VTT

FinnFusion Yearbook 2024

Tommi Lyytinen | Jari Likonen (Eds.)

VTT TECHNOLOGY 438

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Technical Research Centre of Finland Ltd

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Preface

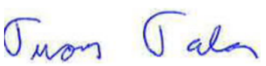
There is an increased political support worldwide for fusion in individual countries, but also in international fora, in particular the IAEA Fusion Energy Group and the G7 Working Group on fusion, both of which had their first meeting at the end of 2024. Strong national fusion energy research strategies have been presented and published by several countries, often combined with a fusion roadmap. EU is also refining its strategy. The Fusion Expert Group, initiated by the EU Commission, is drafting the white paper which will be the basis of the refined EU fusion strategy and roadmap. Ministry of Economic Affairs and Employment (MEAE) is participating in the Fusion Expert Group from Finland.

ITER re-baselining was approved in 2024, with the main design changes being the optimized HCD mix (increase in ECRH power up to 50MW) and boronisation for risk mitigation in achieving Q=10, 500MW operation with the tungsten first wall from day 1. The re-baseline also includes stepwise safety demonstration in DT plasma, with the first DT campaigns only using 1% of the total neutron budget. On the F4E side, year 2024 showed a long list of remarkable ITER project delivery highlights such as the final poloidal field coil, first NBI power delivery, completion of toroidal field coils, first vacuum vessel completion, first cryopump delivery to name few.

International news is full of headlines from fusion research and investments all around the world. Public sector fusion research funding in 2024 showed a lot of growth and inspiration. All ITER parties and also several European countries individually are investing in R&D funding for “beyond ITER” fusion projects. Even more remarkable is the growth in private investments in fusion research and development globally. There are presently around 50 so-called private fusion enterprises worldwide. Roughly half of them is based in the United States, one quarter in Europe and the remaining quarter outside US and Europe. There are more than ten companies with more than 100M€ investments, and a few of them are on the billion scale. The increased public support, together with the massive injection of private capital in fusion research development, will translate an epochal change in fusion energy development in the years to come.

The JET Celebration Day event in February 2024 was hailed as a befitting end to the scientific operations of JET in Culham Campus. The event, dedicated to the success of JET and the people behind it, was attended by dignitaries, scientists, engineers, and other individuals who had worked at JET through the ages including myself. The event was attended with speeches delivered by the UK's Minister for Nuclear and Renewables, Andrew Bowie, MP and the European Commission's Head of Unit, Euratom, Dr Elena Righi as well as by the JET alumni. JET has been instrumental in advancing fusion energy for over four decades, symbolising international scientific collaboration, engineering excellence, and the commitment to harness the power of fusion energy. A separate media event took place earlier in February 2024 to officially report the new world fusion energy record of 69 megajoules released in sustained and controlled fusion energy in JET in October 2023. Released over six seconds from only 0.21 milligrams of Deuterium-Tritium fuel, the energy record equals the energy released from burning 2 kilograms of coal.

The FinnFusion annual seminar 2024 was organised by the University of Helsinki at both Downtown and Kumpula campuses in May 2024. This seminar was the first one "FinnFusion only" annual seminar since 2018 as we have had two Nordic Joint seminars and one combined with Business Finland SMR and Decommissioning Ecosystem seminar in between. In addition to the regular talks from the FinnFusion research organisations, we had a talk from MEAE, United Kingdom Atomic Energy Authority, Barcelona Supercomputing Centre, Quanscient, Platom, Comatec, Fulvisol and Luvata. It was also a great pleasure to announce that Karoliina Salminen from VTT had been chosen for the first FinnFusion individual to lead a EUROfusion work package, in this case the remote maintenance one WPRM. One of the topics discussed in the meeting was fusion reactor safety, environment and licensing. Licensing has become a very important topic. And recently also in Finland, we can all be very glad that the Radiation and Nuclear Safety Authority of Finland has actively pursued fusion energy related legislation issues. This will be an important step towards making Finland an attractive country to host a fusion pilot plant in future.



Tuomas Tala
Head of Research Unit
FinnFusion Consortium

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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.

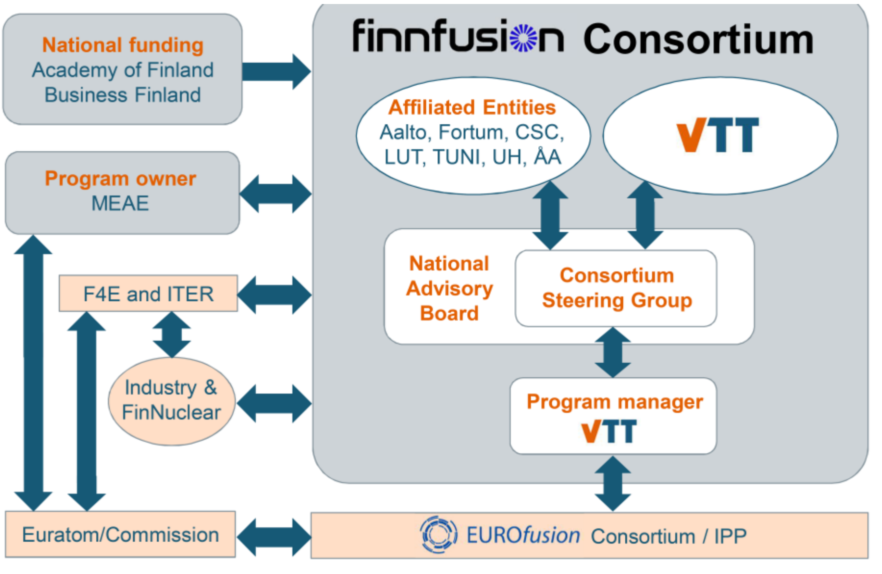

Figure 1.1. Organigram of Finnish Fusion Research Community in 2021–2025.

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 2024:

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, Amanda Bruncrona, Dr. Antti Hakola

(Project Manager), Daniel Jordan, Dr. Aaro Järvinen, Dr. Juuso Karhunen, MSc. Anu Kirjasuo, Adam Kit, Dr. Jari Likonen, MSc. Tommi Lyytinen, Anna Niemelä, MSc. Sixten Norrman, Ulla Peltonen (administration), MSc. Samuli Saari, Dr. Antti Salmi, Kirsi Selin (administration), Joona Sissonen, 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: Atte Antikainen, MSc. Aymara Baumann Duran, Dr. Andris Freimanis, Gizem Ersavas Isitman, Juha Lagerbom, Dr. Anssi Laukkanen, Matti Lindroos, MSc. Lassi Linnala, Dr. Sami Majaniemi, Dr. Olli Pakarinen, Dr. Sicong Ren, MSc. Tomi Suhonen

Activities: Hot cell analyses and experimental materials research
Members: MSc. Jouni Alhainen, MSc. Brahim Dif, Dr. Janne Heikinheimo, Mrs. Madelen Joro, MSc. Petteri Lappalainen, Taru Lehtikuusi, MSc. Juhani Rantala, Mr. Kimmo Rämö, Mr. Jarmo Saarinen

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

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

Activities: Fire safety
Members: Dr. Tuula Hakkarainen, Dr. Timo Korhonen, Tomi Maijala, Aki Pakarinen, 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, Laura Goncalves Ribeiro, MSc. Jouko Heikkilä, Mr. Timo Hietavalkama, MSc. Tero Jokinen, Virpi Jumisko, MSc. Petri Kaarmila, MSc. Petteri Kokkonen, Jarkko Kotaniemi, Juha Kuutti, Dr. Marja Liinasuo, MSc. Janne Lyytinen, MSc. Timo Malm, MSc. Hannu Martikainen, Doan Nguyen, MSc. Riku Pennala, Antti

Pulkkinen, Nithin Puthiyaveettil, MSc. Kari Rainio, Bruno Reinaldo Goncalves, MSc. Hannu Saarinen, MSc. Qais Saifi, Karoliina Salminen, MSc.Janne Saukkoriipi, MSc. Teemu Sipola, Lic.Tech. Mikko Siuko, MSc. Esko Strömmer, 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

School of Science, Department of Applied Physics

Activities: Physics
Members: Prof. Mathias Groth (Group Leader), MSc. Francis Albert, Dr. Ray Chandra, Dr. Riccardo Iorio, Dr. Timo Kiviniemi, Dr. Taina Kurki-Suonio, MSc. Roni Mäenpää, MSc. David Rees, Dr. Seppo Sipilä, Suvi Niemelä (admin. support)

Students: Henri Kuivasniemi, Atte Jämsén, Vesa-Pekka Rikala, Heru Reksoprodjo, Aaron Vesa, Pyry Virtanen

Activities: Materials physics
Members: Sara Bouarich (admin support), Dr. Antoine Clement, MSc. Nima Fakhrayi Mofrad, Msc. Evgeniia Ponomareva, MSc. Rafael Nuñez, Prof. Andrea Sand (Group Leader)

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, Dr. Peng Shang, Dr. Ming Li, MSc. Nikola Petikov, MSc. Zhiyong Wang, MSc. Qi Huang, Docent Huapeng Wu (Project manager), Msc.Qiwei Xue, MSc. Ting Wang, MSc. Pradeep Gaudel. MSc. Danil Vodolazskii, Mr. Juha Koivisto.

Tampere University (TUNI)

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

Suominen, MSc. Tomi Äijälä, MSc. Mehdi Heydarishahna, MSc. Kamran Akbar

University of Helsinki (UH)

Activities: Physics, materials (Accelerator Laboratory)
Members: Dr. Tommy Ahlgren, MSc. Pejk Amoroso, MSc. Xudong An, MSc. Alexandre Bergero, Dr. Jesper Byggmästar, MSc. Zhehao Chen, Prof. Flyura Djurabekova, MSc. Aslak Fellman, Dr. Fredric Granberg, MSc. Xiaoyu Gui, Dr. Kalle Heinola, MSc. Faith Kporha, Dr. Antti Kuronen, MSc. Victor Lindblad, MSc. Anna Liski, Dr. Eryang Lu, Dr. Ilja Makkonen, Dr. Kenichiro Mizohata, Prof. Kai Nordlund (Project Manager), MSc. Igor Prozheev, Prof. Filip Tuomisto (Project Manager), Dr. Tomi Vuoriheimo, Dr. Guanting Wei, MSc. Jintong Wu, 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. Oskar Lappi, Prof. Kai Nordlund, Prof. Jukka Nurminen, Mr. Ville-Markus Yli-Suutala

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
	Mika Finska, Business Finland
	Veikko Puumala, Comatec
	Megumi Asano-Ulmonen, FinNuclear
	Harri Sairiala, Fluiconnecto
	Eero Vesaoja, Fortum
	Arto Timperi, IM Intelligent Machines
	Olli Naukkarinen, Luvata
	Olli Suominen, Operview Oy
	Teemu Uotila, QuanScient
	Sami Kiviluoto, Platom
	Juha-Matti Liukkonen, Reaktor
	Anna Kalliomäki, Research Council of Finland

	Mika Korhonen, Suisto Engineering Juho Korteniemi, MEAE Jarmo Lehtonen, Tevolokomo Karoliina Salminen, VTT
FinnFusion Steering Group	*Mathias Groth, Aalto* *Janne Ignatius, CSC* *Eero Vesaoja, Fortum* *Kai Nordlund, UH* *Huapeng Wu, LUT* *Jouni Mattila, TUNI* *Jani Halinen, VTT* *Ivan Porres, ÅA*
Co-ordinator	Tuomas Tala, VTT
Secretary	Markus Airila, VTT Antti Snicker, VTT

The FinnFusion advisory board had two meetings in 2024, April 25th at VTT Centre for Nuclear Safety, Espoo and December 17th at VTT Centre for Nuclear Safety, Espoo.

1.5 Finnish members in the European Fusion Committees

1.5.1 Euratom Programme Committee, Fusion configuration, Fusion Expert Group

- Timo Haapalehto, MEAE

1.5.2 EUROfusion General Assembly

- Tuomas Tala, VTT

1.5.3 EUROfusion HPC Allocation Committee

- Andrea Sand, AU

1.5.4 EUROFUSION HPC OPERATIONS COMMITTEE

- Fredric Granberg, UH

1.5.5 EUROfusion Project Boards

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

- Fusion Science Department: Markus Airila, VTT

1.5.6 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

1.5.7 Other international duties and Finnish representatives in the following fusion committees and expert groups in 2024

- 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 and of the ICACS (International Conference on Atomic Collisions in Solids), member of 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.
- 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 Hakola is a member of the ITPA expert group on divertor and scrape-off layer physics.
- 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.
- Aaro Järvinen is a member of the Divertor and SOL ITER Science Fellow group.

2 Plasma Science for ITER, DEMO and stellarators 2024

2.1 WP TSVV: Theory-Simulation-Verification-Validation

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

Research scientists: L. Chôné, UH

The full-orbit PIC code SymPiFE development continues as part of TSVV-4. New features are added, such as the creation of parallel extruded meshes, which allow both efficient averaging (e.g. toroidal averaging), and efficient deposition of markers onto a phase-space mesh for diagnostics of the distribution function. An extended class storing particles with a persistent identifier was also added to provide a reliable diagnostic of trajectories. The initialisation of tokamak-relevant analytical equilibria, both with circular concentric flux-surfaces, and extended Solov'ev equilibria based on [Cerfon, Phys. Plasmas 17, 032502 (2010)], is also added to the software base. The creation of new features is accompanied with the addition of corresponding tests to the testing suite in SymPiFE. A Python plotting module based on Matplotlib/PyVista is in development to provide standard plotting tools, including interactive 3D renders. See Figure 2.1, which shows a volume-plot of the potential solution for a manufactured-solution test of the Poisson solver, in a toroidal annulus with circular cross-section.

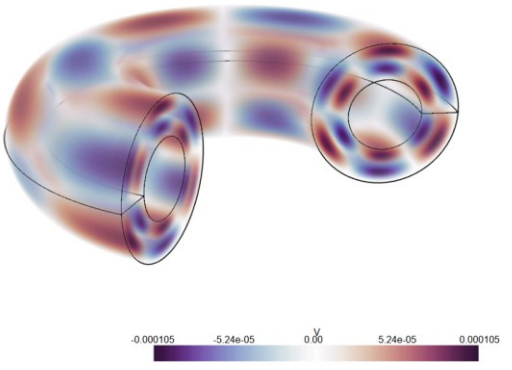

Figure 2.1. Volume-plot of the potential solution for a manufactured-solution test of the Poisson solver, in a toroidal annulus with circular cross-section.

2.1.2 TSVV Task 5 Neutral Gas Dynamics in the Edge

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

Radiation transport simulations of the deuterium Lyman series using EIRENE predict a factor of 2 increase of Balmer-α emission in the JET-ILW low confinement divertor plasmas in high-recycling and detached conditions caused by the re-absorption of Lyman-β emission. The photon tracing model in the EIRENE code is applied to SOLPS-ITER pure deuterium plasma solutions of JET-ILW to evaluate the contribution of Lyman-β capture towards the population density of D(p = 3) and consequently the Balmer-α emission. The local population escape factors of Lyman-α and Lyman-β lines in the JET-ILW divertor show steep spatial gradients and indicate local regions with high opacity in high-recycling and detached conditions. The relative contribution of Lyman-β capture towards the population density of D(p = 3) is significant in high-recycling and detached conditions. This observation is further corroborated by line-integrated calculations using Balmer-α diagnostic line-of-sights.

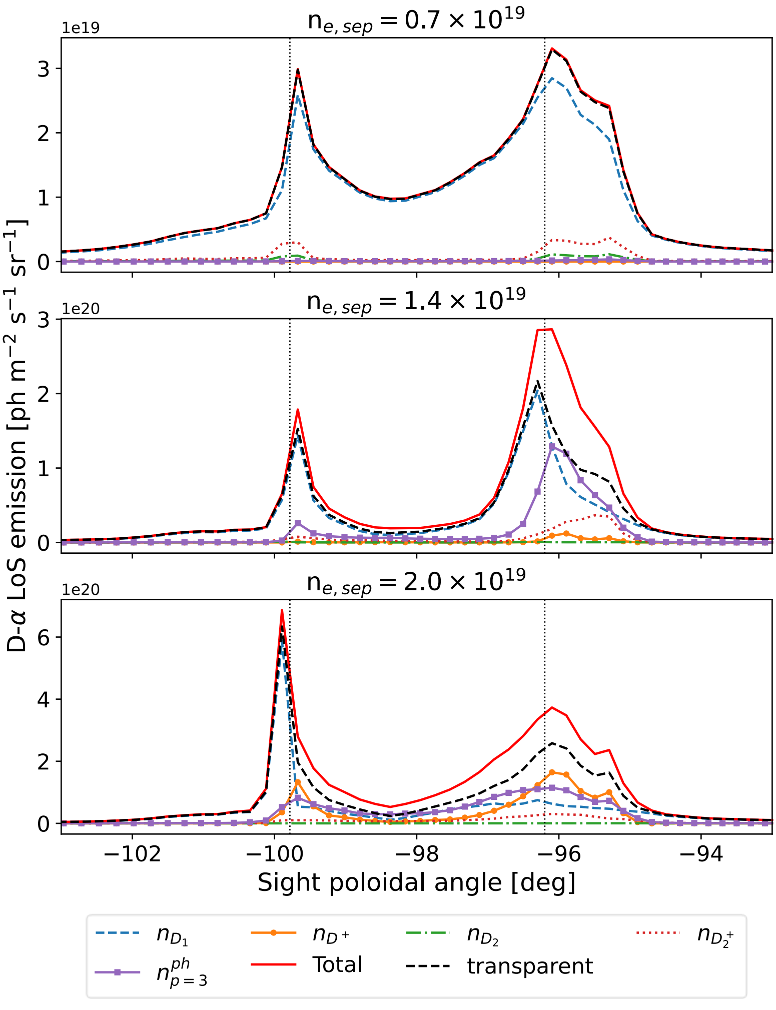

Figure 2.2. Line-integrated D-α emission using KT1 sight lines, separated by contributions from external densities $n_{D_1}, n_{D^+}, n_{D_2}, n_{D_2^+}$, and Ly-$\beta$ absorption $n^{ph}_{p=3}$. The black dashed line represents total emission without opacity effects. Ly-β absorption contributes a significant fraction of the total line-integrated D-α emission at high-recycling and detached regimes.

2.1.3 TSVV Task 6 Impurity Sources, Transport, and Screening

Research scientists: M. Groth, R. Mäenpää, Pyry Virtanen, AU

ERO2.0 simulations executed on hydrogenic EDGE2D-EIRENE back-ground plasma predict that the main erosion location of nickel from the vacuum vessel wall is the LFS vacuum vessel wall, close to the midplane, due to the CX atomic fluxes being predicted strongest in this region. The CX atomic fluxes to the vacuum vessel wall are significant on the LFS because of the large gaps between the limiters and antennas, and the atomic densities being at their highest in the main chamber. On the HFS the Be limiters and the recessed, Be coated tiles block 95% of the flux towards the vacuum vessel wall. The top of the vacuum vessel is not covered with Be-coated tiles, however the CX atomic fluxes are lower than to the LFS midplane, due to lower predicted atomic densities. A part of the sputtered nickel is transported from the vacuum vessel wall into the main SOL where nickel ions are entrained in the predicted SOL flows and be transported towards the HFS divertor top, where they are deposited, forming a co-deposit layer containing nickel. The highest areal density of the nickel deposit layer is predicted on tile 1, of the order of 1-2·10^{19} cm^{-2}, within a factor of six of what is observed in post-mortem analyses. The differences between post-mortem analyses of tiles and the predicted deposition layer are likely due to omitting re-erosion and the limited number of magnetic equilibria used for the combined profile. Additionally, impurity transport in the SOL is determined by the SOL flows and the uncertainty in the SOL flow introduces uncertainty to the deposition profiles.

The net erosion profile of nickel from the vacuum vessel wall requires calculating the deposition profile of nickel on the vacuum vessel wall, which is currently not possible in post-processing of the ERO2.0 simulations. On the HFGC (tile 0) there is insignificant nickel deposition, which is inconsistent with post-mortem analyses. The exact role of the limiter phase for nickel erosion has to be confirmed and ELMs are currently not included in the modelling of the deposition.

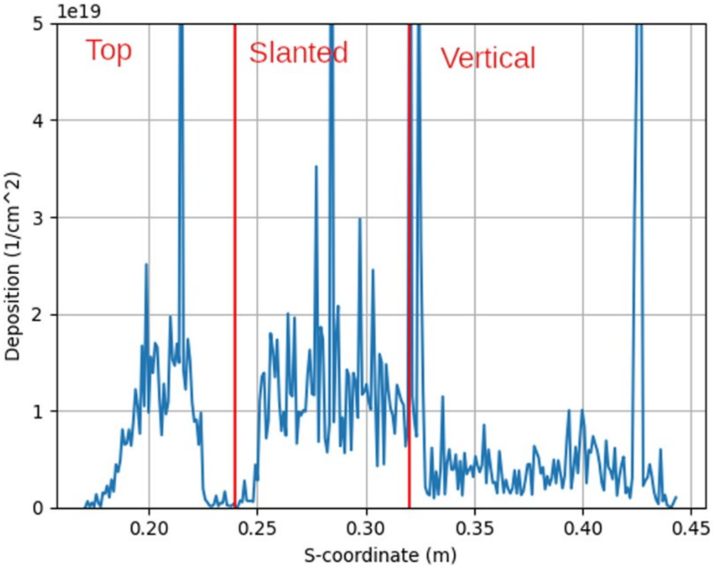

Figure 2.3. ERO2.0 predicted bulk nickel deposition onto tile 1, after operation years 2011–2016 in JET as a function of the S-coordinate, which is the distance

along the divertor/limiter surface starting from tile 0 and moving counterclockwise along the limiter/divertor surface, with markings of the expected deposition and re-erosion zones.

2.1.4 TSVV Task 7 Plasma-Wall Interaction in DEMO

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

The main focus in this project was finalizing the work of deuterium effects on the sputtering of deuterium decorated tungsten surfaces as well as development of a Machine Learning interatomic potential for sputtering simulations. Deuterium will be present on the wall material, and it was found that it will affect the sputtering of the wall material as well as itself sputter under various conditions. We analyzed how different factors, such as energy, ion species, incoming angle affected the tungsten and deuterium sputtering from D-decorated tungsten surfaces. All these factors affected the sputtering. The development of ML potential for the W-O-H systems has been started and is ongoing. With this accurate potential we can study both the deuterium decoration effect as well as synergetic effects with oxygen. This work will continue into 2025.

2.1.5 TSVV Task 12 Stellarator optimization

Research scientists: S. Äkäslompolo, AU, K. Särkimäki, VTT

Aalto University and VTT have contributed software engineering to the TSVV-12. ASCOT5-GPU porting has reached an important milestone: the changes have been merged with the main-line version and first production runs are on-going. We see a significant performance boost: simulations on a single H100-96GB show up to 6x speedup over a dual Intel Xeon CPU node. ASCOT5 has been updated to read inputs from IMAS IDS, but the IMAS infrastructure currently lacks full support for Python actors, limiting its integration.

