Technical Meeting #15, Karlsruhe, Germany, 30 May – 1 June 2023.

Mathias Groth and Antti Hakola participated in the 33rd ITPA meeting of TG SOL and divertor physics, in Oak Ridge, Tennessee, United States, 6 – 9 June 2023.

Markus Airila, William Brace, Francis Albert Devasagayam, Fredric Granberg, Antti Hakola, Juuso Karhunen Aaro Järvinen, Taina Kurki-Suonio, Roni Mäenpää, Saifi

Qais, Evgeniia Ponomareva, Lucia Sanchis, Marton Szogradi, Antti Snicker, Tuomas Tala and Van-Dung Truong participated in the 4th Joint Nordic Fusion Energy Seminar, Gothenburg, Sweden, 12 – 13 June 2023.

Aaro Järvinen participated in 10th Runaway Electron Modelling Meeting in Garching, Germany, 19 – 21 June 2023.

Antti Hakola, Henri Kumpulainen and Ray Chandra participated in the 49th European Conference on Plasma Physics, Bordeaux, France, 3 – 7 July 2023.

William Brace and Van-Dung Truong participated in the IEEE Symposium on Fusion Engineering (SOFE) Conference, Oxford, Uinited Kingdom, 9 – 13 July 2023.

Pejk Amoroso participated in the International Summer School on Crystal Growth, Parma, Italy, 23 – 28 July 2023.

Antti Hakola joined the ECO-Fusion Steering Group meeting in Pori, 22 August 2023.

David Rees participated in the FuseNet PhD Event, Lausanne, Switzerland, 23 – 25 August 2023.

Tuula Hakkarainen, Timo Korhonen and Nikhil Verma participated the Finnish Fire Research Days in Helsinki, Finland, 5 – 6 September 2023.

Pejk Amoroso participated in the International Conference on Defects in Semiconductors, Rehoboth Beach (DE), USA, 10 – 15 September 2023.

Van-Dung Truong participated in the 15th International Symposium on Fusion Nuclear Technology (ISFNT-15) Las Palmas de Gran Canaria, Spain, 10 – 15 September 2023.

Anu Kirjasuo, Antti Salmi, and Tuomas Tala participated in Joint EU-US Transport Task Force workshop, 11 – 15 September 2023.

Aaro Järvinen participated in the TTF DETAILS, Nancy, France, 12 – 15 September 2023.

David Rees and Vesa-Pekka Rikala participated in the 19th International Workshop on Plasma Edge Theory in Fusion, Hefei, China, 18 – 21 September 2023.

Fredric Granberg, Antti Hakola and Jari Likonen participated in the WP PWIE Midterm Meeting 2023, Jülich, 25 – 28 September 2023.

Taina Kurki-Suonio participated in European Fusion Teacher Day 2023, 6 October (remote presentation).

Francis Albert Devasagayam, Mathias Groth, Antti Hakola, Aaro Järvinen, Juuso Karhunen, Antti Snicker and Tuomas Tala participated in the 29th IAEA Fusion Energy Conference, London, UK, 16 – 21 October 2023.

Aaro Järvinen to ENR-MOD.01.FZJ Progress Meeting at DIFFER, Eindhoven, the Netherlands, 6 – 10 November 2023 (WPENR).

Ray Chandra participated in TSVV-5 Workshop, University of Marseille, France, Marseille, France, 20 – 24 November 2023.

Aslak Fellman, Fredric Granberg, Evgeniia Ponomareva and Jintong Wu participated in International Conference on Fusion Reactor Materials (ICFRM 2023), Granada, Spain, 22 – 27 October 2023.

Fredric Granberg attended IREMEV monitoring meeting, 23 – 24 November, Garching, Germany.

Mathias Groth participated in the 2nd Technical Meeting on Tungsten and Hydrogen in Edge Plasmas, Vienna, Austria, 28 November – 1 December 2023.

Tuula Hakkarainen participated the EUROfusion WPSAE Progress Meeting in Garching, Germany, 28 – 29 November 2023.