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

2.2.1 Overview

The main FinnFusion activities under WPPWIE in 2024 concentrated on studying erosion of different plasma-facing components (PFCs) and subsequent migration of material in the scrape-off layer (SOL) plasmas. Most of the results reported below originate from various modelling activities in connection with earlier experiments on JET and ASDEX Upgrade. New topics introduced in 2024 included assessing the role of different sputtering mechanisms on beryllium (Be) PFCs of JET in hydrogen (H), deuterium (D), and tritium (T) plasmas as well as studying plasma-surface interactions during and after boronizations in fusion plasmas; the latter has gained recently an increased interest due to the new ITER baseline of a full-W wall. The LIBS (Laser-Induced Breakdown Spectroscopy) work culminated in coordinating an extensive measurement campaign at JET in October 2024. The LIBS results will be put into perspective by comparing them with the results of *post mortem* analyses – an area where VTT and University of Helsinki have gathered several years of experience. *Post mortem* analyses were in general continued both using the accelerator facilities of University of Helsinki and the secondary ion mass spectrometry (SIMS) device at VTT, mainly for samples coming from JET. Year 2024 marked the end of the VTT's old SIMS apparatus which has been the main workhorse for all types of surface analyses during the past 30+ years; a new Time-of-Flight SIMS (TOF-SIMS) is scheduled to arrive in early 2025.

2.2.2 Modelling marker erosion at the divertor region of ASDEX Upgrade

Research scientists: A. Hakola, A. Järvinen, J. Karhunen, S. Saari, VTT

In 2024, a large effort was put in modelling gross and net erosion of small marker samples during high-temperature L-mode plasma discharges in D on ASDEX Upgrade using the ERO2.0 code. The data originates from an experiment carried out in 2019, in which molybdenum (Mo)-coated graphite samples with gold (Au) marker spots (1×1 mm^2 and 5×5 mm^2) were exposed to a series of plasma discharges at the outer strike point region of ASDEX Upgrade. Compared to earlier efforts using the old ERO code (see A. Hakola *et al.*, Nucl. Mater. Energy **25** (2020) 100863), several improvements were implemented to the modelling setup and the input data of the simulations. Background plasmas were constructed using the onion-skin model (OSM) of the DIVIMP code, based on the available Langmuir probe (LP) data for the poloidal electron density and temperature profiles at the OSP region.

The results for Au net erosion for the different marker spots in the poloidal direction are shown in Figure 2.4. They indicate good correspondence between the experimental and simulated erosion profiles: a peak around the OSP and a gradual but distinct decrease in erosion rates when moving away from it, especially on the SOL side. The application of the new and more accurate presentations of the sputtering and reflection data for Au, provided by the SDTrimSP code, was found to have a key role in significantly improving the agreement with experimental data with respect to earlier simulations with simplified approximations. Our simulations also predict a predominantly toroidally oriented re-deposition pattern downstream of the marker spots, albeit the modelled surface densities are 1-2 orders of magnitude lower than those on the marker spots. Light impurities appear to play the largest role in marker erosion: nitrogen, carbon, and boron, typical impurities on AUG, account for >75% of the obtained net erosion.

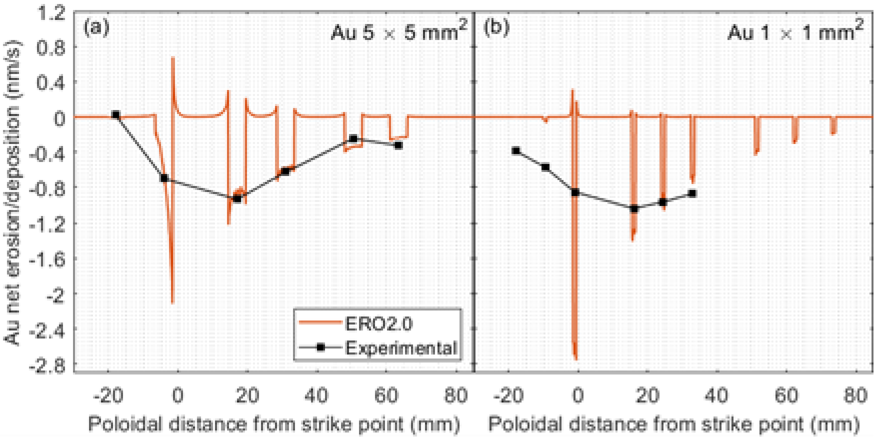

Figure 2.4. Simulated and experimental net-erosion profiles of the (a) 5×5 mm^2 and (b) 1×1 mm^2 gold marker spots.

2.2.3 Molecular yields and excitation from W wall erosion

Research scientists: Nima Fakhrayi Mofrad and Andrea Sand (AU)

Molecular dynamics simulations have been carried out to estimate molecular sputtering yields from W surfaces containing different concentrations of deuterium. Simulations have been analyzed to assess the possible rotational and vibrational states of the released molecules. Results, albeit based on classical computations, indicate that significantly excited states are accessible to molecules sputtered by incoming D ions.

2.2.4 Divertor erosion at ASDEX Upgrade during helium plasma operations

Research scientists: A. Hakola, J. Likonen, VTT, T. Vuoriheimo, UH

The work on measuring erosion patterns at the outer strike point region of ASDEX Upgrade in helium plasmas was finished in 2024 and the results were reported in the PSI 2024 conference (see T. Vuoriheimo *et al.*, Nucl. Mater. Energy **41** (2024) 101766). The analyses were based on experiments carried out during the 2022 He campaigns by using W-coated graphite samples and platinum (Pt) marker spots produced on top; the dimensions are identical to those of the Au markers, see section 2.2.22.2.2.

The measurements of the Pt markers following their exposure to dedicated L- and H-mode discharges confirmed the higher erosion rates under He plasma exposure compared to D plasmas, as expected from the higher sputtering yield of He and its lower sputtering threshold energy. The radial profile of Pt erosion in He also extended further out in the poloidal direction compared to D plasmas where the erosion is much more localized in the strike point zone. Figure 2.5 shows the obtained erosion data in the poloidal direction for the larger markers (5×5 mm^2) in terms of the areal densities (at/cm^2). No redeposited Pt was detected in the vicinity of the large Pt marker spots, suggesting that any redeposition of Pt is strongly localized within the marker spots whereas for the small markers the total amount of redeposited Pt in the vicinity of the marker area is likely to be below the detection threshold. Platinum can act as a proxy for W due to similar shape of the sputtering yield curves and therefore the results can be applied to W surfaces, although the erosion is stronger with Pt surfaces. However, the He plasma itself is the main factor for the erosion unlike with D plasmas where the impurities within the plasma dominate net erosion.

Deposition of residual D and B was observed in the private flux region of the H-mode plasma in between the H-mode and L-mode strike points. The subsequent L-mode discharges were not sufficient to induce significant erosion in this region. Helium retention differed from that of residual D and B, showing an increase further out from the strike point area, with the lower retention values near the OSP attributed mostly to the higher surface temperatures reached in this region during plasma exposure.

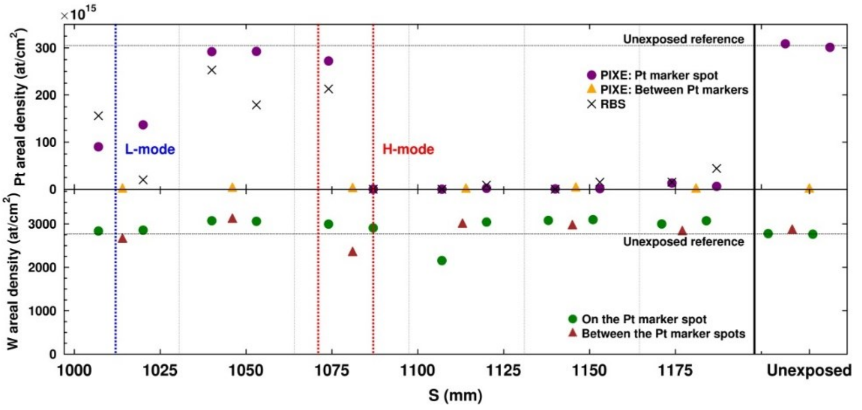

Figure 2.5. Pt (top) and W (bottom) areal densities (at/cm^2) on the 5×5 mm^2 marker samples after plasma exposure measured by particle-induced X-ray emission (PIXE) and Rutherford backscattering spectrometry (RBS). Measurements have been made on and in between the marker spots. The reference PIXE measurement without plasma exposure is shown on the right. The measured PIXE data has been normalized to the RBS data of unexposed Pt samples.

2.2.5 Plasma-edge and plasma-wall interaction modelling

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

Assuming nitrogen to recycle as N2 molecules instead of N atoms in SOLPS-ITER simulations of nitrogen-seeded, partially detached JET L-mode plasmas increases the power radiated by nitrogen ions by up to a factor of four and reduces the electron temperature locally in the low-field side divertor leg by up to an order of magnitude when a fixed nitrogen injection rate is used. The increase in nitrogen radiated power occurs due to an increase in the abundance of nitrogen ions by 80% (for N+) to 600% (for N2+). Enhanced plasma penetration of nitrogen atoms due to the high dissociation threshold of triply-bonded N2 molecules and the kinetic energy release in the dissociation event is shown to explain the increase in the nitrogen ion abundance. When the power radiated by nitrogen ions is matched to the bolometric estimate from experiment by adjusting the nitrogen injection rate, the SOLPS-ITER N2 recycling simulations predict peak line-integrated N II to N IV intensities within 5% to 35% of the atomic recycling case, and both simulations predict peak line-integrated N II to N IV intensities within 5% to 65% of the values measured by the vertically-viewing divertor spectrometer. Neither recycling assumption yields predictions that are overall more consistent with the measurements of line-integrated N II to N IV intensity than the other when the nitrogen injection rate is treated as a free parameter. If a fixed nitrogen injection rate is used in e.g. predictive modelling, a sensitivity analysis testing both atomic and molecular nitrogen recycling is recommended.

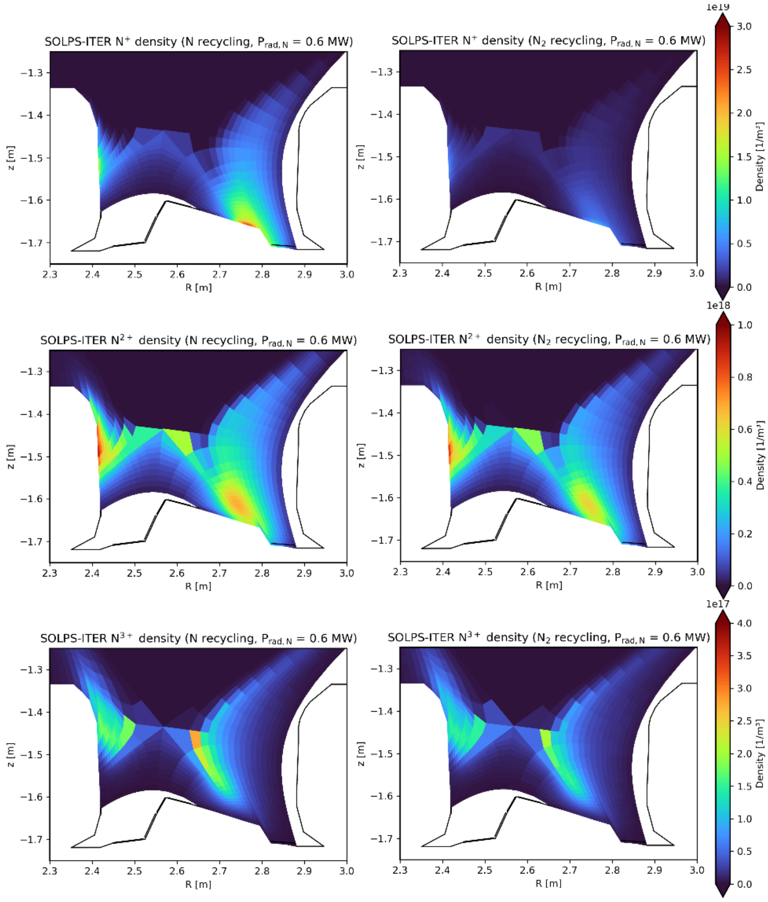

Figure 2.6. Density of N+, N2+ and N3+ in the divertor predicted by SOLPS-ITER under the atomic and molecular recycling assumptions (left and right columns, respectively). The nitrogen injection rate is set to 20×10^{19} and 6×10^{19} N atoms per second in the atomic and molecular recycling simulations, respectively, yielding a predicted nitrogen radiated power of approximately 0.6 MW in both simulations. The electron density at the low-field side midplane separatrix $n_{e,sep,LFS-mp}$ is fixed to 1.8×10^{19} m^{-3}.

2.2.6 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

JET operated without any shutdowns and tile removal in 2019-2023 so no new tiles were available in 2024. 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 were completed in 2023.

In 2024 the main aim was to assess the efficiency of baking as a fuel removal technique. Materials used in the study included samples of plasma-facing components (PFCs) of JET ITER-like wall (ILW). Baseline ITER fuel removal strategy involves baking of the plasma-facing components, at 240°C for the first wall and 350°C for the divertor. Baking simulations were performed, in which samples of JET ILW PFCs were baked in the thermal desorption spectroscopy (TDS) setup at UKAEA for an extended period of up to 140 hours. A combination of ion beam analysis (IBA) at IST (Portugal), TDS and Secondary Ion Mass Spectrometry (SIMS) at VTT was used to measure the changes of deuterium content in different depth regions – in the near-surface region (accessible by IBA and SIMS) and in the bulk (accessible by TDS).

Figure 2.7 (a) shows the ILW-2 D concentration profile for sample 2IWG1A-12a having a near-surface dip extending up to ∼1 μm in depth whereas the H depth profile extends to a depth of ~3 μm. The lack of D in the surface region correlates with the H being co-deposited in this region. Interestingly, however, there is no visible D peak beyond 1 μm marking the end of the D operation. Thus, it may be speculated, that the D near-surface peak being potentially present in the end of D operations diminished and was gradually replaced by H via continuous co-deposition in the course of the H campaign. The H and D depth profiles show clear bump at the interface between the Be co-deposited layer and the W-coated CFC surface.

Annealing of the sample at 350 ^{o}C had a clear effect on the H and D depth profiles (see Fig. 2.7 (b)). The overall H and D amounts have decreased markedly. The H surface peak is lower and thinner than before the annealing indicating the H has been released during the annealing. The dip for D extends now to a depth of ~7 μm so D has been released from the near-surface region. Another effect of the annealing is that the interfacial peaks for H and D have now disappeared almost completely. Unfortunately, SIMS depth profiling could not be done deeper due to very long sputtering times so we have no information on possible hydrogen isotope migration deeper in the bulk or towards the surface.

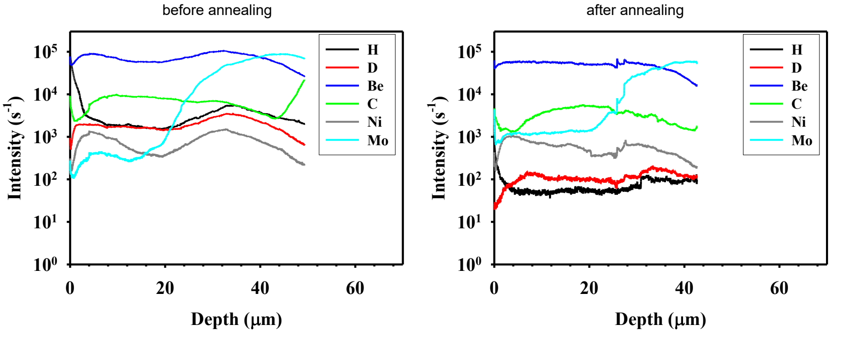

Figure 2.7 SIMS depth profiles for divertor samples 2IWG1A-12a before annealing (a) and after annealing at 350 °C (b).

2.2.7 Development of LIBS for studying tritium inventories on JET PFCs

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

The feasibility of laser-induced breakdown spectroscopy (LIBS) for measuring fuel retention was demonstrated for the first time in a tokamak operating with tritium using a remotely controlled in situ application in JET. In JET and future fusion reactors such as ITER and DEMO, thick co-deposited layers will be formed at the inner wall during extended plasma operations. Experiments in present-day fusion devices indicate that these layers consist of eroded plasma facing materials, various impurities and plasma fuel species like deuterium and tritium. Accumulation of radioactive tritium in the reactor vacuum vessel is a particularly critical safety issue requiring active monitoring. LIBS is one of the few techniques available for monitoring the tritium content and the composition of co-deposited layers during maintenance breaks [1]. This paper will provide an overview of the LIBS experiment that was performed post DTE3 campaign, and D and H cleanup at JET in October 2024.

Prior to the LIBS experiment at JET, preliminary test measurements were performed at VTT using the LIBS tool developed at ENEA and optimized by FZJ. The tool consisted of the LIBS enclosure equipped with a sub-nanosecond Nd:YAG laser and focusing optics, which was connected via a 20 m optical fibre to an Echelle type spectrometer with wide spectral range (260-760 nm. Samples, including from JET limiters and divertor, were characterised for calibration-free LIBS and for calibration of the ablation rate. The final setup of the JET LIBS tool consisted of a high-resolution Littrow spectrometer for separation of the hydrogen isotopic lines, an Echelle spectrometer and photomultipliers. The LIBS enclosure was mounted onto the MASCOT robot which was remotely operated from a dedicated control room by the UKAEA remote handling team. During the LIBS experiment at JET 840 locations on the main wall and the divertor were analysed successfully. The high spatial accuracy of the MASCOT manipulator was also demonstrated by analysing single castellations on the limiter tiles. Validation of results will take place with future ex-situ LIBS measurements and post-mortem analysis on JET tiles.

Figure 2.8. Operation of the MASCOT robot in the RH control room at JET. Cone of the LIBS tool positioned on outer divertor tile 8.

2.3 WP TE: Tokamak exploitation campaigns

2.3.1 Overview

The year 2024 brought along a main milestone under WPTE: no more experimental activities on JET but launching a series of analysis and modelling meetings. The first of these events was arranged in March 2024 in Culham, where a large number of scientists from different experiments and research topics gathered to discuss the near- and long-term needs for data validation and bringing the results into a variety of publications. Experimental campaigns, for their part, were run on TCV, MAST-U, WEST, and from October 2024 onwards on ASDEX Upgrade (AUG); ASDEX Upgrade had undergone a 2-year engineering break for installing a new upper divertor at the top of the vessel to enable studying various alternative divertor configurations (ADCs). In general, the programs especially on AUG and WEST were hugely influenced by the new ITER baseline: focus was put on studying the efficiency of boronizations, sputtering of W in the main chamber, and generally understanding W transport in the vessel. The areas where the Finnish contribution was the most noticeable were investigating particle and momentum transport (TCV, MAST-U, WEST, and JET analyses), studying detachment physics (MAST-U and JET analyses), erosion of Be and W plasma-facing components (AUG and JET analyses), and modelling the behaviour of fast ions with the help of ASCOT (AUG and MAST-U).

2.3.2 Assessment of the impact of the applied molecular charge-exchange reaction rates on detachment access in SOLPS-ITER simulations of MAST Upgrade

Research scientists: J. Karhunen, VTT

The impact of the applied molecular charge-exchange reaction rate data on the onset of outer divertor detachment in SOLPS-ITER simulations of MAST Upgrade was tested by conducting scans of the plasma density utilizing both the standard AMJUEL reaction data of EIRENE and a new improved representation of molecular charge-exchange. The new rate coefficient data was found to yield a significantly increased number of atoms in the divertor volume due to the increased occurrence of molecular charge-exchange reactions, leading to the onset of detachment at a noticeably lower upstream density than with the standard reaction rates of EIRENE.

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

Research scientists: P. Ollus, AU

Dedicated experiments were performed on MAST Upgrade to study beam-ion losses caused by charge exchange (CX) with edge neutrals. The fuelling was switched from the high-field side to the low-field side mid-discharge.
Direct measurements suggest a strong increase in the neutral density around the plasma and a decrease in the beam-ion density, which is qualitatively explained by CX losses. Measurements by a resistive bolometer have suggested particle bombardment during neutral beam injection, providing a unique opportunity to separate CX from other loss mechanisms. To verify and quantify CX losses, the orbit-following code ASCOT, which accounts both for CX neutralization and reionization, was used to simulate beam-particle power loads on the bolometer. Simulations reproduce measured bolometer power loads during high-field-side fuelling, verifying CX losses of approximately 10% of the off-axis beam power. Toroidally symmetric simulations overestimate power loads on the bolometer during low-field-side fuelling, which is explained by toroidal asymmetry in the neutral density distribution, as is demonstrated by toroidally asymmetric simulations.

Results suggest significantly higher CX losses during low-field-side fuelling, up to about 50% of off-axis beam power.

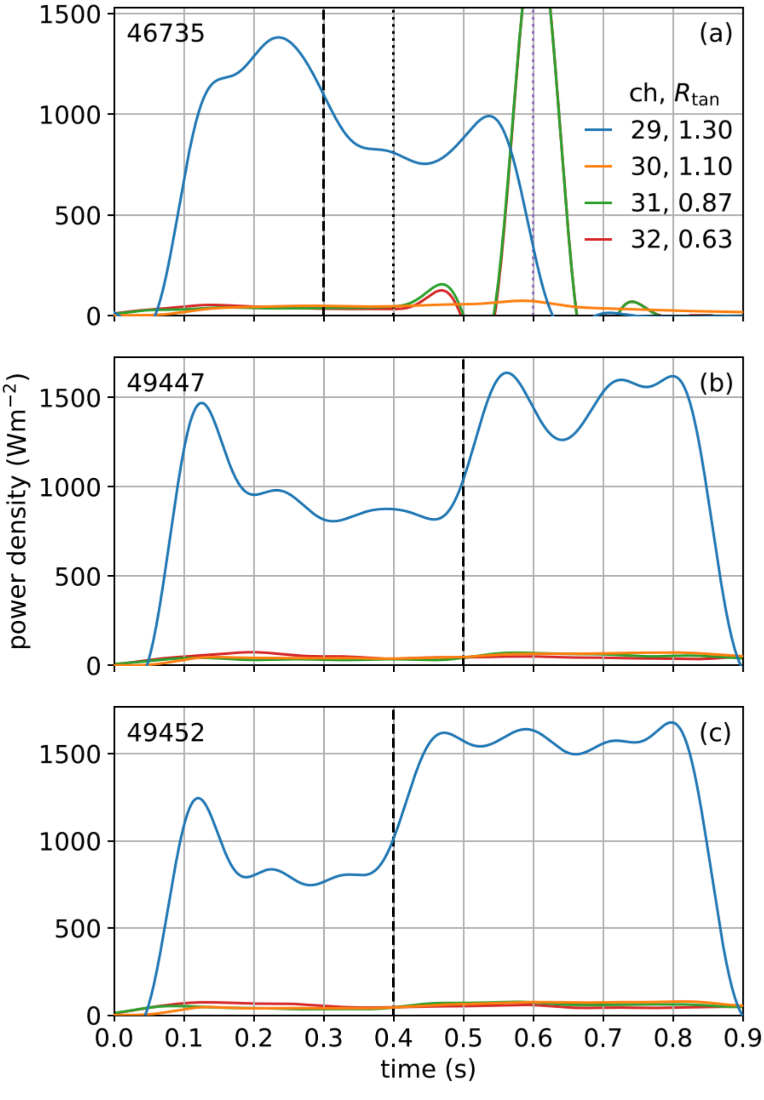

Figure 2.9. Measurements by the counter-beam bolometer channels for three discharges in which the off-axis beam was on for the whole discharges. The edge channel measures power load densities 1—2 orders of magnitude higher than usual. Programmed time points for the switch from HFS to LFS fuelling are indicated by black dashed lines. Time points for when the on-axis beam was turned on and when the plasma disrupted in discharge 46735 are indicated by black and purple dotted lines, respectively. Signals are heavily smoothed in time.

2.3.4 Sputtering from Be-H/D/T surfaces with molecular dynamics

Research scientists: Nima Fakhrayi Mofrad and Andrea Sand (AU)

Sputtering and reflection yields from Be-H/D/T surfaces at different temperatures have been simulated with molecular dynamics. Results show good agreement with SDTrimSP predictions for H/D/T impact energies in excess of 150 eV, while for lower impact energies, a significant peak in yields is observed, due to chemically assisted physical sputtering, which is not predicted by SDTrimSP (N.F Mofrad et al. J. Nucl. Mater. 609 (2025) 155758). Results will support the interpretation of data obtained previously from JET.

2.3.5 Intrinsic torque experiment in TCV

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

Recent analysis of TCV tokamak experiments to study intrinsic torque — using balanced co- and counter-current neutral beam (NB) injection—has incorporated a new technique that roughly accounts for momentum transport fluxes arising from non-zero rotation, particularly the rotation gradient. Preliminary results, including an estimated intrinsic torque profile (see Figure 2.10), support the technique's validity. Concurrently, additional experiments with the balanced NB in L-mode plasmas varied plasma up-down asymmetry and toroidal field direction to further probe intrinsic torque generation. Tentative observations are consistent with earlier TCV experiments and theoretical expectations, although comprehensive analysis is still ongoing.

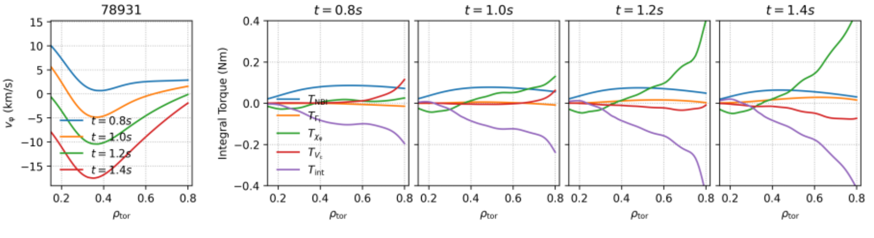

Figure 2.10. Calculated intrinsic torque for the torque ramp for a NB heated L-mode plasma. Due to the slow ramp total torque (from momentum diffusion, convection, particle flux, NB injection and the intrinsic torque) is practically canceled at all times.

2.3.6 Fast ion studies in AUG

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

ASCOT4-RFOF simulations of NBI slowing-down were made to provide fast ion distribution functions for estimating the growth rate of the observed Alfvénic modes (CAE/GAE) in ASDEX Upgrade discharge 38140 by making use of the simulated 4D fast ion distribution $f(R,z,\xi,E)$ in an analytic model of the growth rate.

2.3.7 Task force Leadership activities

Research scientists: A. Hakola, VTT

In 2024, Antti Hakola continued his duties as one of the Deputy Task Force Leaders (TFL) for WPTE, as part of the team of seven TFLs. The TFL team was considerably re-organized during the course of the year, partly due to JET entering its decommissioning phase and several of the team members changing their positions in the first half of 2024. This also brought along new responsibility areas for each continuing and new TFL. Following these changes, Hakola was in 2024 in charge of topics related to (i) material erosion, migration, and fuel retention; (ii) characterization of runaway electrons, and (iii) plasma operations in alternative divertor configurations. Related experiments or analyses/modelling activities were carried out on all the operating devices (AUG, TCV, MAST-U, and WEST). Besides coordinating research activities, the deputy TFL duties included reporting of the scientific outcomes and preparing new campaigns. On AUG and WEST, much effort was put on operating the machines following full or partial boronizations and studying start-up plasma sequences in ITER-relevant cases. MAST-U, for its part, concentrated on scenario development in various ADCs and demonstrated the first high-performance H-mode discharges. Similar work was done on TCV, in addition to which fast particles and physics of runaway electrons were at the core of the 2024 physics programme.

2.4 WP W7X: W7-X exploitation

2.4.1 Effect of SOL plasma and neutrals on beam behaviour in W7-X stellarator

Research scientists: T. Kiviniemi, T. Kurki-Suonio, P. Ollus, L. Sanchis, S. Äkäslompolo, AU

The impact of the scrape-off layer (SOL) plasma and neutrals on deposition, confinement and losses of neutral beam injected fast ions was investigated for a

W7-X plasma. The effect of the SOL width, the density and temperature profiles, the radial electric field, and charge–exchange reactions (CX) was explored in a series of ASCOT simulations. Premature ionization in the presence of SOL plasma was feared to increase wall power loads. In the simulations, however, slowing down in the cold SOL plasma was found to partially compensate for the ionization effects. Furthermore, the effect of SOL plasma on more vulnerable steel components is mitigated over a wide range of different profiles. Also, the effect of the radial electric field is mitigating for steel components in the experimentally observed direction of the field. The effect of CX reactions is shown to lead to a widely spread, low-power load distribution, with no clear effect on the peak load as evident from Figure 2.11. Statistical challenges caused by hugely varying triangle sizes in the discretization of the wall components were discussed.

The efforts resulted into a scientific manuscript, submitted to Plasma Physics and Controlled Fusion on 2.10.2024.

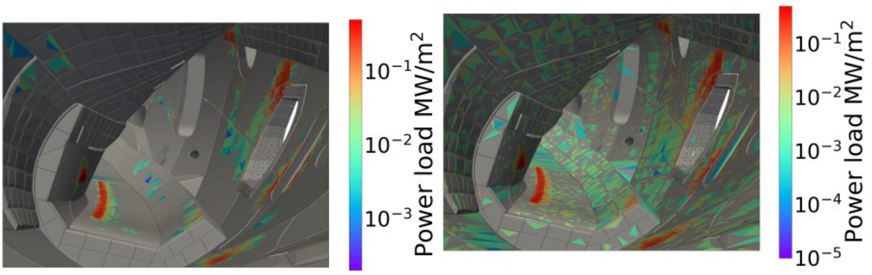

Figure 2.11 Beam power loads in W7-X in the absence (left) and presence (right) of CX reactions. There is no evidence for the appearance of hot spots, neither of strengthening of the peak loads. Rather, the CX reactions contribute to a wide-spread, low-intensity load all across the wall and divertor.

2.4.2 Wall power loads from ICRH-generated ions in W-7X stellarator

Research scientists: T. Kiviniemi, T. Kurki-Suonio, AU, Christoph Slaby, IPP

Predictive simulations of fast-ion power loads to the ICRH antenna components are important to establish safe operational limits. The loads by NBI ions have already been estimated by J. Kontula et al. (2023 *Plasma Phys. Control. Fusion* **65** 075008), but another possible hazard is posed by the extremely high-energetic ICRH-ions created by the antenna itself. We use the magnetic backgrounds and the kinetic profiles from Kontula’s earlier ASCOT4 work which required adjusting them to work with ASCOT5.

As a collaboration between Aalto University and SPC, Switzerland, a test particle ensemble of ICRH ions is generated using the VENUS-LEVIS code, and the guiding-center coordinates of those reaching LCFS are used as seeds for a multitude of new test particles (*markers*) with random gyro angle. Transforming the test particle ensemble from VENUS-LEVIS for ASCOT was not straightforward. For instance, proper *weight factors,* to get *power loads* to the antenna and wall, requires the source term in the units of ”particles/s”. This is natural for NBI markers, but it is still under discussion what is the correct way to assign them to ICRH markers that are picked from a *steady-state* distribution. Instead of absolute numbers, we are first only comparing the relative load on vulnerable antenna straps vs. other parts in the standard configuration for different antenna positions.

The new marker data was successfully tested by the end of 2024, and it technically works with the old background as illustrated in Figure 2.12. The last thing before the flooding in Italy prevented the Marconi simulations was to start numerically testing the consistency of toroidal coordinates which was not clear from documentation. The work is expected to continue in 2025, with new computer resources becoming available.

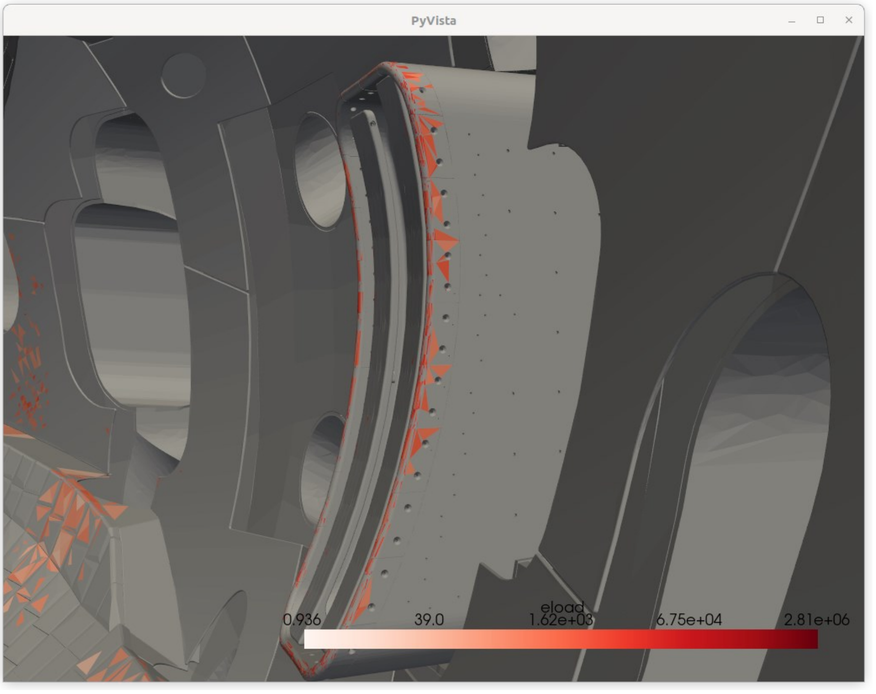

Figure 2.12. Illustration of the power loads (a.u.) on W7-X ICRH antenna components caused by the energetic ions produced by the antenna itself.

3 Digital Solutions for Fusion 2024

3.1 WP AC: Code development for integrated modelling

Research scientists: E. Amnell, B. Cattelan, L. Chôné, F. Granberg, K. Heljanko, O.Lappi, K. Nordlund, J. Nurminen, V-M. Yli-Suutala, UH, J. Åström, CSC, D. Jordan, A. Järvinen, VTT

In 2024, the work at the ACH continued in the same fields are in previous years. The work focused mainly on tasks in the field of Bayesian Inference and Optimization, code optimization, GPU porting and AI/ML applications. The use of Bayesian methods was increased for several codes, and a seminar on the use of them was given by one of the ACH members. Also, the number of interested groups are increasing in this field. In the field of AI/ML, the work continued on surrogate model development and improvement, as well as the use of image recognition. The former to enable fast and light simulations to obtain results and the latter to detect anomalies in simulations and/or automatically detect when simulations are failing. GPU enabling codes to the pre-exascale LUMI cluster was an ongoing work in 2024. Development of EIRON, a model to be able to develop EIRENE further, has continued also in 2024. This is to include more and more features and possible developments to be added to EIRENE in the future. General code optimization and parallelization were done to several codes, which in some cases resulted in significant improvements, both in single-core performance and in a parallel setup.

3.2 WP ENR: Enabling Research

FinnFusion participated in six Enabling Research projects in 2024.

3.2.1 Comparison of He effects in concentrated equiatomic refractory alloys and pure tungsten

Research scientists: F.Djurabekova, G. Wei, J. Byggmästar, Zh. Chen, F. Tuomisto, K. Mizohata UH, T. Suhonen, A. Laukkanen, VTT

In this project, we developed an interatomic potential to model helium (He) interactions in the high-entropy alloy WTaVMoNb. The potential parameters for Mo, Nb, Ta, V, and W with He were fitted to first-principles calculations, targeting He formation energies, He–vacancy binding energies, and He migration energies in pure metals. Using this potential, we computed He cluster binding energies in five metals as well as seven alloys and analyzed He migration from pure W to WTaVMoNb. Simulations revealed that V-containing materials suppress bubble formation, with only a small fraction of He atoms forming bubbles.

Experimental validation was conducted at several research facilities. At the Accelerator Laboratory in the University of Helsinki, arc-melted bulk samples showed that the WTaVMoNb retains the highest He concentration, forming localized cavities with limited migration. Thin-film samples of W, WV, and WVNb were synthesized for future studies. At CNRS-CEMHTI, He plasma reactor conditions were optimized, and ^{3}He NRA cartography was validated, revealing some heterogeneity of helium flux in tungsten samples. Preparations for studying He diffusion and vacancies in refractory-element-containing alloys are ongoing. Meanwhile, at CNRS-IJCLab the TEM protocols and past experiments were reviewed to select the best fitting samples and protocols to analyze the processes of interest, which include investigation of He-induced cavity evolution in tungsten-based alloys in the project's second year.

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

Research scientists: E. Ponomareva, A. Aro, A. Sand, AU

During this project, which ran from May 2021 to April 2024, we have calculated the electronic stopping powers of light ions along channeling and random directions in W, Fe and Fe-alloys using time-dependent density functional theory (TDDFT). Using the data obtained from the TDDFT calculations, we have fitted models for electronic energy losses along arbitrary trajectories, dependent on the local electron density in the position of the projectile, and suitable for use in large-scale molecular dynamics (MD) simulations. We have implemented such an electron density-dependent stopping model for separate projectile and target species in MDRANGE, a computationally efficient ion range code. This allows directly simulating e.g. backscattering spectra for comparison to experiments.

Using energy loss models, we also carried out MD simulations of surface sputtering, finding that the treatment of the electronic energy losses clearly affects results, and hence an accurate model is crucial for high-fidelity predictions. Our results showed that the surface orientation also has an impact on the angular distribution of the sputtering yield. We further found that vacancies up to realistic concentrations under high dose conditions, as well as up to 10% Cr content in Fe-Cr alloys, have a negligible effect on the stopping power predicted by TDDFT.

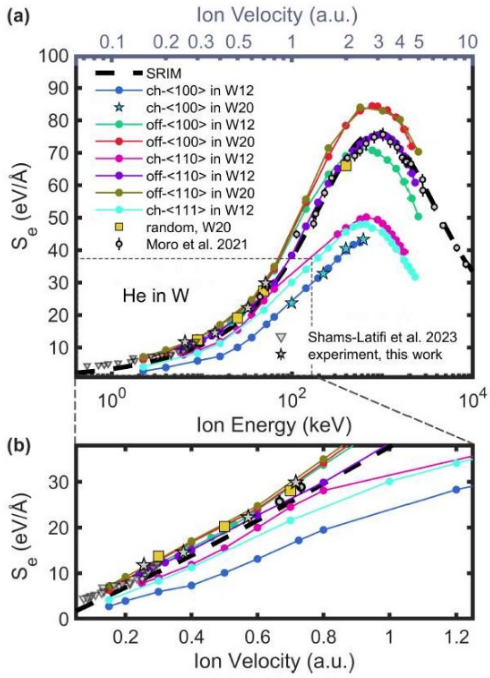

Figure 3.1. Stopping power of He in W along different trajectories. Reproduced from [E. Ponomareva et al., Phys. Rev. B 109 (2024)].

3.2.3 The impact of boron intermixing in PFC on atomic, structural and mechanical features: sputter yields, near-surface morphology, and fuel retention

Research scientists: Antoine Clement, Mohammed Guerboub, Nima Fakhrayi Mofrad, A. Sand, AU

This project is a collaboration between Uppsala University (UU-VR), Vienna University of Technology (TU Wien-ÖAW), and Aalto University (AU- VTT), on erosion and re-deposition of plasma facing materials with particular focus on the formation of boron-containing layers, since boronization is considered as a potentially important process for wall conditioning. The activities carried out at Aalto include the development of a new semi-empirical interatomic potential for the boron (B) – tungsten (W) system. Currently, no interatomic potential exists that is capable of simulating a pure B surface. In particular, no existing potential correctly captures the stable configuration predicted by DFT, which is the trigonal alpha. Our new potential can model both pure W and pure B, as well as tungsten borides of different composition, and will be used for the purpose of predicting sputtering and reflection yields from different surfaces. The complex boron structure proved challenging for the many-body Tersoff interatomic potential formalism, yet a good fit to both bulk and surface properties has been obtained. Figure 3.2 shows some bulk properties predicted by the potential, compared to DFT and to existing Daw (M.S Daw et al. (2011) *Comput. Mater. Sci.*, **50(10)**, 2828-2835) and Albe (K. Able et al. (1997),*Comput. Mater. Sci.* **10(1-4)**, 111-115) potentials. The elastic constants for both the Daw and Albe potentials are off by about 2 orders of magnitude, lying between -10^6 GPa and 10^6 Gpa, and hence are not included.

The adsorption and diffusion behaviour of boron atoms onto and into W surfaces has also been investigated with ab initio methods, showing the impact of different surface orientations on the boron behaviour. Full molecular dynamics (MD) simulations of sputtering from B surfaces have been performed with the new B potential. Comparison between BCA-based Monte Carlo approaches with the advanced MD models shows the importance of the effective binding energy.

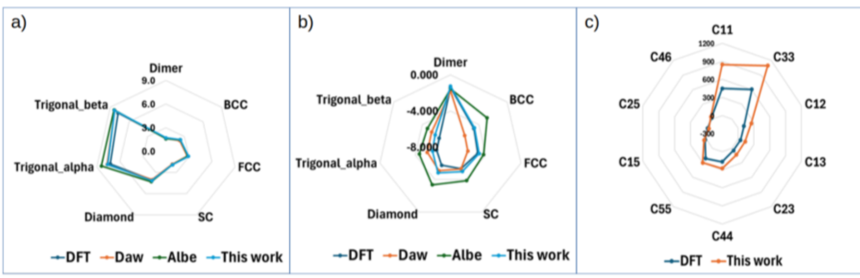

Figure 3.2. Bulk B properties including a) atomic volume (Å³), b) cohesive energy (eV), and c) elastic constants, predicted with the potential developed in this project.

3.2.4 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, A. Järvinen, VTT

The focus of this work was on state representation learning (SRL) algorithm applications for JET electron density and temperature profiles and Europed simulations. An SRL algorithm aims to learn a low-dimensional representation that evolves in time and is influenced by actions of an agent. In 2023, these algorithms were applied for experimental database from JET and AUG tokamaks, as described in the 2023 yearbook, and in 2024 the focus was on combining experimental and simulated data for JET (Figure 3.3). By mixing data from experimental observations and physics simulations and using a class label in the training procedure to distinguish the two, the aim is to learn to represent both the simulations and experiments and to essentially learn a representation for the reality-gap (Sim2real gap in Figure 3.3). After training, the machine learning model can provide predictions for a given machine control parameter sequence for either the experimental observations or Europed predictions (Figure 3.3). This proof-of-principle demonstration for a physics-data hybrid model was presented as a poster contribution in the 50th EPS conference in 2024 and is foreseen to be extended to a peer-reviewed publication.

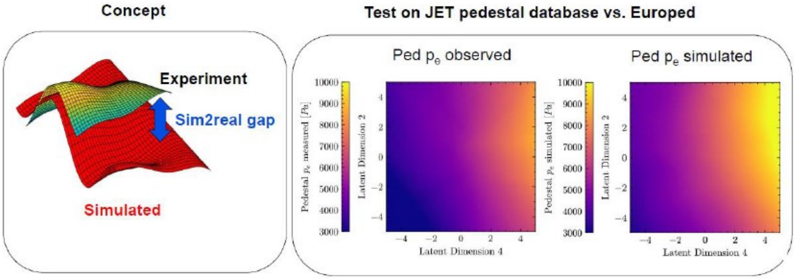

Figure 3.3. Test of physics-data hybrid model training. The model is trained with a class label indicating whether a profile originates from JET or from Europed simulations. The conceptual idea of learning experimental and simulation-based manifolds in the latent space is illustrated at left, and the actual test is illustrated at right.

3.2.5 Novel methods for fast-ion tomographic reconstructions: Fast-ion tomography in 4D

Research scientists: A. Snicker, VTT, O. Hyvärinen, HY

To understand fast ions via measurements requires that sufficient phase-space coverage can be measured. This is typically not the case, rather very limited coverage can be covered by diagnostics. To fill this gap, tomographic methods are designed to invert the fast ion distribution function from the available diagnostic information. The main issue with such tomographic methods is the limited amount of diagnostic information. This needs to be supported with multiple prior information to arrive at sound estimates for the distribution function. Furthermore, the more dimensions the distribution function is wanted, the more prior information needs to be provided.

Within this project, ASCOT5 simulations are used to gather prior information to an unprecedented extent, including full neoclassical slowing-down physics (orbit width effects, Coulomb collisions). This is obtained by constructing a basis out from a set of calculated slowing-down functions. The reconstructed fast ion distribution function is searched as a linear combination of these basis functions in the tomography reconstruction, so that the functional that includes data fidelity term and regularization term is minimized.

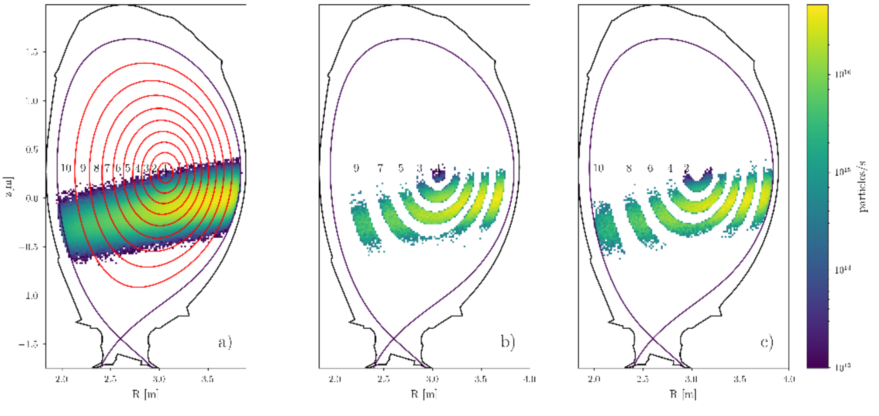

Figure 3.4. The construction of the slowing down basis is made based on the sources and sinks of fast ions in the plasma. These sources are further divided in the phase space to observe the reconstruction’s differences from the prior

information. The figure illustrates the division of JET NBI ionization full energy into ten different sources whose slowing down distributions are basis vectors.