Aaro Järvinen participated in the IAEA Workshop on Artificial Intelligence for Accelerating Fusion and Plasma Science, Wien, Austria, 28 November – 1 December 2023.

Fredric Granberg attended 2nd IAEA Technical Meeting on the Collisional-Radiative Properties of Tungsten and Hydrogen in Edge Plasma of Fusion Devices, IAEA, Vienna, Austria, 28 November – 1 December 2023.

Taina Kurki-Suonio, Tommi Lyytinen and Antti Snicker participated in 4th HPC Workshop 29 November 2023 (remote).

Aaro Järvinen participated in the Boundary and PWI ITER Science Fellow meeting at ITER, Saint Paul lez Durance, France, 4 – 8 December 2023.

9.3 Visitors

Thomas Puetterich of Institute for Plasma Physics, Garching, Germany, visited Aalto University, 15-16 June 2023.

Diego Negrete-Delgado of Institute for Oak Ridge National Laboratory, Oak Ridge, USA, visited Aalto University, 19-21 June 2023.

10. Publications 2023

Hyperlinks to electronic publications in the pdf version of this Yearbook.

10.1 Refereed journal articles

1. Q. Wang, H. Wu, Y. Song, H. Handroos, Y. Cheng and G. Qin, Parameter identification of heavy-duty manipulator using stochastic gradient Hamilton Monte Carlo method, IEEE Access, **11** (2023) 78561.

2. Cupak, C., Biber, H., Brötzner, J., Fellinger, M., Brandstätter, F., Aumayr, F., Lopez-Cazalilla, A., Granberg, F., Nordlund, K., Szabo, P. S., Mutzke, A., and González-Arrabal, Sputter yield reduction and fluence stability of numerically optimized nanocolumnar tungsten surfaces, Physical Review Materials, **7** (2023) 65406.

3. Granberg, F., Mason, D. R., and Byggmästar, J., Effect of simulation technique on the high-dose damage in tungsten, Computational Materials Science, **217** (2023) 111902.

4. Lopez-Cazalilla, A., Jussila, J., Nordlund, K., and Granberg, F, Effect of surface morphology on tungsten sputtering yields, Computational Materials Science, **216** (2023) 111876.

5. R. Ochoukov, S. Sipilä, R. Bilato, V. Bobkov, M. Dreval, M. Weiland, R. Dendy, H. Faugel, T. Johnson, A. Kappatou, Y. Kazakov, K.G. McClements, D. Moseev, M. Salewski, P. Schneider, ASDEX Upgrade Team and EUROfusion MST1 Team, Analysis of high frequency Alfvén eigenmodes observed in ASDEX Upgrade plasmas in the presence of RF-accelerated NBI ions, Nuclear Fusion, **63** (2023) 46001.

6. S.S. Henderson, M. Bernert, D. Brida, M. Cavedon, P. David, R. Dux, O. Fevrier, A. Järvinen, A. Kallenbach, M. Komm, R. McDermott, M. O'Mullane, Divertor detachment and reattachment with mixed impurity seeding on ASDEX Upgrade, Nuclear Fusion, **63** (2023) 86024.

7. T. Tala, A.E. Järvinen, C.F. Maggi, P. Mantica, A. Mariani, A. Salmi, I.S. Carvalho, A. Chomiczewksa, E. Delabie, F. Devasagayam, J. Ferreira, W. Gromelski, N. Hawkes, L. Horvath, J. Karhunen, D. King, A. Kirjasuo, E. Kowalska-Strzeciwilk, S. Leerink, M. Lennholm, B. Lomanowski, M. Maslov, S. Menmuir, R.B. Morales, R. Sharma, H. Sun, K. Tanaka, and JET Contributors, Isotope mass scaling and transport comparison between JET Deuterium and Tritium L-mode plasmas, Nuclear Fusion, **63** (2023) 112012.

8. M. Komm, M. Faitsch, S. Henderson, M. Bernert, D. Brida, O. Février, A. Järvinen, S. Dilvagni, D. Tskhakaya, the ASDEx Upgrade Team and the EUROfusion MST1 Team, Mitigation of divertor edge localized mode power loading by impurity seeding, Nuclear Fusion, **63** (2023) 126018.