3.2.6 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

Our research on the Faraday effect in silicon-on-insulator (SOI) based waveguides has reached its conclusion, highlighting fundamental challenges that severely limit the feasibility of a highly sensitive magnetic field sensor using this technology. Key issues such as surface roughness of the waveguide and its 3D stress distribution likely enhanced mode coupling between the fundamental and higher-order harmonics, leading to increased noise levels and higher scattering losses (damping), ultimately rendering our attempts unviable. While these challenges severely limit sensor performance with current SOI technology, future advancements in fabrication precision or alternative material choices could potentially mitigate these effects.

With only three months remaining in the project, we focused on finalizing our analysis and consolidating our findings. Our work resulted in a publication in IEEE Journal of Lightwave Technology, where we presented detailed modelling and experimental measurements of birefringence. The results showed good agreement and demonstrated that effective index birefringence can be minimized—potentially even reaching zero—over a narrow wavelength range, despite the presence of dispersion.

Additionally, we identified Faraday rotation in the presence of a magnetic field (~1T), but the observed effect was weaker than anticipated and exhibited complex spectral variations that were not well captured by our current models. This spectral dependence further complicates the practical use of the effect for sensing applications.

Given these limitations, the prospects for a high-performance SOI-based Faraday sensor remain low. While this project has concluded, the insights gained may still be relevant for future investigations into SOI waveguide birefringence and alternative magneto-optical applications.

4 ITER Technology and DEMO Preparation 2024

4.1 WP PrIO: Preparation of ITER first experimental campaigns

4.1.1 Accelerating pedestal MHD stability evaluations through machine learning

Research Scientists: A. Järvinen, A. Bruncrona, VTT

In 2024, a project was started within WP PrIO to develop fast, machine learning surrogate models for the evaluation of magnetohydrodynamic stability of pedestal plasmas. This project is conducted in collaboration with UKAEA and KTH. A proof-of-principle surrogate model for the ideal MHD stability code MISHKA was developed for a parameter space relevant for a subset of the JET plasma scenarios from the JET EUROfusion pedestal database. The surrogate model is able to assess the MHD stability properties of given magnetic equilibrium and pedestal profiles in a fraction of the time that it takes for the full model. The work was presented in the 5th ICDDPS conference in 2024.

4.1.2 Numerical modelling of the ITER FILD diagnostics using ASCOT

Research Scientists: A. Snicker, K. Särkimäki, VTT

The ASCOT5 code was used to support the design activity of the ITER FILD project. The project foresaw a big milestone as in February 2024 the conceptual design review (CDR) took place. The work in 2024 then concentrated on resolving the issues raised by the CDR, including the possibility to use a double slit design to measure both positive and negative pitch values (which was shown not to be possible due to the absence of high enough flux for negative pitch alphas) and the radial location of which the alpha particles still contribute to the signal. Furthermore, neoclassical tearing modes (NTMs) were included in the modelling to see the effect of these modes on the velocity space of lost alphas, as shown in Figure 4.1.

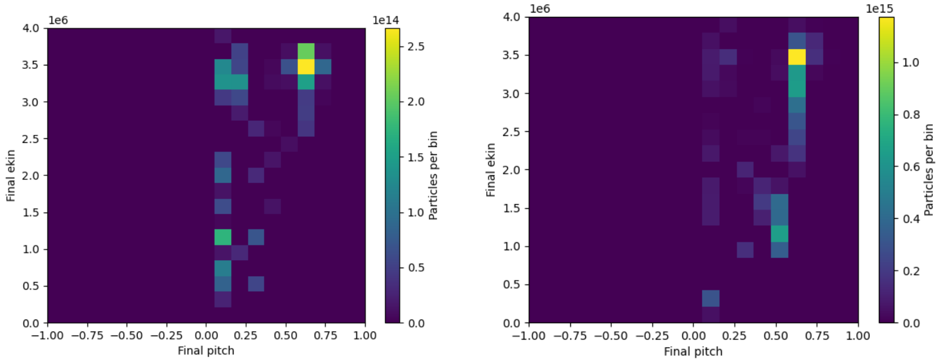

Figure 4.1. ASCOT simulations of the velocity space of the lost alpha particles in ITER assuming no NTMs (left) and assuming a 15cm wide (2,1) NTM (right). Notice the additional fingerprint due to NTM around 1 MeV and 0.5 final pitch value.

4.1.3 AI/ML methods for ASCOT NBI physics

Research Scientists: A. Snicker, K. Särkimäki, D. Jordan VTT, P. Vinzenci, R. Delogu.

The ITER operation relies on using multiple heating systems, including the neutral beam injection system. One of the issues related to this system is that a safe operation is obtained only with high enough density – otherwise the beam will go through the plasma heating the first wall panels and possibly causing damage. The limit for the safe operation is typically obtained using Monte Carlo simulations. However, these simulations can be time-consuming and a faster model with a wider scenario parameter range would be optimal. To this end, this project aims to develop using artificial intelligence and machine learning tools to train a surrogate model for the shine-through estimation. The plan is to construct a toolchain able to take into input the plasma scenario parameters, then calculating the equilibrium and kinetic profiles using METIS, refining the equilibrium using the CHEASE code, and then finally running BBNBI5 (part of the ASCOT5 suite-of-codes) to get the shine-through.

The project was launched in 2024, with the workflow set-up and initial surrogate model generated with a small database showing promising results as seen in 4.2. During 2025, the project foresees to widen the work to model also the slowing-down physics and to produce a model for JT60-SA NBI system, where a model validation can be carried out.

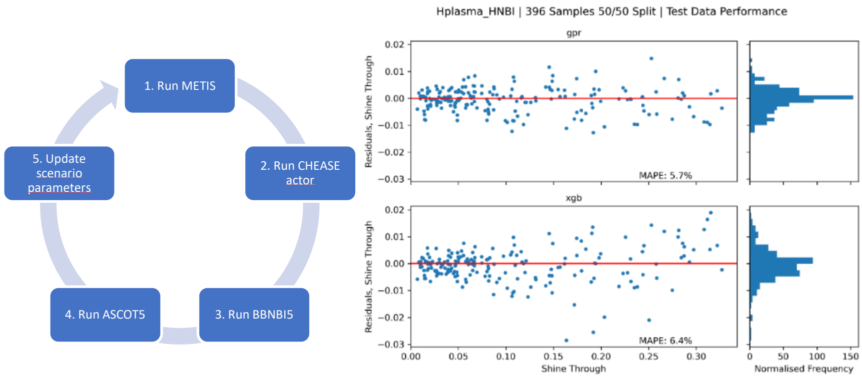

Figure 4.2. Workflow to calculate the shine-through and slowing-down physics based on scenario parameters (left). This will be controlled by active learning tools. On the right, the initial results for the residual errors for the shine-through estimation. Both Gaussian process regression (gpr, above) and gradient-boosted decision trees (xgb, below) show promisingly low residual errors, this was obtained using non-active learning and using 288 plasma cases.

4.2 WP DES: Design activities

4.2.1 ASCOT simulations for the volumetric neutron source

Research Scientists: A. Snicker, K. Särkimäki, VTT

The ASCOT5 code was used to support the design activity of the volumetric neutron source (VNS) designed by EUROfusion. Since VNS foresees to produce fusion neutrons mainly with beam-driven DT reactions, from the fast particle confinement view the critical component is the confinement of the neutral beam ions. During 2024, analysis concentrated on the new design point for VNS. For this configuration, a loss level of merely 0.2% of beam ion power was simulated by ASCOT. This will ensure that enough neutrons are generated. ASCOT5 was also used to simulate the confinement of the resulting DT alpha particle population. Since the design does not rely on the heating from the alpha particles, the only criterion is that there will be no hot spots in the first wall. ASCOT5 predicted up to 7% of alpha particle losses, but importantly no hot spots close to the design value for the power load to first wall elements. Lastly, the beam ionization calculating was carried out assuming no plasma. This corresponds to an unlikely but possible scenario where plasma control is lost but the massive NBI system cannot be shut down in the same timescale. Figure 4.3 shows the resulting power load to the first wall of the device due to full 100% shine-through. As can be seen, heat power loads up to 10s of MW/m^2 can be reached.

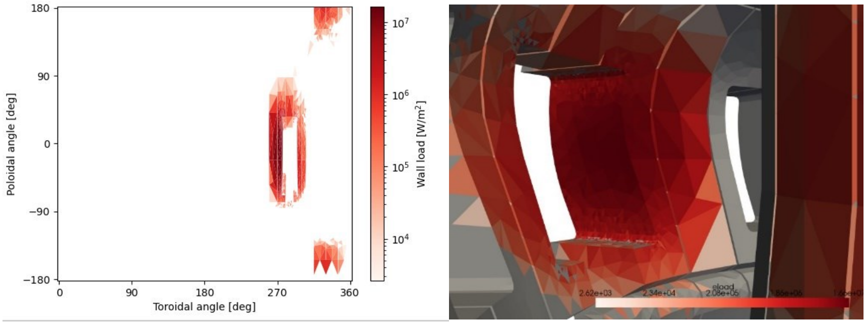

Figure 4.3. BBNBI5 simulations of neutral beam ion shine-through in the absence of plasma. Such scenario is unlikely but plausible in the loss of plasma event. Power loads up to over 10 MW/m^2 can be reached.

4.3 WP RM: DEMO Remote maintenance

Research scientists: W. Brace, J. Lyytinen, H. Martikainen, M. Siuko, J. Alanen, L. Ribeiro Goncalves, V. Truong, P. Kokkonen, S. Qais, E. Strömmer, A. Ylisaukko-Oja, T. Sipola, T. Vaarala, T. Tenhunen, M. Alamäki, J. Koskinen, M. Tahkola, T. Välisalo, J. Sarsama, Z. Akhtar, Karoliina Salminen, Petri Tikka, VTT, H. Wu, C. Li, M. Li, Q. Han LUT, Comatec, Fulvisol Oy, Coresbond

4.3.1 Overview

The DEMO Remote Maintenance Work Package (WPRM) is evolving into the digital application of design and development, signifying a paradigm shift towards creating new design tools and methodologies. It has also involved rethinking the design and research approach, focusing on identifying and using existing technologies and systems in the market. This evolution is based on the digital transformation in design. It is also driven by the quest to involve more industries in the fusion power plant development based on Public-Private Partnership (PPP). Finland's WPRM research activities are a key part of this digital and PPP transformation. Therefore, the research focus has shifted to digital application development, combining design with testing and deploying software applications across various platforms, utilising cloud integration. The goal is to develop a holistic and hierarchically organised digital environment for data-driven, interconnected design and testing. Design thinking and novel methodologies such as AI support risk analysis design are implicated for probabilistic risk reasoning, by formalising design problems as mathematical models to quantify and implement machine learning in the conceptual design phase. To enhance the involvement of key industrial companies, design-by-cataloguing is developed and implemented to index, as pending technologies for remote maintenance, key components and systems in the market, to be refurbished for use in the fusion power plant, together with the manufacturer, thus creating instance industrial partners. The Finland WPRM research group include research institutes VTT and LUT, as well as industry participants, including Comatec, Fulvisol, and Coresbond.

4.3.2 RM System Design

The RM System Design work is now focusing on the long-term objective, incorporating fundamental science and innovative technologies, with a particular emphasis on design for prototyping (DFP). The DFP methodology applied by the Finnish research group comprises the design by cataloguing (DBC) combined with a blend of digital and physical prototyping. This approach aims to attract and engage Finnish industrial companies in active participation in fusion power plant development. The DBC approach maximises the use of systems and technologies in the market for fusion applications. It involves, at the initial stages, the mission statement, constraints analysis, search for commercial-off-the-shelf (COTS), and assessing through various methods to identify equipment with a defined TRL. In collaboration with the manufacturing company, the specified COTS equipment is reengineered or retrofitted to achieve the desired level of readiness, ensuring compatibility with the technical constraints and requirements of the fusion power plant. This approach maximises the participation of industrial companies. Additionally, an enabling environment is being created for manufacturing companies to test equipment through the Remote Maintenance Test Platform (RMTP). The RMTP incorporates the existing VTT Divertor Test Platform (DTP2) and involves the development and advancement of five main test rigs: the Digital Thread Rig, which facilitates data acquisition; Metrology Data Rigs, designed to process large amounts of simulation parameters; Flexible Body Dynamic Rigs, providing precise measurements of large payloads; Human Factor Rigs, aimed at simulating fusion power plant operators; and the COTS & Actuator Rig, intended to build confidence during trials of current market equipment.

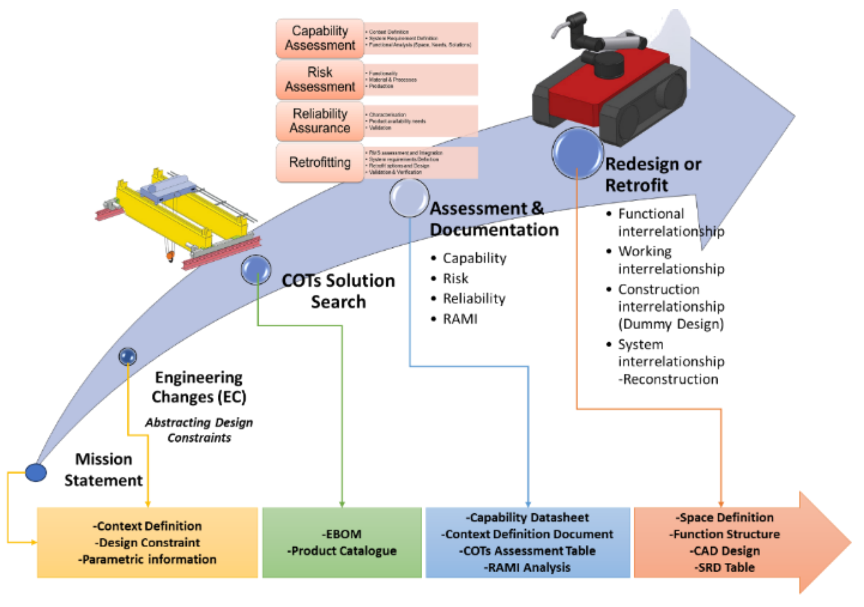

Figure 4.4. Design by cataloguing methodology.

4.3.3 RM Technology R&D

The research effort by RM Technology R&D in Finland focuses on developing innovative design tools and methodologies that leverage digital transformation in design. The exploration of digital design tools encompasses: developing reusable parametric 3D CAD models that facilitate the straightforward creation of alternative component layouts; parameterised models for remote maintenance feasibility assessments of alternative options to support coupled physics and engineering models within a shared design framework; automating the generation of maintenance trajectories in plant architecture assessments; AI-supported probabilistic risk analysis through mathematical modelling; and software development for prognostic health management (PHM) of welded pipes. One direction of the research is the development of the Integrated Remote Operations Handler (IROH), which combines different tools and functionalities into a single, unified system. The tool is developed through a collaborative effort with research institutes from Germany, France, and Italy, as well as with Finnish industrial companies including Fulvisor Oy. IROH is part of an overall integrated design tool being created that digitally connects various modelling and simulation data with data from RMTP measurements. This integration is to produce a unified source for combining software tools, supporting real-time information sharing and data acquisition, which improves communication, minimises risks involved in processing large datasets, and aids distributed communication in real-time.

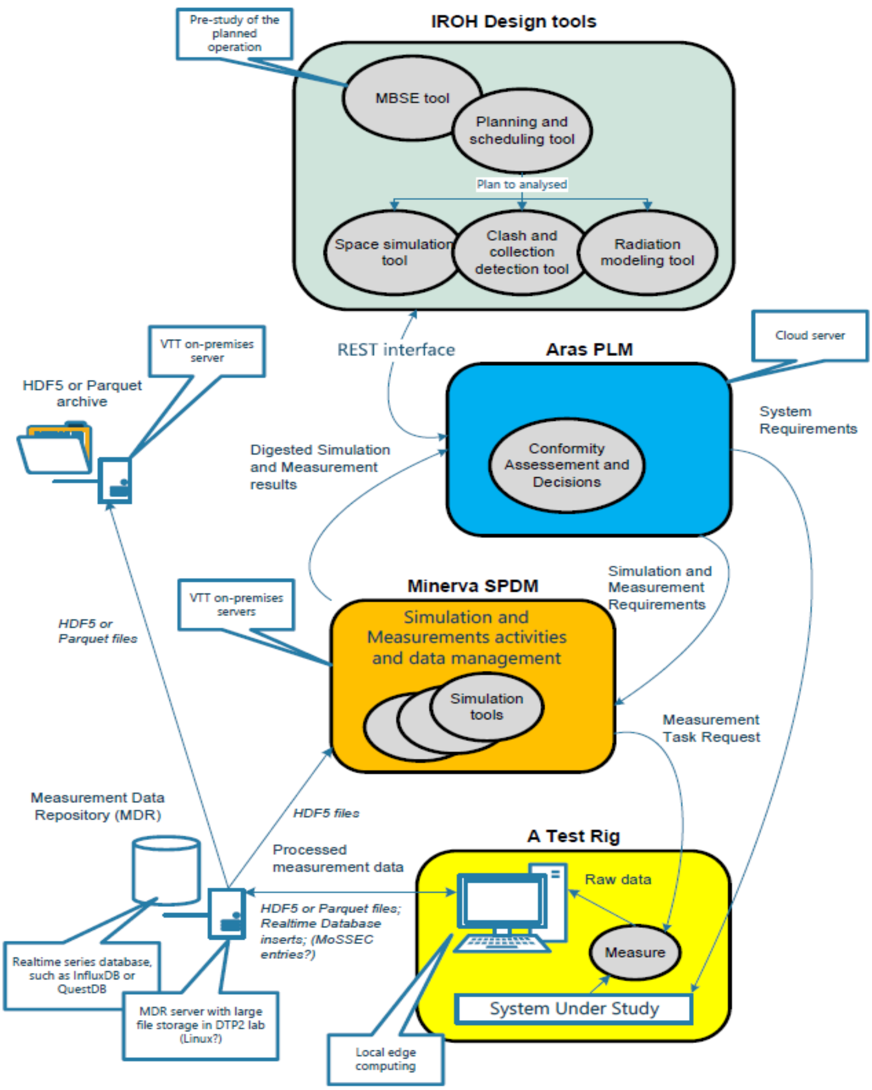

Figure 4.5. Overall integrated design tools for RM (Jarmo Alanen).

4.3.4 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

LUT participates the WP RM with 4 major areas: Plant Architecture Assessments WP2&3 (Bluemira modeling), condition monitoring, Stochastic modelling, Port Closure Plate, and support to Port Plant Systems. In-Vessel Maintenance R&D WP6 Development (MPD).

1. In In-vessel maintenance system, Development of MPD for Limiters maintenance. A new concept of MPD has been studied.
2. In Condition monitoring AI algorithms (Data-driven methods) are studied, and the methods of human condition monitoring in man-in-loop remote handling systems are developed.
3. In the stochastic 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 modeling and optimization of Architecture considering remote maintenance boundary conditions.
5. Port Closure Plate and support to Port Plant Systems, study the methods for closure plate, NC, and EC remote maintenance.

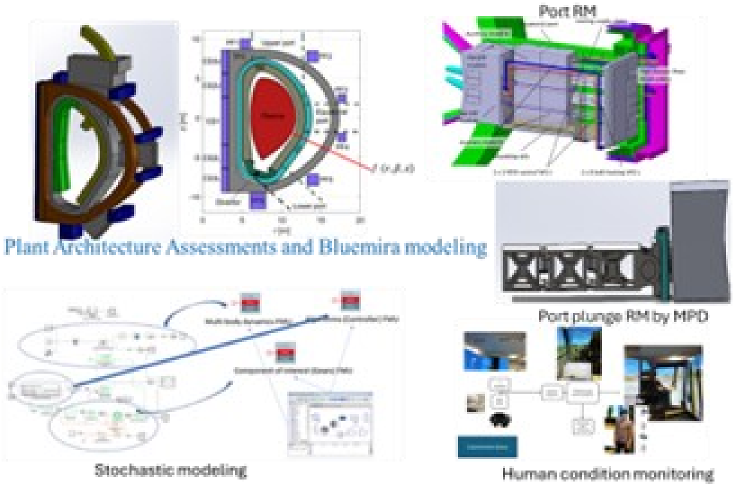

Figure 4.6.LUT activities on remote maintenance.

4.3.5 EUROfusion WP RM Project Leader

In 2024, Karoliina Salminen was selected as the Project Leader and VTT as the Lead Beneficiary of the Remote Maintenance Work Package (WPRM) within the EUROfusion programme. As Lead Beneficiary, VTT took on the responsibility of coordinating efforts across the WPRM partners, ensuring effective collaboration and alignment with the overarching goals of the EUROfusion roadmap. VTT is now responsible for the scope, budget, and results of the WPRM. This is the first ever FinnFusion Project Leader position in EUROfusion. In addition to the Project Leader position, VTT introduced two other management roles in WPRM: Project Support Officer Petri Tikka and Technical Clerk Ulla Peltonen.

In 2024, a significant investment within WPRM began with the planning and design of a new full-size Breeding Blanket Remote Handling Test facility in Denmark. Other key achievements of the Work Package included a maintenance system assessment for the plant architecture options, feasibility studies and concept designs for in-vessel and ex-vessel operations, test campaigns for pipe joining and parting technologies, and advancements in maintenance processes withing the three port areas. The WPRM Project Leader role included continuous collaboration with WPRM Research Units, EUROfusion programme management, and the European Commission.

5 Innovation, DEMO and Fusion Power Plants 2024

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

Research scientists: S. Norrman, VTT

Both the Water-Cooled Lithium-Lead (WCLL) and Helium-Cooled Pebble-Bed (HCPB) thermal-hydraulic Apros models were further developed during 2024 according to available reference data. The WCLL concept in focus was the Direct Coupling Design (DCD) with a small Energy Storage system (ESS). The configuration contains two separate cooling loops, enveloping the Breeding Blanket (BB) with 2x2 identical Once-Through Steam Generators (OTSGs). Control logics were implemented for steady state runs. Some data were still missing, hence transient runs were still not performed with the model.

For the HCPB concept, model modifications and transient runs were made to the Indirect Coupling Design (IDC) alternative with a large energy storage system. The Primary Heat Transfer System layout was retained from previous configurations while the Intermediate Heat Transfer System (IHTS) was updated following Kraftanlagen Heidelberg GmbH (KAH) recommendations and Ebsilon results with respect to the global heat balance. However, horizontal Intermediate Heat Exchangers (IHX) were still not implemented, instead vertical exchangers from previous models were used. The Power Conversion System (PCS) was retrofitted in order to align the Apros model with the modified Ebsilon layout for the 2023 configuration. The adopted heat balance map resembles the 'maximum of the maximum' case where divertor powers increased most notably. In general, the transient analysis identified numerous opportunities for improvements, mainly in the IHTS and PCS as the PHTS design was not profoundly altered.