9. C.F.B. Zimmermann, R.M. McDermott, C. Angioni, B.P. Duval, R. Dux, E. Fable, A. Salmi, U. Stroth, T. Tala, G. Tardini, T. Pütterich and the ASDEX Upgrade Team, Comparison of momentum transport in matched hydrogen and deuterium H-mode plasmas in ASDEX Upgrade, Nuclear Fusion, **63** (2023) 126006.

10. C.F.B. Zimmermann R.M. McDermott, C. Angioni, B.P. Duval, R. Dux, E. Fable, T. Luda, A. Salmi, U. Stroth, T. Tala, G. Tardini, T. Pütterich and the ASDEX Upgrade Team, Experimental determination of the three components of toroidal momentum transport in the core of a tokamak plasma, Nuclear Fusion, **63** (2023) 124003.

11. D. Matveev, D. Douai, T. Wauters, A. Widdowson, I. Jepu, M. Maslov, S. Brezinsek, T. Dittmar, I. Monakhov, P. Jacquet, P. Dumortier, H. Sheikh, R. Felton, C. Lowry, D. Ciric, J. Banks, R. Buckingham, H. Weisen, L. Laguardia, G. Gervasini, E. de la Cal, E. Delabie, Z. Ghani, J. Gaspar, J. Romazanov, M. Groth, H. Kumpulainen, J. Karhunen, S. Knipe, S. Aleiferis, T. Loarer, A. Meigs, C. Noble, G. Papadopoulos, E. Pawelec, S. Romanelli, S. Silburn, E. Joffrin, E. Tsitrone, F. Rimini, C.F. Maggi, and JET Contributors, Tritium removal from JET-ILW after T and D–T experimental campaigns, Nuclear Fusion, **63** (2023) 112014.

12. S. Lee, Y. Hatano, S. Masuzaki, Y. Oya, M. Tokitani, M. Yajima, T. Otsuka, N. Ashikawa, Y. Torikai, N. Asakura, H. Nakamura, H. Kurotaki, T. Hayashi, T. Nozawa, A. M. Ito, J. Likonen, A. Widdowson and M. Rubel, Tritium distributions in castellated structures of Be limiter tiles from JET-ITER-like wall experiments, Nuclear Fusion, **63** (2023) 46023.

13. T. Wauters, J. Buermans, J. Cavalier, E. Huett, R. Ragona, J. Svoboda, V. Bobkov, M. Griener, A.S. Jacobsen, A. Kallenbach, J. Likonen, T. Loarer, T. Lunt, S.K. Nielsen, R. A. Pitts, D. Ricci, V. Rohde, J. Stober, P. Schneider, M. Usoltseva and EUROfusion MST1 Team, Characterisation of electron cyclotron wall conditioning plasma in ASDEX Upgrade, Nuclear Fusion, **63** (2023) 66018.

14. Elbez-Uzan, J., Williams, L., Forbes, S., Dodaro, A., Stieglitz, R., Airila, M.I., Holden, J., and Rosanvallon, S., Recommendations for the future regulation of fusion power plants, Nuclear Fusion, **64** (2024) 037001.

15. Wu, J., and Granberg, F, Simulation of defect build-up in tungsten during low energy irradiation, Journal of Nuclear Materials, **586** (2023) 154653.

16. D. Li, K. Lu, Y. Cheng, H. Wu, H. Handroos, X. Zhang, X. Guo, S. Yang and L. Du, Synchronization control of blanket remote maintenance robot based on MPC-CCC algorithm, Robotica, **41** (2023) 3380.

17. R. Yin, H. Wu, M. Li, Y. Cheng, Y. Song and H. Handroos, Monocular Camera-Based Robotic Pick-and-Place in Fusion Applications, Applied Sciences, **13** (2023) 4487.

18. G. Qin, H. Wu, C. Li, A. Ji and S. Budden, Performance Analysis of Hybrid Kinematic Mechanism for Fusion Reactor Maintenance, Applied Science, **13** (2023) 1740.