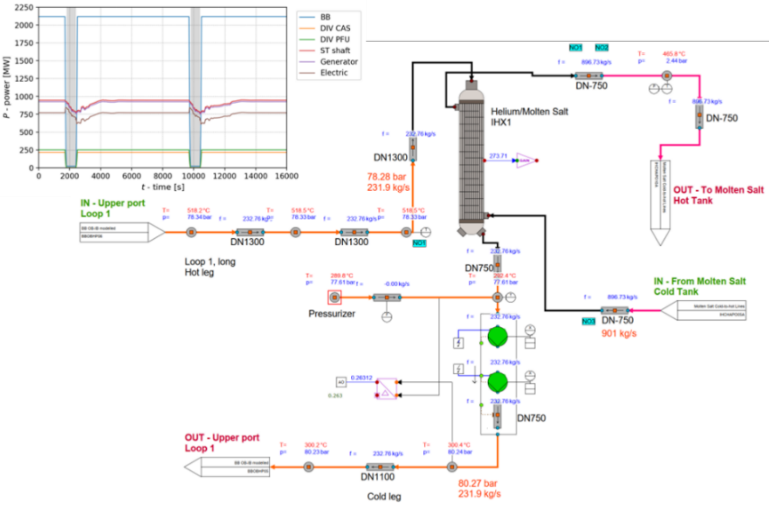

Figure 5.1. HCPB PHTS loop #1 and primary system power balance.

5.2 WP ENS: Early Neutron Source definition and design

5.2.1 Probabilistic risk assessment

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 2024, 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. Improvements were made to the modelling of the consequences of accident sequences, modelling of the safety control system, and modelling of isolation functions in radionuclide release scenarios. Sensitivity analyses were performed to highlight the uncertainties related to the modelling assumptions and to show how risk estimates could be improved.

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

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

Some parts of the IFMIF-DONES facility are under such strong radiation that maintenance procedures must be carried out by robots. The operations must be monitored remotely using radiation-resistant cameras. A few dozen cameras are needed to comprehensively monitor these maintenance procedures. Most of the cameras are overview cameras, which must have Pan-Tilt-Zoom capabilities, whereas some cameras will be attached to moving parts, and the light weight (at most ~1 kg) of these cameras is essential.

Color cameras based on semiconductor technology are available in the market, which can withstand high radiation, some models up to 1 MGy. The price of the cameras is up to ~100 000 €, and most camera models have Zoom-Pan-Tilt capabilities, and often lighting. The cameras require supporting parts, including fixed cables (up to 100 m) and camera controllers, which must be placed in radiation-protected spaces.

The camera models to be used have been selected, and the locations and wiring of the cameras have been planned. The work used Virtual Reality animations, which show maintenance procedures in facilities under radiation, and these VR animations show as realistically as possible what the IFMIF-DONES facility maintenance operators will see in the future when the facility is in operation.

At first two camera models (from 2 different manufacturers) were selected, one for overview purposes, the other for lightweight purposes. Both have 1 MGy radiation tolerances. These cameras fulfil the system requirements, but alas, the total price exceeded the budget. Therefore, cheaper less radiation-tolerant models from the same two manufacturers were investigated, to be used in locations where there is less radiation. Now a configuration with 4 camera models is proposed, and the total price is much cheaper.

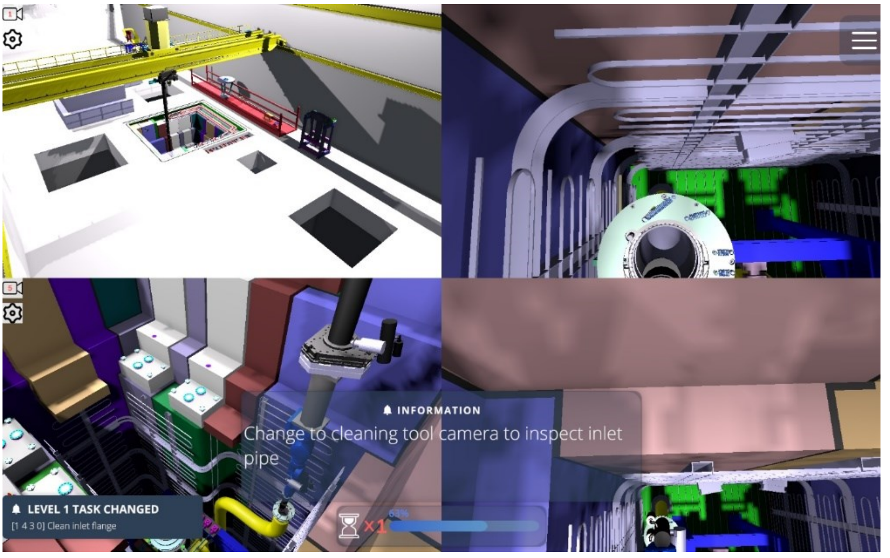

Figure 5.2. Screenshot of VR model with 4 partial images showing views from different cameras.

5.3 WP MAT: Materials

5.3.1 WP MAT Hot cells

Research scientists: P. Lappalainen, P. Arffman, J. Saarinen, M. Ulfves, J. Lukin, VTT

CuCrZr alloy is a promising candidate for high heat flux applications in ITER components, such as the divertor and the first wall, due to its high thermal conductivity, strength, toughness, and radiation resistance. This study investigates how neutron irradiation at ITER-relevant doses affects the mechanical behaviour of precipitation-hardened CuCrZr alloy.

Specimens were irradiated at approximately 150 °C and 235 °C with doses between 0.66 and 1.30 dpa. Tensile tests were conducted at both room temperature and the corresponding irradiation temperatures to evaluate changes in mechanical properties. The stress-strain behaviour of CuCrZr alloy specimens subjected to neutron irradiation at different temperatures and doses is shown in Figure 5.3.

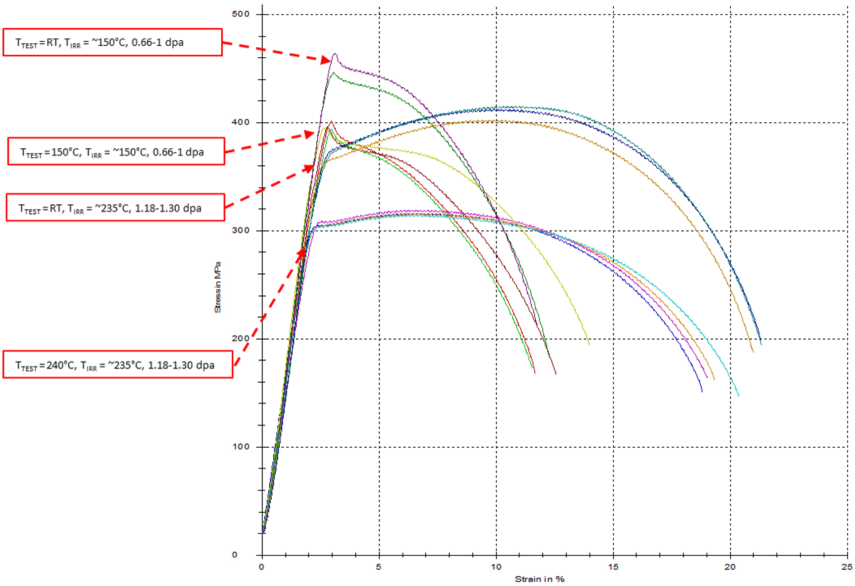

Figure 5.3. The stress-strain behaviour of CuCrZr alloy specimens subjected to neutron irradiation at different temperatures and doses.

At 150 °C irradiation with room temperature testing (0.66–1.0 dpa), the alloy showed pronounced hardening and embrittlement, characterized by necking immediately after yielding—a typical “hardened but brittle” response. This indicates a notable loss in ductility due to irradiation. Testing at the irradiation temperature (150 °C) produced slightly lower strength but exhibited similar embrittled behaviour, suggesting that testing temperature alone does not mitigate irradiation-induced embrittlement.

In contrast, specimens irradiated at 235 °C and tested at room temperature (1.18–1.30 dpa) displayed slightly lower strength compared to those irradiated at 150 °C, but significantly improved ductility. This suggests that higher irradiation temperatures promote more stable plastic deformation. Furthermore, when both irradiation and testing were conducted at 235–240 °C, specimens demonstrated the lowest strength among all conditions but retained improved ductility. This implies that elevated temperatures facilitate recovery mechanisms that counteract radiation-induced damage, enhancing plasticity.

In summary, neutron irradiation increases the strength of CuCrZr but reduces its ductility, particularly at lower temperatures. However, higher irradiation and testing temperatures can partially recover plasticity, underscoring the importance of temperature in assessing mechanical performance for nuclear applications.

5.3.2 MicroStructural characterization, in-situ micromechanical testing and multiscale materials modeling

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

Only minor effort has been put to the work during the year 2024. Most of the focus has been on developing the model to be able to capture the cyclic behaviour of copper better as with the current model it has proven to be almost impossible to capture the cyclic and monotonic behaviour with single set of parameters. The year has mostly been used to produce experimental data and to find suitable patterning method for DIC (digital image correlation). Work will be continued during the year 2025.

5.4 WP PRD: Prospective R&D

5.4.1 HHFM High heat flux materials

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

This work focused on developing and applying an Integrated Computational Materials Engineering (ICME) framework for Process, Structure, Properties, and Performance (PSPP) chain for Cu and CuCrZr alloys, supporting industrial-scale development within the HHFM project. Experimental efforts included mechanical testing (tensile, fatigue, creep, cyclic loading) using standardized and miniature methods, thermophysical property determination, and microstructure characterization via SEM and TEM. A new miniature mechanical testing stage operating up to 1000 °C was integrated into a high-resolution SEM (with EBSD and P-FIB). The ICME framework linked manufacturing steps—casting, drawing, cold working, annealing, forging—to PSPP models. Samples from all manufacturing steps also plate and pipe samples from EUROfusion partners (SCK.CEN, ENEA respectively) were analyzed. Special emphasis was placed on casting simulations and how differences in proces affects the final microstructure. Numerical microstructure produced with casting simulation were used in Crystal Plasticity (CP) simulations using three damage modelling approaches—porous, crystalline, and phase field—to simulate performance. The integration of experiments, modeling, and characterization enhances understanding and supports material design and scale-up aligned with VTT's multiscale modeling strategy.

5.4.2 Serpent2 neutron model for HELIAS stellarator

Research scientists: T. Lyytinen, A. Snicker, VTT

In 2024, stellarator modeling efforts focused on obtaining more realistic TBR estimates by incorporating divertor components and refining coil shielding calculations using different tally approaches and variance reduction techniques. The divertor, particularly its coolant and structural components, displaces breeding material, reducing tritium production and altering the reactor's neutron and photon radiation environment. Since magnetic islands and island divertor placement can be controlled by magnetic field configurations, a parametric study was conducted to explore variations in area (width and length), thickness (cooling and structural parts), placement, and material composition. TBR results for different divertor configurations were compared to a reference case without a divertor, which yielded high values of 1.42 for HCPB and 1.27 for DCLL blankets. With a realistic divertor area fraction of 13% of the first wall, TBR remained above the 1.15 target using an HCPB breeding blanket and a top-bottom divertor placement (see Figure 5.4). However, replacing HCPB with DCLL and switching from helium to water coolant caused TBR to drop below the target, highlighting the critical role of divertor configuration in achieving tritium self-sufficiency.

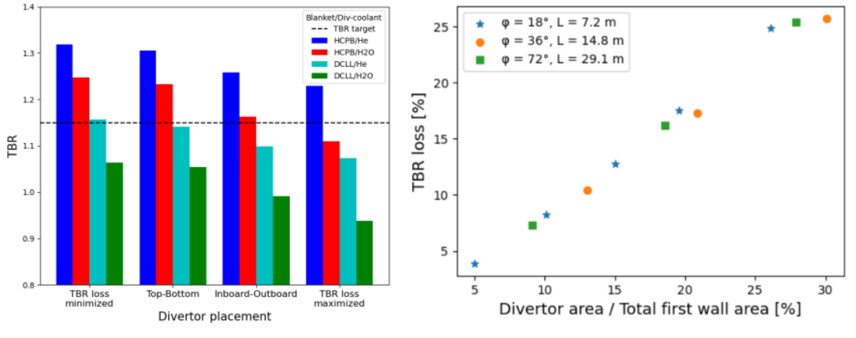

Figure 5.4 Left: TBR with four divertor placement configurations, DCLL and HCPB blankets, and water and helium divertor coolants. Right: TBR loss as a function of divertor area fraction for the top-bottom placement configuration. Different markers represent varying divertor lengths, while the x-axis primarily reflects changes in divertor width.

5.4.3 IREMEV activities

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

At UH work was done on understanding the evolution of tungsten when deuterium is present during the irradiation. We found that having deuterium present will dramatically affect the defect build-up compared to tungsten without deuterium. We found that limited recombination and high defect production were the reasons for this increase in defects in samples with deuterium. The findings are in-line with experimental results, both in single deuterium implantation setup and in dual-beam irradiation setups. The results also showed that voids filled with deuterium will not act as good defect sinks as voids that are empty. This will further affect the defect evolution, especially at higher doses, where voids are present.

At Aalto, we have investigated the effect of external loading on the average damage from individual collision cascades in pristine and high dose limits using molecular dynamics. The effects of compressive and tensile strain in both the <100> and <111> directions on the defect numbers and the elastic dipole tensors of the damage resulting from cascades in the PKA energy range of 10 keV – 100 keV was studied. We also analysed the response of polycrystalline microstructure to cascade damage under loading conditions, providing motivation for using a vacancy-rich lattice as a proxy for the purpose of obtaining statistics of individual cascades in a high dose regime.

5.5 WP SAE: Safety and Environment

5.5.1 Decommissioning plan outline

Research scientists: Vesa Laitinen, Tomi Pakarinen, Platom, Markus Airila, VTT

To create a proper basis for the decommissioning of a nuclear facility, factors affecting its execution should be identified and considered already during the facility's design phase. This has been well experienced during actualised D&D projects, where the lack of recognizing decommissioning as one design principle has led to the dismantling of the facility being more complicated than expected.

The basic fundamentals steering decommissioning projects are globally the same: minimization of nuclear waste generation, workforce radiation exposure and impacts on the public and the environment. At a national level, these principles may be put into practice with slightly different requirements. This deliverable examines the nuclear decommissioning related requirements of the Finnish regulatory framework, which largely adapts international guidelines on the subject. Understanding key requirements and their possible differences between different regulatory environments provides essential input to the development of DEMO as well.

In addition to the regulatory aspect, also lessons learned during implemented D&D projects should be utilized in the engineering of DEMO. Even though past experiences are practically available only from the D&D projects of fission power plants, they are broadly applicable to DEMO since the challenges are mostly the same. However, it is also important to be aware of the factors that are specific or of greater concern in case of fusion power plants, such as the management of tritium.

For the long-term planning of decommissioning, it is relevant that the decommissioning plan is updated and developed in relation to the progress of the DEMO design and the overall project. As are many topics, also decommissioning is strongly dependent on the national regulatory framework and nuclear industry practices, which is why detailed decommissioning planning can be started only after the host country of DEMO has been chosen. In the meanwhile, the upcoming decommissioning should be facilitated by integrating this discipline as one fundamental in the design process.

5.5.2 Waste recycling process optimization

Research scientists: Tomi Pakarinen, Vesa Laitinen, Platom
Markus Airila, VTT

DEMO will produce radioactive waste during both the operational phase and decommissioning. Part of the waste includes valuable materials, which are highly desirable to be recycled in order or improve the cost-efficiency and environmental aspects of the plant's lifecycle.

For this reason, the recyclability of DEMO radioactive waste must be studied and developed. National regulatory frameworks and operational environments contribute significantly to the feasibility of recycling radioactive waste. In this deliverable, these factors are described from the aspect of Finnish nuclear sector. On the one hand, this description gives an outlook on how practically the radioactive waste recycling can be implemented in Finland, and on the other hand, it raises points that are relevant to consider for DEMO regardless of the eventual host country.

Another point of view for improving the waste recycling process is to consider how it can be taken into account in the planning of DEMO and connected R&D activities of radioactive waste management technology. The material choices of DEMO components are one example of a design feature that has a direct and significant effect on the characteristics of the produced waste. Based on this, fusion reactors produce some radioactive waste that does not currently have efficient waste treatment techniques available, or they are not yet proven.

As national regulations and practices have an inevitable impact on the radioactive waste recycling and management in general, the waste management should be one of the key factors to be assessed when the host country evaluation process is started. The assessment should not be limited only to the regulatory framework, but the national radioactive waste management scheme with the infrastructure, practices and different stakeholders as a whole.

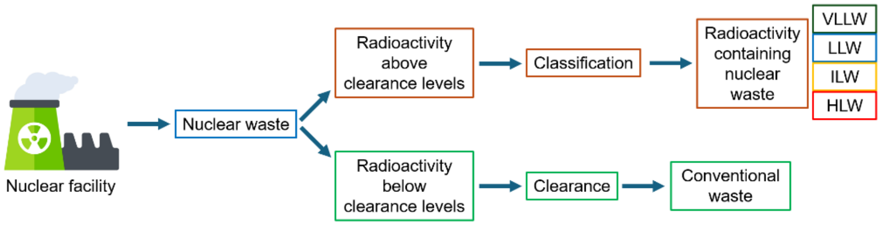

Figure 5.5. All waste generated at a nuclear facility's radiation-controlled area is considered nuclear waste unless it has been cleared from regulatory control.

5.5.3 Liquid waste flow diagram considering the Finnish regulation

Research scientists: Markus Airila, VTT

In 2024, VTT undertook a task in EUROfusion WP SAE to review the management of liquid radioactive waste in Finland. This task involved developing a liquid waste flow diagram that adheres to Finnish regulations.

Finland's nuclear power industry has an excellent track record in safety and plant availability, combined with transparent governance and a trusted regulator, STUK. This has led to high public support for new nuclear projects. The Nuclear Energy Act sets the foundation for nuclear waste management in Finland, with principles including the definition of nuclear waste, the ban on export and import, and the waste management obligation of license holders. The Waste Acceptance Criteria (WAC) in Finland are derived uniquely for each repository from long-term safety requirements to protect human health and the environment. These criteria include nuclide-specific activity limits and surface dose rates of waste packages and transport containers. The long-term safety assessment for low- and intermediate-level waste (LILW) disposal involves site characterization, waste characterization, and performance assessment of safety barriers. This process ensures compliance with regulatory standards set by STUK. We found in the study that YVL Guides are in fact setting quite loose boundary conditions for liquid waste management. Furthermore, the Regulations and YVL Guides do not set explicit WAC but instead the development of WAC is the responsibility of licensees. Therefore, there are only limited possibilities to transfer Finnish experiences to DEMO, and it is recommended to collect experiences and established practices also from several other countries.

5.5.4 Fire accident analyses

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

The fire risk analysis of the DEMO fusion power plant includes fire hazard identification and fire consequence assessment. Areas of primary interest are high-risk areas which include critical equipment, radioactive material inventories or large fire loads. In 2024, the work concentrated on the fire safety analysis of the cryostat. In the cryostat, fires can occur only during long maintenance breaks when there is air inside, that is, no vacuum as in normal operation.

Different tools with varying levels of complexity (analytical calculations, zone fire models, CFD simulation) were used, and their applicability for different purposes were assessed. Fire Dynamics Simulator (FDS) code was used to study the cryostat's load-bearing capacity in case of fire. The simulations based on the assumptions made about the cryostat showed that ficres occurring inside the cryostat are not threatening its load-bearing capacity globally. Some local problems close to the fire might arise, but these can be dealt with a proper design with enough robustness for load-bearing capacity.

5.5.5 Tritium diagnostics in DEMO

Research scientist: J. Likonen, VTT

In this task, VTT has 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 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.

In 2024 VTT commissioned a new LIBS setup which was used at JET in October 2024. Calibration measurements at VTT were performed jointly with LIBS experts from several EUROfusion laboratories using real JET samples.

6 Communications

6.1 FinnFusion Annual seminar

The University of Helsinki organized the FinnFusion Annual Seminar in 2024, which took place at the university's main building in the Helsinki city center and at the Kumpula Campus on May 27–28. The event gathered approximately 85 participants. The seminar featured presentations from FinnFusion research organizations, as well as invited talks from the Ministry of Economic Affairs and Employment (MEAE), United Kingdom Atomic Energy Authority (UKAEA), Barcelona Supercomputing Center (BSC), Quanscient, Platom, Comatec, Fulvisol, and Luvata. The Annual Report, *FinnFusion Yearbook 2023*, VTT Technology 427 (2024) 118 p., was released during the meeting.

6.2 Articles and public relations

During 2024, Finnish media published numerous articles on the fusion research activities in Finland. Prof. Anssi Laukkanen was interviewed in more than 100 news articles regarding collaboration between VTT and US Department of Energy's (DOE's) ARPA-E (Advanced Research Projects Agency – Energy) programme focusing on enabling commercialisation of fusion energy and the list below gives only few examples.

- Tuomas Tala, ”Fuusion ja fission vastakkainasettelu on turhaa” – Eurooppa on fuusioenergian tutkimuksen kärjessä (“The confrontation between fusion and fission is pointless” – Europe is at the forefront of fusion energy research), Tekniikka&Talous , 8.2.2024.

- Anssi Laukkanen, Finnish VTT collab with US for commercial fusion energy, Electronic specifier, 30.10.2024.

- Anssi Laukkanen: Finnish researchers join top fusion energy research group, YLE, 30.10.2024.

- Anssi Laukkanen, Kaupallista fuusioenergiaa viiden vuoden päästä? VTT alkaa ratkoa materiaalihaasteita USA:n huippuohjelmassa (Commercial fusion energy in five years? VTT begins solving materials challenges in top US program), Tekniikan Maailma, 30.10.2024.

- Anssi Laukkanen: Suomalaiset pääsevät kiihdyttämään fuusioenergiaa nyt Yhdysvaltojen kanssa – yllätys on, että fuusio voi toimia jo 5 vuoden kuluttua (Finns can now accelerate fusion energy with the United States – the surprise is that fusion could work in just 5 years). Tekniikka&Talous, 1.11.2024.

- Anssi Laukkanen: Fuusioenergia voi olla totta jo viidessä vuodessa – Suomalaiset mukana (Fusion energy could be a reality in just five years – Finns are involved), Talouselämä, 2.11.2024.

- Anssi Laukkanen: Suomalaiset pääsevät kiihdyttämään fuusioenergiaa nyt Yhdysvaltojen kanssa – yllätys on, että fuusio voi toimia jo 5 vuoden kuluttua (Finns can now accelerate fusion energy with the United States – the surprise is that fusion could work in just 5 years), Kauppalehti, 3.11.2024.

- Anssi Laukkanen: Finland's VTT joins US fusion research programme, Nuclear Engineering International, 5.11.2024.

- Anssi Laukkanen: VTT historialliseen tutkimusyhteistyöhön yhdysvaltalaistahojen kanssa – aiheena fuusioenergian kaupallistaminen (VTT to enter historic research collaboration with US partners – topic: commercialization of fusion energy). Promaint, 14.11.2024.

- Anssi Laukkanen: Finnish researchers collaborating with US entities to commercialise fusion energy, Good News from Finland, 14.11.2024.

- Anssi Laukkanen: Fuusioenergia yhä lähempänä – VTT mukaan merkittävään hankkeeseen (Fusion energy getting closer – VTT joins a significant project). KEMIA 1.12.2024.

1.1 Courses on fusion studies

Lecture courses at Aalto University, School of Science:

- *Fusion Energy Technology (M. Groth, T. Kiviniemi, spring 2024).*
- *Introduction to plasma physics for fusion and space applications (T. Kurki-Suonio, autumn 2024).*

- *Radiation Damage in Materials (A. Sand, spring 2024)*

7 Education and training

7.1 WP EDU: FinnFusion student projects

7.1.1 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 2024, two Doctoral dissertations, one Master's thesis and one Bachelor's theses were completed (see Section 12.4).

7.1.2 Doctoral students

Aalto University

Student: Nima Fakhrayi Mofrad

Supervisor: Andrea Sand (AU)
Instructor: Andrea Sand (AU)
Topic: *Exploring Plasma-Wall Interactions: Computational Insights into Behavior of Plasma-facing Materials*
Report: An investigation into the sputtering in beryllium surfaces with varying hydrogen isotope concentrations was undertaken to elucidate the role molecular sputtering plays in the overall erosion process. This study was conducted through the employment of molecular dynamics (MD) simulations, which were implemented using both a small time-step and a variable cell size, thereby ensuring the precision and reliability of the findings. Such an

approach enabled a comprehensive assessment of the impact that molecular sputtering has on total erosion, as well as the identification of the specific energy range where the predictions derived from MD simulations diverge from those obtained via the binary collision approximation (BCA). Additionally, MD simulations were performed on tungsten surfaces with a focus on elucidating the behavior of WD and D2 molecules as they leave the surface, encompassing efforts to provide some insight into the possible rotational-vibrational states of these molecules.

Student: Rafael Nuñez (AU)
Supervisor: Andrea Sand (AU)
Instructor: Andrea Sand (AU)
Topic: *Tailored Pseudopotentials for Improved Electronic Stopping Accuracy in Plasma-Facing Materials*
Report: Accurate estimates of electronic stopping are crucial for understanding the radiation damage process, particularly in plasma-facing materials. These energy losses to the electronic system can be precisely calculated using the real-time Time-Dependent Density Functional Theory (rt-TDDFT) approach, which requires pseudopotentials that explicitly represent all the electrons involved in the energy dissipation process. Given the high computational cost of these calculations, it is important to identify where explicit core electrons are necessary and to assess their impact on electronic stopping predictions. To address this challenge, we have developed pseudopotentials for iron with augmented cores that deliver accurate results while efficiently managing computational resources.

Student: Evgeniia Ponomareva (AU)
Supervisor: Andrea Sand (AU)
Instructor: Andrea Sand (AU)
Topic: *Capturing electronic stopping effects in ion irradiation simulations of nuclear materials*
Report: The electronic stopping power of hydrogen and helium ions in tungsten was previously calculated using real-time time-dependent density functional theory (rt-TDDFT), providing trajectory-resolved insights into low-energy ion propagation. This ab initio data was then used to parameterize a dissipative electron-ion interaction model, enabling its integration into molecular dynamics (MD) simulations. With this model, we investigated ion reflection and target atom sputtering in tungsten, revealing the impact of trajectory-dependent stopping on near-surface energy dissipation. We observed modifications to sputtering yields due to electronic excitations, highlighting the necessity of accurately accounting for

electronic stopping in ion irradiation simulations. More recently, we extended these studies to iron, focusing on the effects of alloying and defects on electronic energy losses. Our findings demonstrate how material composition and microstructural variations influence energy dissipation mechanisms, contributing to a more comprehensive understanding of electronic stopping in metals under fusion-relevant conditions.

Student: Patrik Ollus (AU)
Supervisor: Mathias Groth (AU)
Instructors: Antti Snicker (VTT)
Topic: *Modelling fast ions in current and future fusion devices under the effect of charge exchange reactions*
Report: A fast-ion CX model was implemented in the Monte Carlo orbit-following code ASCOT, which simulates minority particles in fusion devices. The model uses tabulated reaction probability data to simulate the CX neutralisation of fast ions and the possible reionisation of the resulting fast CX atoms. The densities of background atoms and molecules, which are key inputs when simulating CX, were reconstructed using experimentally constrained kinetic modelling and empirical estimates. ASCOT was used to study the impact of CX on fast ions as they are colliding with bulk particles and slowing down in the spherical tokamak MAST Upgrade. The predictions were verified against analytical calculations, compared to another widely used simulation code and validated against three types of experimental measurements. For NBI aimed outside the centre of the plasma, CX causes approximately 10% of power loss when the plasma is gas-fuelled from the high-field side of the tokamak. Losses are lower for NBI aimed into the centre of the plasma, but losses increase when gas-fuelling from the low-field side. Various other effects were predicted, such as local increase in NBI current drive due to inward transport of fast ions by CX, and wall power loads from escaping fast CX atoms.

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 plasmas in the Joint European Torus (JET) predict that the electron temperature in the low-field side (LFS) divertor leg is reduced locally by up to an order of magnitude when nitrogen is assumed to recycle as molecules (N_2) instead of atoms using a fixed nitrogen injection rate. The LFS divertor temperature

reduction under the assumption of molecular recycling occurs due to a three-step mechanism: 1) the plasma penetration of nitrogen atoms is increased due to the strong triple bond of the N_2 molecule and the kinetic energy release in the dissociation event, both mechanisms contributing equally, 2) the abundance of (particularly multiply-charged) nitrogen ions in the divertor is increased and 3) the electron temperature is reduced due to the increase in radiation (by up to a factor of 4) from nitrogen ions.

Setting the volume-integrated nitrogen radiated power to a constant value (0.6 MW) instead of the nitrogen injection rate, SOLPS-ITER predicts under the molecular nitrogen recycling assumption that the peak line-integrated N II, N III and N IV intensities in the LFS divertor are approximately within 15%, 35% and 5%, respectively, of the reference atomic nitrogen recycling case. The predicted peak N II, N III and N IV intensities under either assumption are within 30%, 65% and 5%, respectively, of measurements using the vertically viewing mirror-link divertor spectrometer (A. Meigs et al., 2010) in nitrogen-seeded JET L-mode plasmas (B. Lomanowski, et al., 2019). ERO2.0 simulations using a constant nitrogen seeding rate on static background plasma solutions from EDGE2D-EIRENE (previously presented in R. Mäenpää et al., 2022, revised here to include fast reflections) predict that N II to N IV line emission is increased by 20% to 30% 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: 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: SOLPS-ITER density scans of JET-ILW L-mode deuterium (D) and helium (He) plasmas with 1MW of NBI heating (additionally with 5MW of NBI for He) are qualitatively consistent with the experiment. Both the ion flux to the targets and the total radiated power respond to upstream density as observed in experiments. However, the predicted ion flux is half that of Langmuir probe measurements, and the predicted total radiated power is half the bolometry estimate for both species. The reduced ion flux in He plasmas compared to D plasmas is due to a 1.5-3 times higher effective ionization energy in the He simulations. The high ionisation energy acts to reduce the ion flux for the same power to the targets because the recycling loop that can be supported is smaller. At higher densities, both

experiments and simulations show an increase in core radiation. Despite the expected longer mean-free path for He neutrals, SOLPS predicts the neutral flux through the separatrix is similar for both species, and shows the radiation increase is due to He+ being a more effective radiator than neutral D. The rise in core radiation reduces the power across the separatrix, leading to power starvation and thus driving the rollover of ion flux in helium plasmas. Furthermore, the simulations show a lack of pressure loss along the scrape-off layer in He compared to D, which supports the differing contributions of power starvation and momentum and volumetric power loss in the ion flux rollovers for the two species.

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: To predict the SOL physics in the FT-2 tokamak, several code changes are implemented in ELMFIRE to recycle the particles exiting the simulation domain in the toroidal direction closer to the poloidal limiters in FT-2. Using radial particle source profiles from ASTRA simulations along with recycling plasma ions and electrons closer to the limiters exhibited qualitative agreement of the electron density profiles within 30% of the profiles measured by Langmuir probes. However, the electron temperature profiles are predicted systematically higher by a factor of 1.5 to 2 with the respective Langmuir probe measurement, still within the uncertainties of measurements.

Using the GENE code, the GAM intermittency in the core of FT-2 is studied by performing a global non-linear simulation. The simulation results revealed intermittency in GAMs close to the low-order rational surface (q=3). This finding constitutes the first observation of GAM intermittency in a gyrokinetic simulation. The underlying cause of this GAM intermittency is attributed to the non-linear coupling between GAMs and turbulence at this radial location. Furthermore, the density fluctuations exhibited intermittency at the same radial location, confirming the non-linear coupling between GAMs and turbulence. The impact of the Krook-type source operators on the GAM dynamics in the GENE simulations is investigated. The global non-linear simulations showed that the GAM amplitude increases with the Krook-type source operator increase, driven by increased GAM drive. The zonal flows amplitude decreases with increase in the value of the Krook-type source operators in the center region. Notably, the GAM damping in the center region slightly increases with the operator values. The Krook-type source operators also influence GAM intermittency. Despite the GAMs exhibiting intermittency, their quiescent and active periods differ with operator values. Comparing GENE simulations with experimentally observed GAM intermittency is necessary to validate results.

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 2024, research focused on modelling the effects of divertor on tritium breeding in the HELIAS reactor. A parametric study was conducted varying island divertor area (width and length), thickness (cooling and structural parts), placement, and material composition. Increasing the divertor area and thickness led to the replacement of a larger volume of breeding material, resulting in a reduction in TBR. The TBR for various divertor configurations was compared to a reference case without a divertor, which achieved high total TBR values of 1.42 for HCPB and 1.27 for DCLL blanket compositions. With a realistic divertor area fraction of 13% of the first wall, TBR remained above the target of 1.15 when using an HCPB breeding blanket and a top-bottom divertor placement. However, replacing HCPB with a DCLL blanket and switching from helium to water coolant led to performance falling below the target, highlighting the significance of divertor configuration in achieving the tritium self-sufficiency. This work is reported in more detail in an accepted publication T. Lyytinen et al. *Effect of divertor on tritium breeding in HELIAS" (2025)* Fus. Eng. Design.

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: Only minor effort has been put to the work during the year 2024. Most of the focus has been on developing the model to be able to capture the cyclic behaviour of copper better as with the current model it has proven to be almost impossible to capture the cyclic and monotonic behaviour with single set of parameters. The year has mostly been used to produce experimental data and to find suitable patterning method for DIC (digital image correlation). Work will be continued during the year 2025.

Student: Van Dung Truong (VTT)

Supervisor: Petri Kuosmanen (AU)
Instructors: William Brace
Topic: *A Model-Based Methodology for Quantification of Risks for Probabilistic Reasoning in Complex Systems*
Report: The research focuses on developing a novel approach to identify and quantify technical risks during the early conceptual design phase of high-risk technical systems, such as Remote Maintenance systems in DEMO fusion power plants. This method addresses risks from three key facets: failure modes, situational, and quality risks. The project's first year introduced a balancing model based on domain modelling and qualitative physics reasoning aligned with Dimensional Analysis and the Buckingham Pi theorem to capture fundamental system relationships. It was published in a peer-reviewed journal article in 2024.

Further work is leveraging this approach to gain deeper insights into causal relationships between input risk factors and system behaviour, including integrating machine learning models for predictive capabilities based on historical design data. In parallel, the research also explores addressing quality risks by modelling design problems using Stochastic Petri Nets combined with statistical methods.

Student: Qais Saifi (VTT)
Supervisor: Huapeng Wu (LUT)
Instructors: William Brace (VTT)
Topic: *Stochastic model engine development for reliability in remote maintenance*
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. The research 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 (LHC), where several input variables are statistically determined. Our

estimation of the probability of the predicted state closely aligns with results obtained using LHC. Furthermore, we explore the implications of our findings and outline future directions in stochastic simulations aimed at strengthening reliability assessments.

Student: Brahim Dif (VTT)
Supervisor: Andrea Sand (AU)
Instructors: Janne Heikinheimo (VTT)
Topic: *The mechanical behaviour of ITER-grade tungsten via small punch test*
Report: The mechanical properties of ITER-grade tungsten (IGW) were thoroughly evaluated using Small Punch Testing (SPT). ITER-grade tungsten, produced by A.L.M.T. Corporation with 99.99% purity, a critical material for fusion reactor applications, was tested to measure key properties like yield strength and ultimate tensile strength (UTS) under biaxial loading. SPT was performed on carefully prepared disc samples at temperatures ranging from room temperature to 300°C, 400°C, 500°C, 600°C, and 700°C, following the EN10371 standard (2021). Results indicated that meaningful mechanical data from SPT could only be reliably obtained above 400°C, with brittleness hindering accurate testing at lower temperatures. Despite challenges with test anomalies and limited valid data points, the study provided valuable insights. A collaborative publication with SCK CEN in Belgium is currently underway to compare these SPT results with tensile test data, aiming to refine correlation factors and enhance the accuracy of ITER-grade tungsten mechanical property assessments using the SPT method.

University of Helsinki

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 show the benefits of surrogate models for dislocation binding energy simulations when atom vacancies are present. We used a neural network with a density distribution output layer, which allowed us to estimate both the energy and the quality of the prediction. From our experiments using a large Iron dataset, we saw that 30% of the points have low certainty, and can be automatically identified and removed. These can be rerun at a later time using traditional methods. Once these points are

removed, we get a MAPE of 7.5%. Furthermore, we show that the model can easily be extended to materials with similar characteristics (we use Tungsten) using a simple transfer learning technique. Despite a slightly less precise result (MAPE of 9.6% after removal of points) we have a similar behavior using only a small input dataset when compared to the Iron case. We plan on presenting detailed results in the 5th Joint Nordic Fusion Energy Seminar 2025. A paper is currently under review at Springer Neural Computing and Applications.

Student: Otso Hyvärinen (UH)
Supervisor: Samuli Siltanen (UH)
Instructor: Antti Snicker VTT
Topic: *Using ASCOT and inversion methods to solve 4-D distribution function of burning plasmas*
Report: Research focused on creating methods and workflow for constructing a 4D slowing down basis, in which the reconstruction problem of solving fast ion distribution function from diagnostic measurements could be solved. The slowing down distributions were collected using ASCOT, which encoded neoclassical physics into the spanned vector space and therefore imposed this structure into the reconstructions. In 2024, the reconstructions and bases were calculated on JET using neutral beam injector (NBI) ionization as the source, which was divided into basis vectors. The reconstructed basis vector coefficients were found to agree with true coefficients well, implying a successful creation of a physics encoded basis.

Student: Aqsa Ashraf (UH)
Supervisor: Filip Tuomisto (UH)
Instructor: Mizohata Kenichiro (UH)
Topic: *Development of Medium Energy Ion Scattering Technique*
Report: The primary reason for constructing the MEIS system in the Helsinki Accelerator Laboratory (HAL) is to provide a better depth resolution than RBS while maintaining the same spectra interpretation, allowing a more detailed study of surface and interface regions of thin samples. The MEIS analyzer design facilitates the collection of energy and angular spectra, enabling examination of surface region atomic locations and crystalline structure along with composition and depth distribution data. We have measured Hf_2O_3/Al_2O_3 nanolaminate samples of different thicknesses with our MEIS setup and observed the clear distinct peaks of Hf and Al within the sample. We will soon upgrade our system with Microchannel plates (MCPs), which will allow us to detect and measure lower energy and heavier particles. Blocking

and Channeling effects could also be observed with the addition of position-sensitive MCPs.

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 16th conference of Computer Simulation of Irradiation Effects in Solids (COSIRES, June 16-21, 2024, Kingston, ON, CA) with the title of "Overlapping cascades in FCC high-entropy alloys using ML potentials". The poster won the best student poster award during the conference. Additionally, the work was presented in the form of an oral talk at the 11th International Conference on Multiscale Materials Modeling (MMM11, September 22-27, 2024, Prague, Czech Republic) with the title of "Machine-learning interatomic potential for FCC high-entropy alloys".

Student: Victor Lindblad (UH)
Supervisor: Kai Nordlund (UH)
Instructors: Fredric Granberg (UH)
Topic: *Studying kink formations on screw dislocation lines, using MD*
Report: Numerous independent experiments and some simulations have consistently shown that the presence of deuterium during irradiation can significantly influence defect evolution in irradiated tungsten. However, the underlying mechanisms driving these effects, particularly at the atomistic level, remain poorly understood. To investigate the observed increase in defect accumulation and deuterium retention under certain conditions, we performed a series of MD irradiation simulations. These included single-impact simulations on cells containing pre-existing vacancies, both with and without trapped deuterium, to explore the fundamental interactions. Additionally, high-dose irradiation simulations were carried out across different configurations to replicate the experimental conditions reported in earlier studies. Our findings show that simulations incorporating simultaneous irradiation and deuterium implantation result in increased defect production and higher deuterium retention, aligning well with

experimental observations. We attribute these trends primarily to enhanced defect formation during the heat-spike phase and a reduction in defect recombination efficiency.

Student: Iuliia Zhelezova (UH)
Supervisor: Filip Tuomisto (UH)
Instructors: Filip Tuomisto (UH)
Topic: *Vacancy defects in Si-doped β-$(Al,Ga)_2O_3$*
Report: We investigated vacancy-type defects in β-Ga_2O_3 single crystals using temperature-dependent Positron Lifetime Spectroscopy, complemented by Doppler Broadening measurements sensitive to both temperature and crystallographic orientation. The crystals were grown by the Czochralski method, either unintentionally doped (UID) or Si-doped (0.2 mol%) for n-type conductivity, and contained varying Al concentrations (0, 10, 20, or 25 mol%) to enhance electronic and optical properties. Our findings reveal that split Ga vacancies are the dominant defect configuration in all unintentionally doped β-$(Al_xGa_{1-x})_2O_3$ crystals (x = 0–0.25), independent of Al content. Unrelaxed Ga vacancies emerge at higher temperatures in UID crystals with 20–25 mol% Al and are clearly observed in all Si-doped samples. These unrelaxed vacancies appear to be stabilized by Si-doping and higher Al content, in agreement with first-principles calculations. Negatively charged ion-type defects (acceptors), which may contribute to electrical compensation, are observed below 100 K - but only in Al-containing samples.

Student: Faith Kporha (UH)
Supervisor: Kai Nordlund (UH)
Instructors: Fredric Granberg (UH)
Topic: *Sputtering of Deuterium Decorated Tungsten Surfaces*
Report: In 2024, research on understanding the effects of Argon (Ar), Neon (Ne), and Tungsten (W) ions on the sputtering of both pristine and deuterium-decorated tungsten surfaces. Additionally, the work focused on developing a machine learning (ML) interatomic potential for simulating sputtering in fusion-relevant W-O-H systems. A molecular dynamics study on the sputtering of pristine tungsten surfaces revealed that ion mass effects emerge at specific angles. Furthermore, all investigated parameters including surface orientation, ion energy, and incidence angle were found to significantly influence tungsten sputtering yields. A paper detailing these findings was prepared for publication. Research findings on the sputtering yields of pristine and deuterium-decorated tungsten surfaces under Ar, Ne, and W ion bombardment were presented in a poster titled "Sputtering of Tungsten and Deuterium-Decorated

Tungsten Surfaces" at the 11th International Conference on Multiscale Materials Modeling (Sep. 22–27, 2024, Prague, Czech Republic).

Student: Alexandre Bergero (UH)
Supervisor: Fredric Granberg (UH)
Instructors: Fredric Granberg (UH)
Topic: *Sputtering mechanism for fusion relevant materials*
Report: During 2024, we investigated sputtering of W and High Entropy Alloys WNbV and WMoTaNbV using molecular dynamics. Both single and cumulative impact simulations by Argon have been carried out at different energies and incoming angles. We found that there is a sputtering yield peak between 45° and 60° and HEAs sputter more than pure W. Lower mass elements such as Vanadium or Nobium tends to sputter more than W.

Student: Zhehao Chen (UH)
Supervisor: Filip Tuomisto (UH)
Instructors: Filip Tuomisto (UH)
Topic: *Irradiation damage on high entropy alloys*
Report: In 2024, we have conducted a series of experiments to study the Helium irradiation effect of RHEA bulk materials, including Ta, MoNbTa, and MoNbTaWV. All samples were irradiated with 25 keV He ions at a fluence of 5×10^16 ions/cm2 at room temperature. Subsequent annealing was conducted at various temperatures up to 1773 K. ERDA was employed to determine the helium depth profile at each annealing point. TEM lamella samples were prepared using FIB techniques at room temperature, 873 K, and 1773 K to characterize the morphology of helium cavities. Our results indicate slight variations in helium concentration and cavity size prior to annealing at 1773 K. Significant changes occurred after annealing at this temperature, which is above half the melting point of all samples. Specifically, the helium concentration in Ta decreased to 3×10^15 ions/cm2, whereas MoNbTa exhibited a concentration of 9×10^15 ions/cm2, and the HEA MoNbTaWV showed the highest helium concentration at 3×10^16 ions/cm2. TEM Bright Field imaging revealed that helium cavities in HEA MoNbTaWV are concentrated at the damage peak area, whereas in MoNbTa and Ta, cavities are distributed further from the original irradiation damage region and can form microscale cavities at grain boundaries. This suggests that long-range helium migration is limited in HEAs. Molecular dynamics simulations indicate that helium diffusion paths become more complex with an increase in the principal elements, resulting in shorter diffusion displacements. These overall results are consistent with our previous findings in

FCC HEAs (https://doi.org/10.1016/j.jnucmat.2024.155238), suggesting that this may be an intrinsic property of the random elemental structure of HEAs. These observations can provide general guidance for the behavior of W-based refractory equiatomic alloys.

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 2024 concluded the previous experiments in nitride semiconductors with positrons and X-ray absorption. A strong short-range effect was observed in formation of Si-related acceptor charge carrier traps in Ga-poor regions of AlGaN alloys. The formation of open volume acceptor-type defects was ruled out as 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. The state-of-the-art calculations based on density functional theory for obtaining electrical configuration of studied defects in nitride lattices showed preference of Si incorporating Ga-rich sites exhibiting a donor nature. Further investigation and enhanced electronic structure calculations continue in 2024 on other acceptor impurities that are known for amphoteric behaviour in AlN.