19. Mason, D. R., Nguyen-Mahn, D., Lindblad, V. W., Granberg, F., and Lavrentiev, M. Y., An empirical potential for simulating hydrogen isotope retention in highly irradiated tungsten, Journal of Physics: Condensed Matter, **35** (2023) 495901.

20. Velisa, G., Granberg, F., Levo, E., Zhou, Y., Fan, Z., Bei, H., Tuomisto, F., Nordlund, K., Djurabekova, F., Weber, W. J., and Zhang, Y, Recent progress on understanding the temperature-dependent irradiation resistance ranking among NiFe, NiCoCr and MiCoFeCr alloys: A review, Journal of Materials Research, **38** (2023) 1510-1526.

21. T. Vuoriheimo, A. Liski, K. Heinola, P. Jalkanen, K. Mizohata, T. Ahlgren, J. Räisänen, Deuterium retention in tungsten studied by sequential implantations at ELM-relevant energies, Nuclear Materials and Energy, **34** (2023) 101392.

22. T. Vuoriheimo, A. Liski, P. Jalkanen, T. Ahlgren, K. Mizohata, K. Heinola, Y. Zayachuk, K.–K. Tseng, C.–W. Tsai, J.–W. Yeh, F. Tuomisto, Hydrogen isotope exchange experiments in high entropy alloy WMoTaNbV, Nuclear Materials and Energy, **34** (2023) 101348.

23. Adam Kit, Aaro Järvinen, Sven Wiesen, Yoeri Poels, Lorenzo Frassinetti, JET Contributors, Developing deep learning algorithms for inferring upstream separatrix density at JET, Nuclear Materials and Energy, **34** (2023) 101347.

24. Aaro Järvinen, Leena Aho-Mantila, T. Lunt, F. Subba, G. Rubino, L. Xiang, Parametric scaling of power exhaust in EU-DEMO alternative divertor simulations, Nuclear Materials and Energy, **34** (2023) 101378.

25. M. Groth, A.G. McLean, W.H. Meyer, A.W. Leonard, S.L. Allen G. Corrigan, M.E. Fenstermacher, D. Harting, C.J. Lasnier, F. Scotti, H.Q. Wang, J.G. Watkins, the DIII-D team, Validation of EDGDE2D-EIRENE predicted 2D distributions of electron temperature and density against divertor Thomson scattering measurements in the low-field side divertor leg in DIII-D, Nuclear Materials and Energy, **34** (2023) 101372.

26. M. Groth, V. Solokha, S. Aleiferis, S. Brezinsek, M. Brix, I.S. Carvalho, P. Carvalho, G. Corrigan, D. Harting, N. Horsten, I. Jepu, J. Karhunen, K. Kirov, B. Lomanowski, K.D. Lawson, C. Lowry, A.G. Meigs, S. Menmuir c, E. Pawelec, T. Pereira, A. Shaw, S. Silburn, B. Thomas c, S. Wiesen d, P. Börner, D. Borodin, S. Jachmich j, D. Reiter, G. Sergienko, Z. Stancar, B. Viola, P. Beaumont, J. Bernardo, I. Coffey, N.J. Conway, E. de la Luna l, D. Douai m, C. Giroud c, J. Hillesheim, L. Horvath, A. Huber, P. Lomas, C. F. Maggi, M. Maslov, C. Perez von Thun, S. Scully, N. Vianello, M. Wischmeier, the JET contributors, Characterisation of divertor detachment onset in JET-ILW hydrogen, deuterium, tritium and deuterium–tritium low-confinement mode plasmas, Nuclear Materials and Energy, **34** (2023) 101345.

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28. Brötzner, J., Cupak, C., Fellinger, M., Biber, H., Lopez-Cazalilla, A., Granberg, F., Kporha, F., Mutzke, A., González-Arrabal, R., and Aumayr, F., Sputter yield reduction for nano-columnar w surfaces under d ion irradiation, Nuclear Materials and Energy, **37** (2023) 101507.