Student: Anna Liski (UH)
Supervisor: Filip Tuomisto (UH)
Instructors: Kenichiro Mizohata (UH)
Topic: *Hydrogen in the refractory high-entropy alloy WMoTaNbV*
Report: The study focuses on hydrogen absorption in the refractory high-entropy alloy WMoTaNbV. The alloy is known for its high hydrogen absorption, driven by its elemental composition and complex lattice structure. In 2024, we studied the impact of microstructure on hydrogen retention using a combination of experimental and computational methods. The results indicate a correlation between grain size and hydrogen absorption, with smaller grains showing higher hydrogen concentrations. In addition to microstructure, hydrogen concentration is influenced by the elemental composition, with Ta, Nb, and V elements promoting absorption. An increase in hydrogen trapping due to irradiation-induced damage is observed experimentally and linked through modeling to changes in local elemental composition (vanadium clustering) and point defect formation.

Student: Daniel Jordan (VTT)
Supervisor: Minna Palmroth
Instructors: Aaro Järvinen (VTT)
Topic: *Physics informed neural network surrogate model for gyrokinetic plasma turbulence simulation of tokamak pedestal dynamics*

Report: This research aims to predict scalar quantities associate with turbulent plasma instabilities (such as growth rate, mixing length and flux ratios) for a pedestal-relevant parameter space of GENE gyrokinetic turbulence simulations. An initial dataset of 2500 samples have been created using miller geometry and directly sampling the GENE parameter space. When using 50% of the samples to train a MLP there was a mean average percentage error of 9.7% when predicting the instability growth rate for the test samples. It is known that miller geometry does not sufficiently capture the shape of flux surfaces in the pedestal and so expanding to the higher dimensional and less interpretable generalised miller parameterisation is necessary. To avoid sampling in a non-relevant equilibrium space there has been significant work done to generate the equilibrium with the HELENA code. With HELENA one can generate an equilibrium from density and temperature 1.5D profiles. Relevant profiles can be sampled and passed to HELENA to produce relevant equilibria. The profiles and equilibria can then be passed to GENE to compute instability properties of interest.

Student: Amanda Bruncrona (VTT)
Supervisor: Minna Palmroth (UH)
Instructors: Aaro Järvinen (VTT)
Topic: *Acceleration of MHD stability simulations with machine learning techniques*
Report: Developing a proof-of-principle machine learning surrogate model for the ideal MHD stability code MISHKA-1 and integrating it into the pedestal prediction workflows Europed. The surrogate model was trained on JET-ILW parameter space. However, assumptions for separatrix temperature and density, KBM constraint, and more, are currently employed to reduce the dimensionality of the sampling space. These assumptions will be relaxed in the future. 1D and 5D models are done and a manuscript is in preparation

Student: Anu Kirjasuo (VTT)
Supervisor: Filip Tuomisto (UH)
Instructors: Antti Salmi (VTT), Tuoma Tala (VTT)
Topic: *Core confinement time and density peaking dependencies on selected core and edge parameters in JET L-mode plasmas*

Report: Plasma performance in L-mode is very important for ITER, because every plasma will have to pass an L-mode phase to reach burning plasma stage, and this should be achieved with least possible external energy loss and avoiding W accumulation. To better understand the interplay between plasma confinement time and separatrix parameters a database of JET ITER-like wall (ILW) steady state time interval samples in L-mode has been analysed. The selected database has pulses with NBI and ICRH heating, and their combination, to enable the study of heating method on core performance. Other key parameters in the database include information about the different divertor configurations, and whether the pulse is with or without seeding. Electron temperature at the separatrix has been calculated with the two-point model and used to determine electron density at the separatrix using the measurement data from High-Resolution Thomson Scattering (HRTS). The database enables investigation of correlations between core performance metrics such as confinement time and density peaking to separatrix parameters mentioned above. The database is intended to be combined into an ITPA multi-machine L-mode database

LUT University

Student: Nikola Petkov (UKAEA)
Supervisor: Huapeng Wu (LUT)
Instructor: Huapeng Wu
Topic: *Kinematic Synthesis and Optimisation Framework for Serial Manipulator Robots in Cluttered Environments*
Report: Finding optimum kinematic designs for non-standard robotic manipulators, such as those used in medical, nuclear, and space applications is challenging due to the need to adapt to complex tasks within constrained environments. This design optimization problem is multi-dimensional and non-convex, with nonlinear constraints. Ensuring reachability, i.e., the existence of continuous trajectories between required positions for serial articulated manipulators in the presence of obstacles, adds another layer of complexity. To address these challenges, we introduce a new robust design framework grounded in a generalized parametric kinematic model. This framework enables simultaneous optimization of both the robot’s link dimensions and its kinematic topology for arbitrary tasks within constrained environments, enhancing both computational efficiency and the quality of the resulting designs. The effectiveness of the proposed design framework is verified and evaluated through comparisons with baseline benchmarks. Results demonstrate that the novel design

framework, by using Genetic Algorithm, can accelerate kinematic design optimization compared to the current state-of-the-art and optimize link dimensions and joint types simultaneously for serial robots operating in cluttered environments.

Student: Zhixin Yao (LUT)
Supervisor: Huapeng Wu (LUT)
Instructor: Huapeng Wu (LUT)
Topic: *Surrogate model-based cognitive digital twin for remote maintenance robot system of fusion reactor: Modeling and implementation*
Report: A remote maintenance robot system (RMRS) plays a critical role in safeguarding the fusion energy experimental device's security and stability. It replaces human operators to perform the inspection and maintenance tasks inside the device, which requires excellent working performance of the RMRS. Digital twins (DT) are widely considered capable of improving complex equipment's performance and reducing management burden by employing a visualized system. However, the DT virtual space cannot mirror the RMRS which is a kind of flexible multi-body system in real-time and with high fidelity. Therefore, we propose a cognitive digital twin (CDT) modeling method based on a surrogate model for the RMRS. Firstly, model-based system engineering (MBSE) is leveraged to build a structural modular architecture, which can decrease the modeling complexity of CDT and increase the modeling efficiency. Then, the surrogate models are self-learning within the CDT physical space, which reconstructs the RMRS's real-time dynamic performances and endows CDT with cognitive capabilities. Finally, after integrating the CDT system, a smart decision-making plan that compensates for the operation error is generated for RMRS's accurate control. We take a CFETR multi-purpose overload robot (CMOR) as an example to demonstrate the implementation process. According to the results, the method can achieve real-time high-fidelity monitoring and accurate control of CMOR. The method can also be applied to other fusion energy devices.

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: This study proposes an electroencephalogram (EEG)-based workload classification algorithm for real-time monitoring of remote

handling (RH) operators with the aim of enhancing operational safety and efficiency by assessing operator workload and facilitating timely adjustments. EEG signals undergo denoising through independent component analysis (ICA) and bandpass filtering to remove artifacts and improve signal quality. Feature extraction and selection identify the top EEG features most indicative of workload, including power spectral density (PSD) metrics and fractal dimensions, which then serve as inputs to an optimized artificial neural network (ANN) model. The ANN model, trained on both the STEW dataset and custom data, achieves 82% classification accuracy, generalizing well across varying cognitive load levels in multi-task settings. The model's performance metrics, including validation accuracy and confusion matrix results, confirm its reliability in discerning workload levels. The findings demonstrate the utility of EEG-based workload monitoring in RH environments, providing a foundation for future improvements in human-machine interaction and operational safety

Student: Qingfei Han (LUT)
Supervisor: Heikki Handroos (LUT), Huapeng wu
Instructor: Huapeng Wu (LUT)
Topic: *Multilevel kinematic modulations of geckos running on inclined surfaces*
Report: To explore the modulation mechanisms employed by geckos, this research 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.

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 investigates the motion control of the heavy-duty Bionic Caterpillar-like Robot (BCR) for the China Fusion Engineering Test Reactor (CFETR) maintenance. Initially, a

comprehensive nonlinear mathematical model for the BCR system was formulated using a physics-based approach. The nonlinear components of the model were compensated through nonlinear feedback linearization. Subsequently, a fuzzy-based regulator was employed to enhance the receding horizon optimization process for achieving optimal results. A Deep Neural Network (DNN) was trained to address disturbances and other factors. Consequently, a hybrid Nonlinear Model Predictive Controller (NMPC) was developed, incorporating both the Fuzzy Regulator (FR) and Deep Neural Network Feedforward (DNNF). Finally, the efficacy of the control system was validated through simulations and experiments. The results indicated that the Root Mean Square Error (RMSE) of the controller with FR and DNNF decreased by 33.1% and 48.9%, respectively, compared to the controller without these enhancements. This research provides a theoretical foundation and practical insights for ensuring the future highly stable, safe, and efficient maintenance of blankets.

Student: Ting Wang (LUT)
Supervisor: Huapeng Wu (LUT)
Instructor: Huapeng Wu, Li Changyang (LUT)
Topic: *Multi-objective Optimization of Architecture Based on Bluemira*
Report: In this research, multi-objective optimization is essential due to the need to balance various competing factors in the reactor design. These factors include maximizing plasma confinement, ensuring efficient tritium breeding, minimizing material degradation, and optimizing the overall energy output. The Bluemira framework, with its robust capabilities in handling complex, multi-variable optimization problems, is well-suited to this task. The research will utilize Bluemira to conduct sensitivity analyses and iterative design improvements. By systematically exploring different architectural configurations, the research aims to identify design solutions that meet the stringent requirements of fusion reactor operation. Key objectives include improving the magnetic confinement system to enhance plasma stability, optimizing the reactor's geometry for better tritium breeding, and ensuring that the materials used can withstand the harsh conditions inside the reactor over extended periods. Through this study, reactor design optimisation based on Bluemira will be carried out and used to increase the hydrogen multiplication rate for performance and sustainability.

Student: Yongping Shi (LUT)
Supervisor: Huapeng Wu (LUT)
Instructor: Huapeng Wu (LUT)
Topic: *Adaptive dynamic compensation motion control for Fusion reactor*

Report: This study intends to build a laboratory moving base manipulator platform. According to the design of the cladding structure, the equivalent moving base manipulator is designed. The Stewart moving platform is used to control the base of the manipulator. The ground verification system is built to simulate the fusion robot system, and the ground test of reaction optimization is completed. The correctness of the simulation experiment is verified by comparing the simulation results with the simulation results, and the effectiveness of the optimization method is verified by comparing the optimization parameters with the ground test results.

Student: Zhiyong Wang (LUT)
Supervisor: Huapeng Wu (LUT)
Instructor: Huapeng Wu (LUT)
Topic: *Development of Mechanical Properties of Plasma-Facing Components of Blanket Utilizing Selective Laser Melting Techniques*
Report: In this study, RAFM steel PFCs was fabricated using selective laser melting (SLM), and the impact of heat treatment processes on its microstructure and properties was thoroughly analyzed. The results indicated that tempering after normalizing (NT) most effectively enhanced the comprehensive mechanical properties of RAFM steel (σb =668.8 MPa, δ=16.1%). The Original RAFM steel exhibited a pronounced checkerboard scanning feature with cubic texture, characterized by an orderly distribution of coarse lath martensite and fine acicular martensite. The checkerboard feature disappeared, and grains tend to be uniform after heat treatment. The dense dislocation networks appeared, and carbides precipitated in original specimens, which exhibited dislocation strengthening as the primary mechanism. However, dislocations began to release, and carbides precipitated along the lath boundaries or within the martensitic grains with the recrystallization process after thermal treatment. Precipitations were mainly Cr-rich M23C6 carbides and Ta, V-rich MX carbonitrides via detected. The dominant mechanisms were precipitation and fine grain strengthening in NTed, HIPed and NHed specimens. Overall, the 740℃ tempering after 980℃ normalizing heat treatment processes were effective in enhancing the microstructure and comprehensive mechanical properties of RAFM steel.

Student: Saifi Qais (VTT)
Supervisor: Huapeng Wu (LUT)
Instructor: Huapeng Wu, 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.

Tampere University

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: Kamran Akbar (TUNI)
Supervisor: Robert Bregovic (TUNI)
Instructor: Atanas Gotchev (TUNI)
Topic: *Quality measurement and assessment of light field displays*
Report: In this study, we aim to utilize light field displays for 3D immersive visualization in remote maintenance systems. However, light field displays can only generate a limited number of light rays, restricting high-quality 3D content to a specific depth range around the screen. Content outside this range appears distorted. The primary goal of this project is to develop a method that estimates the display's limitations and optimizes visualization based on the scene. To achieve this, we have developed a quality model that predicts how the light field should be processed according to the scene's characteristics. This approach is particularly valuable for remote handling in maintenance systems, where complex scenes within a fusion reactor and critical task execution demand precise visualization. By ensuring that 3D scenes are rendered appropriately based on their context, our quality model is expected to enhance the effectiveness and reliability of remote operations

Student: Mehdi Heydari Shahna (TUNI)
Supervisor: Jouni Mattila (TUNI)
Instructor: Jouni Mattila (TUNI)
Topic: *Safety-guaranteed fault-tolerant control for ITER Remote Handling (RH) manipulators*
Report: ITER Remote Handling (RH) manipulator operations in vacuum vessel are susceptible to modeling uncertainties, and external disturbances because of high-nonlinearity dynamics and arduous tasks under heavy loads. To enhance the control performance during these challenges in both model-based and model-free system framework, this study focuses on designing a robust fault-tolerant control strategy, ensuring user-defined safety by constraining the system signals within a safely predefined values. In addition, the control design ensures the stability, and robustness of the system under heavy loads, while optimal control gains can be auto-tuned to minimize control performance errors.

Student: Tomi Äijälä (TUNI)
Supervisor: Jouni Mattila (TUNI)
Instructor: Jouni Mattila (TUNI)
Topic: *Generic data driven methods for high precision reversable modeling for ITER RH manipulators*

Report: In ITER Remote Handling (RH) manipulator operations in vacuum vessel are subject to heavy loads and due to the limited space, they require high-precision absolute accuracy in their motion control. For operations safety, all individual RH manipulators need to be calibrated for absolute accuracy which comprises compensation of mechanical properties as well as deflections due to the load. This process is so-called kinematic calibration of forward kinematic (FK) model that describes robot's 6 DOF tool center point as a function of joint angles. However, for the robot's closed loop control purposes, inverse kinematic (IK) model is also needed, thus FK model developed has to be invertible, continuous function. This process is non-trivial with data-driven methods requiring reversable models. The objective of this study is to develop generic data-driven methods for obtaining both FK and IK models for heavy-duty RH manipulators subject to structural deflections.

7.2 WP TRA: EUROfusion Researcher and Engineering Grants

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

Research scientist: A. Freimanis, VTT

This activity focused on developing, validating, and verifying computational tools for modelling irradiated materials, specifically targeting EUROFER97, a reduced activation ferritic-martensitic steel. Materials in future fusion reactors will face complex and extreme environmental conditions. As a result, the modeling approach needed to be comprehensive, combining multiscale and multi-physics solutions to capture material behavior under such conditions accurately. VTT leveraged open-source software to accelerate the development and benefit from the broader community's contributions. The primary framework used was the finite element (FE) platform MOOSE, developed by the Idaho National Laboratory. MOOSE provided excellent parallel scalability, high-quality code, and a permissive open-source license, which facilitated code dissemination and future development. On the computational side, the development work was split into two categories.

Material models

With material models, the focus was on crystal plasticity (CP) modeling. We implemented three new flow rules (which describe material deformation under applied loads) and eight different state variable models (which capture the current properties of the materials). These flow rules are essential to model the wide range of temperatures and strain rates encountered in fusion environments, while the state variable models address different material structures and conditions, such as FCC and BCC crystal types, irradiation hardening, and phenomena like the Hall-Petch effect. By offering multiple model options, users can perform a simplified and quick initial analysis or a more detailed, albeit slower, one afterwards. Additionally, eigenstrain calculations within the CP framework were developed to simulate irradiation-induced swelling and thermal expansion—critical factors in fusion reactors due to the high irradiation flux and thermal gradients expected.

We introduced a significant improvement by decoupling flow rules from state variable models. Previously, these components were combined within a single material model, requiring complete rewriting of the codes to implement new models. Our enhancement allows users to select flow rules and state variable models independently, significantly increasing flexibility and enabling reusing the codes. This modular approach also accelerates future developments.

Fracture models

Fracture modeling was enhanced using peridynamic theory, a non-local approach that better accommodates crack nucleation, propagation, and arrest. To improve accuracy near crack surfaces and model boundaries, we developed an enhanced strain calculation method. We also implemented a brittle fracture model based on cleavage stress and a ductile fracture model based on void coalescence.

Material-scale simulations are computationally intensive due to the large models required to capture fine details of the material microstructure. We tested the performance of our models on the Finnish Supercomputing Centre's (CSC) clusters, utilizing over 2000 CPUs, and continue to conduct larger-scale tests. Validation and verification of the models were conducted using existing data from the EUROFER97 material handbook, developed by the EUROfusion Consortium. The models have been validated across a broad range of irradiation doses, temperature conditions, and loading scenarios. Additionally, experimental fracture tests are ongoing. The work was carried out as part of a EUROfusion Engineering Grant and will extend beyond the timeline of ECOFusion, thus full validation of the fracture models is still underway. First results on simulating material microstructure and initiation of damages can be found in Figure 7.1 while the modelling results for the total accumulated slip, maximal principal strain, and von Mises stress are shown in Figure 7.2.

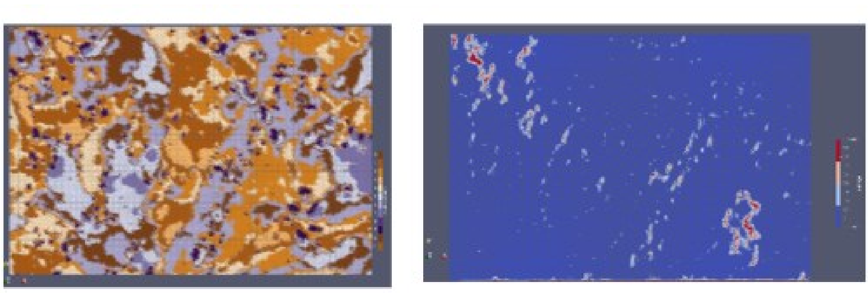

Figure 7.1. Material microstructure and simulated damage initiation.

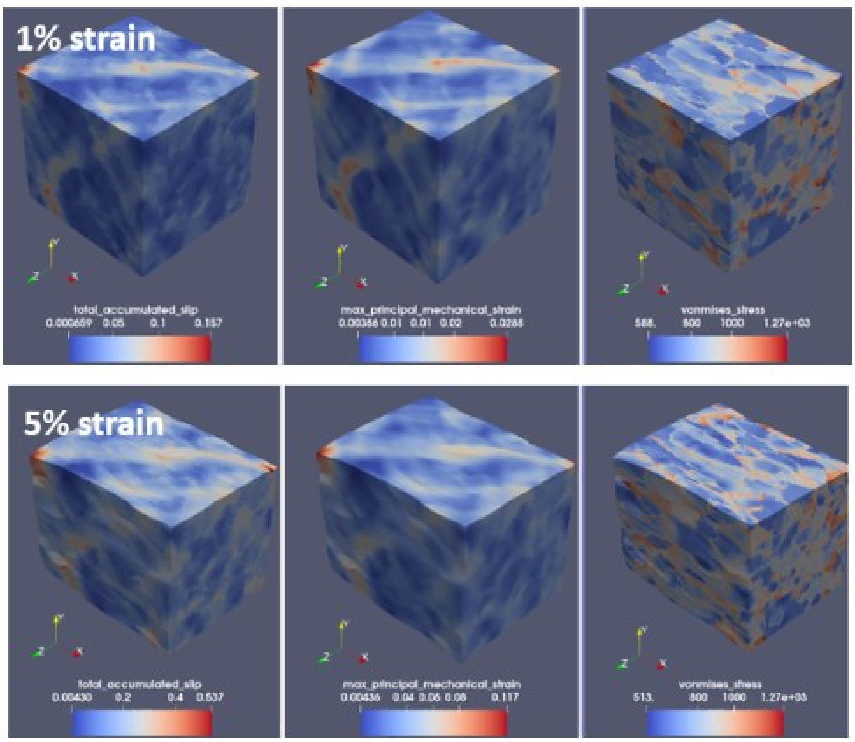

Figure 7.2. Total accumulated slip, maximal principal strain, von Mises stress at 1% and 5% strain.

8 International collaborations

8.1 DIII-D tokamak

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

Research scientists: M. Groth, AU

EIRENE predictions constrained with the measured 2D plasma profiles and recycling predict, for attached conditions, the measured (1D) Lyman-alpha, and the Balmer alpha, beta and gamma emissions within the uncertainties of the measurements. Compared to unconstrained predictions from EDGE2D-EIRENE, EIRENE predicts a reduction of Fulcher band emission by a factor of 8, reproducing the measurements within a factor of. Furthermore, EIRENE predictions significantly stronger recombination-driven Balmer emission, thus stronger plasma three-body recombination, and the peak Lyman-alpha emission to move off target plate, while the peak Balmer emission to remain at plate.

For detached conditions, unconstrained EDGE2D-EIRENE simulations do not predict high electron density front halfway up the divertor leg. Thus, when constrained, EIRENE predicts low/absent Fulcher band emission in LFS divertor, a two-peak structure of Lyman-alpha emission at the X-point (driven by direct excitation) and at the plate (driven by recombination). The predicted peak Balmer emission remains at plate, driven entirely by recombination.

8.1.2 Momentum and intrinsic torque in ITER-relevant conditions

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

Extrapolating momentum transport from current experiments to future fusion devices requires detailed understanding of intrinsic torque behavior under ITER-relevant conditions. In 2024, new experiments addressing this challenge were conducted on DIII-D as part of the ITPA TC-9 group on intrinsic rotation and torque for ITER rotation predictions. The experimental approach utilized optimized neutral beam injection (NBI) torque modulation settings, enabling a wide scan of electron cyclotron heating (ECH) and torque parameters in scenarios with dominant electron heating (Te ≥ Ti) and low plasma rotation. These experiments were successfully performed, and preliminary analysis is currently ongoing. Initial observations suggest notable intrinsic torque presence potentially associated with mixed-mode turbulence regimes, transitioning between ion temperature gradient (ITG) and trapped electron mode (TEM). Future analyses, including gyrokinetic modeling and fluctuation measurements, are planned to further clarify the results and refine momentum transport predictions relevant for ITER.

8.2 CFETR tokamak

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

LUT has participated in the development of welding/cutting machine CFETR VV assembly, and the development of a mobile robot and control algorithm for blanket RM maintenance. The works were done by double doctor degree researchers.