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10.4 Academic theses

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115. Ruochen Yin, Research on key technologies for lightweight maintenance operations of the remote handling system for a fusion reactor, PhD Thesis, LUT University, 2023.

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118. Pauli Mustalahti, Improving Automated Operations of Heavy-Duty Manipulators with Modular Model-Based Control Design, PhD thesis, Tampere University, 2023.

119. Laura Gonçalves Ribeiro, Target Tracking Using Optical Markers for Remote Handling in ITER, PhD thesis, Tampere University, 2023.

120. Otso Hyvärinen, Estimation of ITER FILD fast ion fluxes using ASCOT simulations, MSc thesis, Aalto University, Espoo, 2023.

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Author(s)	Jari Likonen and Tommi Lyytinen (Eds.)
Abstract	This Yearbook summarises the 2023 research and industry activities of the FinnFusion Consortium. The present emphasis of the FinnFusion programme is the following: (i) Technology R&D for ITER construction and systems including industry contracts; (ii) Implementation of the Fusion Roadmap to the Realization of Fusion Energy as a member of the EUROfusion Consortium; (iii) Creating concepts for the next generation fusion power plant DEMO in Europe. FinnFusion participates in several EUROfusion work packages, the largest being experimental campaigns at JET and ASDEX Upgrade and related analyses, advanced computing, materials research, plasma-facing components and remote maintenance. F4E projects in 2023 focused on the development of 3D machine vision HLCS modules and GENROBOT, and the water hydraulic digital valve for ITER Remote Handling System. EUROfusion supports post-graduate training through the Education work package that allowed FinnFusion to partly fund 36 PhD students in FinnFusion member organizations. In addition, two EUROfusion Researcher and Engineering Grants were running in 2023. The FinnFusion annual seminar in 2023 was organized jointly with the Swedish and Danish research units in Gothenburg in June.
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Nimeke	**FinnFusion vuosikirja 2023**
Tekijä(t)	Jari Likonen ja Tommi Lyytinen (toim.)
	Tiivistelmä Tähän vuosikirjaan on koottu FinnFusion-konsortion vuoden 2023 tulokset. Konsortion ohjelman painopistealueet ovat (i) ITER-reaktorin rakentamiseen ja järjestelmiin liittyvän teknologian kehitys yhdessä teollisuuden kanssa; (ii) osallistuminen Fuusion tiekartan toteuttamiseen EUROfusion-konsortion jäsenenä; (iii) seuraavan sukupolven eurooppalaisen DEMO-fuusiovoimalan konseptikehitys. FinnFusion-konsortion muodostavat Teknologian tutkimuskeskus VTT Oy, Aalto-yliopisto, Comatec Oy, CSC - Tieteen tietotekniikan keskus Oy, EOS Finland Oy, Fortum Power and Heat Oy, Helsingin yliopisto, Lappeenrannan-Lahden teknillinen yliopisto, Luvata Oy, Tampereen yliopisto ja Åbo Akademi. FinnFusion-konsortio osallistuu useisiin EUROfusion-projekteihin. Suurin työpanos kohdistuu JET- ja ASDEX Upgrade -koelaitteissa tehtäviin kokeisiin ja analyyseihin, kehittyneen tietojenkäsittelyn keskukseen, materiaalitutkimukseen, ensiseinämäkomponentteihin ja etäkäsittelyyn. FinnFusionin F4E-työt liittyivät ITERin etäkäsittelyn järjestelmätason suunnitteluun (3D Machine Vision, GENROBOT, Digivalve) ja etäkäsittelyn ohjelmistokehitykseen. EUROfusion tukee jatko-opiskelua omalla rahoitusinstrumentillaan, jonka turvin FinnFusion rahoitti osittain 36 jatko-opiskelijan työtä jäsenorganisaatioissaan. Lisäksi vuoden 2023 aikana oli käynnissä yksi EUROfusionin rahoittama tutkijatohtorin projekti. Fuusioalan vuosiseminaari järjestettiin yhdessä Ruotsin ja Tanskan fuusiotutkimusyksiköiden kanssa Göteborgissa kesäkuussa 2023.
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