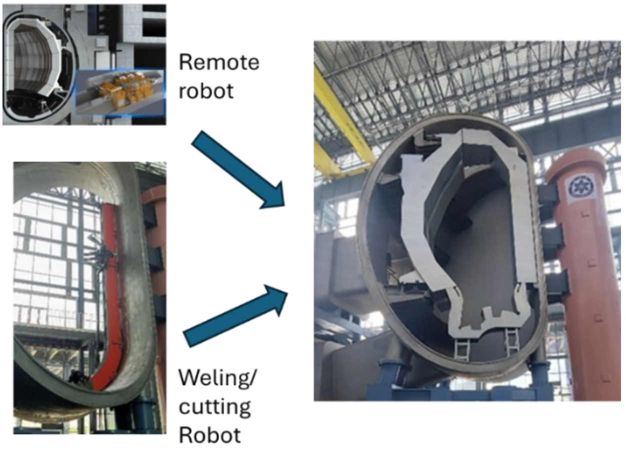

Figure 8.1. Welding/cutting machine and mobile robot and control algorithm for CFETR maintenance.

9 Fusion for Energy activities

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

F4E grant: F4E-GRT-0901

Research scientists: J. Alanen (VTT), H. Saarinen (VTT), L. Gonçalves Ribeiro (VTT), A. Gotchev (TUNI), O. Suominen (Operview), P. Ojala (Coresbond), M. Paloniitty (Coresbond)

The grant involved integration of new ITER Remote Handling Control System (RHCS) with the following system elements:

- 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 grant ended on January 19, 2025. During the period starting from February 2024, plans for calibrating the Cassette Multifunctional Mover (CMM) and validating its Remote Handling Control System were made. Additionally, the Application Layer Specification (aka HLC Specification) for the ITER Control Network's Control Interface Protocol was submitted. Furthermore, the Unity-based Virtual Reality (VR) application was updated, and a transition to VR4Robots-based VR began.

DigiValve development continued under this grant (F4E-GRT-0901) instead of the original DigiValve grant (F4E-GRT-0974). The DigiValve's Structured Text programmable logic controller code was converted to C-code, and solutions for stiffness, noise, and vibration issues were designed.

Figure 9.1. Demonstration of the divertor cassette remote handling operations with the ITER compliant Remote Handling Control System at VTT, DTP2, Tampere.

10 Complementary research in Finnfusion

10.1 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. This project was finished in mid-2024. The Sparselizard open-source C++ finite element library was used and 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. 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 were benchmarked against the SD1D code for cases of uniform volumetric source and energy transfer due to either heat conduction or heat convection or both.

10.2 Partner activities

10.2.1 Comatec Group, remote maintenance

Research scientists: V. Puumala, A. Kinach, S. Muhlig-Hofmann, Comatec Group

Comatec Group a growing Finnish engineering company providing and developing design, project management and expert services. We are particularly known for our ability to implement challenging assignments for the technology industry and mechanical engineering.

In ECOFusion we have expanded our expertise in various aspects of designing remotely operated machines. These include verification and simulator-based testing of safety-critical software, simulation of electric power transmission, and visualization with virtual reality technologies.

Comatec has participated in the development of remote maintenance equipment for the DEMO fusion reactor. This year's work focused on a review and identification of potential tooling for remote maintenance activities. The tools are used for specific tasks like gripping, lifting, bolting, cutting, welding, heating, cleaning, alignment, connecting and disconnecting, or non-destructive testing activities.

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

Research scientists: A. Mutanen, M. Nyström, 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 have been 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. As a part of the fusion energy, EOS Finland Oy has concentrated on simulation-aided AM process development of pure tungsten material. The target has been to develop a high-productivity process with optimal microstructure (bulk) for selection of applications. The activities in this project have led us closer to the key factors for less prone to cracking structure and therefore better quality.

10.2.3 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

ITER has set up tight requirements for heat sinks and other CuCrZr components throughout the reactor. In toughest places, these heatsinks are under heavy heat- and mechanical load at the same time as they are hit by neutron flow. To withstand these conditions without disintegrating too fast CuCrZr must be optimized to the best possible state regardless of the processes that it has to go through in manufacturing the blanket or divertor wall modules.

A forging trial campaign was conducted with Luvata IG CuCrZr. Heat cycle simulations that imitate HIPping to steel are made for these materials to find the optimal way of forging. With VTT-developed Propertune model recommendations multiaxial load, heating and cooling rates, and forging ratio were all tested. In 2025 EBDS imaging will be done to prove and possibly validate the Propertune model results.

10.2.4 Platom Ltd, International Licensing Framework in Challenging Environments

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

In 2024 Platom concluded the project "International Licensing Framework in Challenging Environments", which started in 2021. Therefore, the activities focused on finalizing the various tasks that were still ongoing after approval for one-year continuation. Main topics in 2024 included requirement processing (categorization, and management of technical requirements) developing the use of requirements management software, adding features to the so-called "licensing tool", and summarizing licensing processes covering international licensing models and how fusion is currently handled or will be handled in select countries in comparison. Some of the project results were also piloted in a project. In the end, Platom is satisfied with the results of the project in total and all the areas of the project will be evaluated for further development. Work in the field of fusion will continue at Platom.

10.3 STEP collaboration

10.3.1 Activation of cross-field drifts in SOLPS-ITER simulations of STEP with fully tracked Ar impurities

Research Scientists: J. Karhunen, A. Järvinen VTT

Cross-field drift terms have been successfully activated in SOLPS-ITER simulations of STEP with fully tracked Ar impurities. Following earlier numerical challenges with the task, a new drift-free initial state with more realistic Ar concentrations and improved particle balance was generated, upon which the drift term contributions were gradually ramped up from 0% to 100%, utilizing a range of numerical stabilization schemes. While yet to fully converge, the simulations with the drifts active indicate widened up-down asymmetries in the divertor conditions and increased accumulation of Ar in the pedestal region, leading to up to 50% increase in radiation inside the separatrix.

10.4 Code development in FinnFusion

10.4.1 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,, S. Sipilä, G. Fourestey, AU

The ASCOT5 codebase saw significant advancements over the past year, enhancing both performance and usability. A major milestone was porting gyro-orbit simulations to NVIDIA GPUs, culminating in the release of the first production-ready GPU version. Integration with the Integrated Modelling and Analysis Suite (IMAS) progressed, with ASCOT5 now capable of reading input from the Interface Data Structure (IDS). Work continues on writing outputs to IDS and developing the ASCOT5 IMAS-actor. Usability improvements were also a focus: ASCOT5 can now be run directly from Python, and installation was streamlined by adding Conda compatibility. Physics-wise, the focus was in developing the ICRH source which now entered the testing phase. The neutral beam source was improved by making it able to use ADAS data for more precise beam ionization calculations.

In addition, ASCOT4 code development, management and support has been continued in 2024 under IMAS. The ASCOT4-RFOF actor, capable of modelling fast ion distributions in the presence of ICRH using wave data from CYRANO, reached operational status.

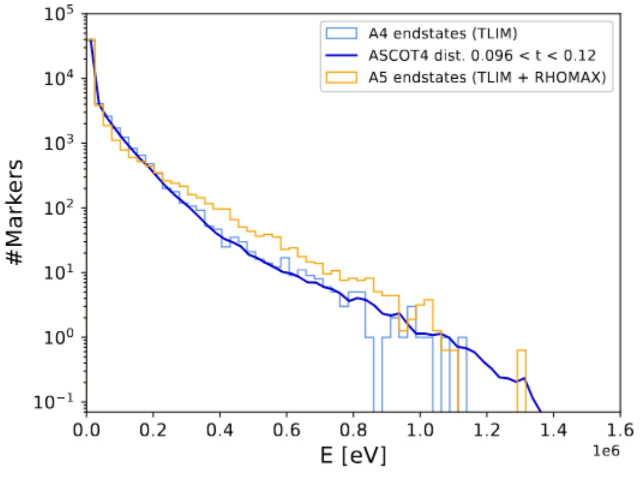

Figure 10.1. Comparison between the distribution of ICRH accelerated hydrogen ions in ASCOT4 and ASCOT5. The cause of the discrepancy between the results is being investigated.

10.4.2 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 is commonplace now, however, much more CPU intensive than conventional potentials. The porting of these potentials to GPU and all the needed other features, such as electronic stopping, has been ported to GPU. This enables simulations of cascade energies up to MeV and system sizes up to billions of atoms, with accurate ML potentials.

11 Other activities

11.1 Missions and secondments

Fredric Granberg to ITER, TSVV-11 workshop 22-26 January, Cadarache, France.

Juuso Karhunen to STEP modelling collaboration, UKAEA, Culham, UK, 26.2.—1.3.2024.

Tuomas Tala, Anu Kirjasuo and Antti Salmi to WEST, experiment, 4 – 8 March 2024 (WPTE).

Mathias Groth to DIII-D, General Atomics, San Diego, USA, 4 – 29 March 2024 (WPTE, International Missions).

Antti Hakola to JET facilities, Culham, United Kingdom, 11 – 13 March 2024 (WPTE).

Tuomas Tala, Anu Kirjasuo and Antti Salmi to MAST-U, experiment, 11-15 March 2024 (WPTE).

Aaro Järvinen and Amanda Bruncrona to WPTE RT01 JET analysis week at CCFE in Culham, UK, 11 – 15 March 2024

Nima Mofrod to RT06 JET Analysis and Modelling week, UKAEA, Culham Campus, 11-15 March, 2024.

Tommi Lyytinen to SPPS Work & Strategy Meeting, Einhdoven University of Technology, Netherlands, 15-17 April 2024 (WPPRD).

Antti Hakola to TCV facilities, Lausanne, Switzerland, 16 – 20 April 2024 (WPTE).

Jari Likonen to JET facilities, Culham, United Kingdom, 29 April – 9 May 2024 (WPPWIE).

Antti Hakola to TCV facilities, Lausanne, Switzerland, 09 – 14 June 2024 (WPTE).

Fredric Granberg and Victor Lindblad to IREMEV monitoring meeting 10 – 12 June, Helsinki, Finland

Jari Likonen to JET facilities, Culham, United Kingdom, 17 – 21 June 2024 (WPPWIE).

Nima Mofrad to Forschungszentrum Jülich GmbH (FZJ), Germany, 17 – 28 June, 2024.

Tuomas Tala to JET facilities, Culham, United Kingdom, 17 – 26 June 2024 (WPTE).

Antti Hakola to WEST facilities, CEA, Cadarache, France, 30 June – 02 July 2024 (WPTE).

Jari Likonen to JET facilities, Culham, United Kingdom, 5 – 23 August 2024 (WPPWIE).

Aaro Järvinen to DIII-D National Fusion Facility, General Atomics, San Diego, California, USA, 5 – 9 August 2024.

Tuomas Tala and Antti Salmi to DIII-D, General Atomics, San Diego, California, USA, 22-29 August 2024 (experiment, Intl. collaboration EuroFusion), PMU-IC.05.

Faith Kporha to the JT60-SA summer school, Naka, Japan, 26 August - 13 September 2024 (WPSA)

Antti Hakola to JET facilities, Culham, United Kingdom, 08 – 11 September 2024 (WPTE).

Antti Hakola to Aix-en-Provence, France, 16 – 19 September 2024 (WPTE).

Jari Likonen to JET facilities, Culham, United Kingdom, 24 September – 4 October 2024 (WPPWIE).

Juuso Karhunen to JET LIBS campaign participation, UKAEA, Culham, UK, 7—16 October 2024 (WP PWIE).

Juuso Karhunen to SOLPS-ITER Code Camp, IPP CAS, Prague, Czech Republic, 29.—31 October, 2024 (WPTE)

Tuomas Tala and Antti Salmi to TCV, experiment, 21 Oct - 2 Nov 2024 (WPTE).

Fredric Granberg to E-TASC general meeting, 11-15 November, Garching, Germany.

Aaro Järvinen, Daniel Jordan and Anna Niemelä to the University of Texas at Austin in Austin, Texas, USA, 11 – 15 November 2024.

Aaro Järvinen, Daniel Jordan, and Anna Niemelä to Texas A&M University in College Station, Texas, USA, 18th November 2024.

Antti Hakola to Garching, Germany, 18 – 22 November 2024 (WPTE).

Tuomas Tala, Antti Salmi, Amanda Bruncrona, and Anna Niemelä to JET, analysis week, 24-29 Nov 2024 (WPTE).

Tuomas Tala and Anu Kirjasuo to MAST-U experiment, 2-6 December 2024 (WPTE).

Jari Likonen to JET facilities, Culham, United Kingdom, 9 – 13 December 2024 (WPPWIE).

Fredric Granberg and Victor Lindblad to IREMEV monitoring meeting 25 – 26 November, Garching, Germany.

Antti Hakola to JET facilities, Culham, United Kingdom, 03 – 07 December 2024 (WPTE).

11.2 Conferences, seminars, workshops, and meetings

Aaro Järvinen participated in the 3rd Advances in Tokamak Integrated Modelling (ATIM) and EUROfusion TSVV11 workshop at ITER Organization headquarters, Cadarache, France, 22 – 26 January 2024 (WPAC).

Antti Hakola and Tuomas Tala participated in the 31st European Fusion Programme Workshop, Prague, Czech Republic, 29 January – 01 February 2024.

Aaro Järvinen, Antti Hakola, Fredric Granberg, Daniel Jordan Amanda Bruncrona, and Nima Mofrod participated in the Tervaniemi SOL and PWI workshop at Tervaniemi, Finland, 6 – 9 February 2024 (WPTE).

Antti Hakola participated in the 34th ITPA meeting of TG SOL and divertor physics, Kyoto, Japan, 26 – 29 February 2024.

Mathias Groth participated online in the ITPA-DSOL meeting February 2024, Kyoto, Japan, 26-29 February 2024.

Antti Hakola participated in the Nordic LIBS 2024 conference, Tampere, 05 – 06 March 2024.

Nima Mofrod participated in the Physics Days, Helsinki, 4-6 March, 2024.

Aaro Järvinen participated in the program committee meeting of the 50th EPS conference in Salamanca, Spain,4 – 5 March 2024.

Ray Chandra participated in the Joint ICTP-IAEA School on Data for Modelling Atomic and Molecular Processes in Plasmas, Trieste, Italy, 18 -22 March 2024.

Aaro Järvinen participated in the FuseCOM annual meeting in Cadarache, France, 19 – 22 March 2024.

Tommi Lyytinen participated in the 15th ITER Neutronics meeting and Fusion Neutronics Workshop, ITER Headquarters, France, 8-10 April, 2024.

Antti Hakola, Mathias Growth, and Pyry Virtanen participated in the WPPWIE midterm meeting, Espoo, 09 – 11 April 2024.

Tuomas Tala participated in the F4E Governing Board meeting in Barcelona, 12 April 2024.

Tuomas Tala participated in the ITPA TC meeting at ITER, France, 16-19 April 2024.

Tomi Vuoriheimo, Antti Hakola, Juuso Karhunen, Mathias Growth, Ray Chandra, Roni Mäenpää, Vesa-Pekka Rikala, and Pyry Virtanen participated the 26th International Conference on Plasma Surface Interaction in Controlled Fusion Devices (PSI-26), May 12 – 17, 2024, Marseille, France.

Evgeniia Ponomareva participated in the 8th EIROforum School on Instrumentation, Garching, Germany, hosted by ESO and EUROfusion, 13-17 May 2024.

Aaro Järvinen, Tuomas Tala, Antti Salmi, Tommi Lyytinen, Amanda Bruncrona, Daniel Jordan, Juuso Karhunen, Seppo Sipilä, Evgeniia Ponomareva, Ray Chandra, David Rees, Roni Mäenpää, Alexandre Bergero participated in the FinnFusion annual seminar at the University of Helsinki, Helsinki, Finland, 27 – 28 May 2024.

Aaro Järvinen participated in the Joint Runaway Electron Modelling (REM) and JET SPI Analysis meeting at EPFL in Lausanne, Switzerland, 10 – 14 June 2024 (WPAC).

Tuula Hakkarainen and Nikhil Verma participated in the Nordic Fire and Safety Days in Lund, Sweden, 18–19 June 2024

Fredric Granberg attended the conference COSIRES 16 - 21 June 2024, Kingston, Canada.

Antti Hakola participated in the 47th EUROfusion General Assembly meeting, Kaunas, Lithuania, 03 – 04 July 2024.

Aaro Järvinen, Tuomas Tala, Antti Salmi, and Francis Albert participated in the 50th EPS conference in Salamanca, Spain, 8 – 12 July 2024

Tuomas Tala participated in the F4E Governing Board meeting in Barcelona, 10 – 12 July 2024.

Antti Hakola, Ray Chandra, and Fredric Granberg participated in the Decennial IAEA Technical Meeting on Atomic, Molecular, and Plasma-Material Interaction Data for Fusion Science and Technology, Helsinki, 15 – 19 July 2024.

Aaro Järvinen, Daniel Jordan, and Amanda Bruncrona participated in the 5th International Conference on Data-Driven Plasma Science in Berkeley, California, USA, 12 – 16 August 2024.

Fredric Granberg attended the conference MMM 22 – 27 September 2024, Prague, Czech Republic.

Tommi Lyytinen, Janne Lyytinen, Petri Tikka, Akhtar Zeb, Van-Dung Truong and William Brace participated in the 33rd Symposium on Fusion Technology (SOFT2024), Dublin, Ireland, 22 – 27 September 2024.

Aaro Järvinen and Tuomas Tala participated in the 33rd ITPA Transport and Confinement Topical Group Meeting in Naka, Japan, 30 September – 3 October 2024.

Evgeniia Ponomareva participated in the 8th Nuclear Materials Conference (NuMat), Singapore, 12-13 October 2024.

Fredric Granberg, Victor Lindblad, and Nima Mofrod attended the conference, NUMAT, 14-17 October 2024 Singapore, Singapore.

Aaro Järvinen, Anna Niemelä, Amanda Bruncrona, and Daniel Jordan participated in the FCAI AI day conference, Finnish AI Day 2024 and Nordic AI meet at the University of Helsinki, Finland, 21-22 October, 2024.

Antti Hakola and Mathias Groth participated in the 35th ITPA meeting of TG SOL and divertor physics, Prague, Czech Republic, 21 – 24 October 2024.

Fredric Granberg attended the meeting Challenges and perspective in computational modelling for fusion reactors, 28-29 October 2024, Lausanne, Switzerland.

David Rees and Ray Chandra participated in the SOLPS-ITER Code Camp 2024, Prague, Czech Republic, 28 October – 1 November 2024.

Antti Hakola and Tuomas Tala participated in the 8th Asia-Pacific Conference on Plasma Physics, Melaka, Malaysia, 04 – 08 November 2024.

Aaro Järvinen participated in the meeting of the Boundary and Edge ITER Science Fellows at ITER Headquarters in Cadarache, France, 9 – 13 December 2024.

Aaro Järvinen presented a seminar talk at the University of Texas at Austin in Austin, Texas, USA, 12 November 2024.

Aaro Järvinen presented a seminar talk at the Texas A&M University in College Station, Texas, USA, 18 November 2024.

Ray Chandra participated online in the TSVV-5 Code Camp 2024, Eindhoven, Netherlands, 19-22 November 2024.

Timo Kiviniemi participated in the TSVV-5 Code Camp 2024, Eindhoven, Netherlands, 19-22 November 2024.

Aaro Järvinen participated in the WPTE RT01 JET analysis week at CCFE in Culham, 25 – 29 November 2024 (WPTE).

Tuula Hakkarainen participated the EUROfusion WPSAE Progress Meeting in Garching, Germany, 26–27 November 2024.

Amanda Bruncrona participated in the 13th ITER International School in Nagoya, Japan, 9 – 13 December 2024.

Tuomas Tala participated in the F4E Governing Board meeting in Barcelona, 9 – 10 December 2024.

Tuomas Tala participated in the EUROfusion General Assembly meeting in Barcelona, 11 – 12 December 2024.

11.3 Visitors

István Pusztai from Chalmers University of Technology, Gothenburg, Sweden, visited Aalto University 25-26 January 2024.

Salvatore Almaviva from ENEA, Frascati, Italy, visited VTT on 18 – 24 February 2024.

Salvatore Almaviva (ENEA, Italy), Sahithya Atikukke (Comenius University, Slovakia), Jelena Butikova (University of Latvia, Latvia), Pawel Gasior (IPPLM, Poland), Indrek Jõgi (University of Tartu, Estonia), Jasper Ristkok (University of Tartu, Estonia), Shweta Soni (Comenius University, Slovakia), Rongxing Yi (FZJ, Germany) and Ionut Jepu (UKAEA, UK) visited VTT on 18 – 22 March 2024.

Chiara de Piccoli from University of Padova, Italy, visited Aalto University, 24 November – 21 December 2024.

Elizabeth Paine from Eindhoven University of Technology, Netherlands, visited VTT 8 July – 11 September.

12 Publications 2024

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

12.1 Refereed journal articles

1. M. Willensdorfer, JET, EUROfusion contributors, Observation of magnetic islands in tokamak plasmas during the suppression of edge-localized modes, Nature Physics, **20** (2024), 1980–1988.
2. A.Murari, JET, EUROfusion contributors et al., A control oriented strategy of disruption prediction to avoid the configuration collapse of tokamak reactors, Nature Communications, **15** (2024), 2424.
3. S. Markelj, X. Jin, F. Djurabekova, J. Zavašnik, E. Punzón-Quijorna, T. Schwarz-Selinger, M. L. Crespillo, G. García López, F. Granberg, E. Lu, K. Nordlund, A. Šestan, and M. Kelemen, Unveiling the radiation-induced defect production and damage evolution in tungsten using multi-energy Rutherford backscattering spectroscopy in channeling configuration, Acta Materialia, **263** (2024), 119499.
4. Guanying Wei et al., Revealing the critical role of vanadium in radiation damage of tungsten-based alloys, Acta Materialia, **274** (2024), 119991.
5. M. Lindroos, G. Corrêa Soares, A. Biswas, W. Karlsen, A. Freimanis, S. Ren, M. Serrano and A. Laukkanen, On the grain level deformation of BCC metals with crystal plasticity modeling: Application to an RPV steel and the effect of irradiation, Materials Science and Engineering: A,Volume 914 (2024).
6. Th. Stoll, M. Schmitt, L. Lohr, R. Lürbke, A. v Müller, T. Pinomaa, J. Grünewald, A. Laukkanen, K. Wudy and R. Neu, Influence of laser beam shaping on the cracking behavior of tungsten at single weld lines, International Journal of Refractory Metals and Hard Materials, Volume **125** (2024), 106864.
7. K Bryant, A Hokkanen, D Shahwar, M Harjanne, A Salmi, and T Aalto, Zero Birefringence and Zero Birefringence Dispersion in 3 µm-Thick Silicon-on- Insulator Waveguides, J. Lightwave Technol., **43** (2024), 747-756.
8. R. Mateus, D. Dellasega, M. Passoni, Z. Siketić, I. Bogdanović Radović, J. Likonen, A. Hakola and E. Alves, Deuterium loading of redeposited-like W coatings present in tokamaks by ion implantation, Vacuum, **227** (2024), 113403.

9. Y. Torikai, G. Kikuchi, A. Owada, S. Masuzaki, T. Otsuka, N. Ashikawa, M. Yajima, M. Tokitani, Y. Oya, S.E. Lee, Y. Hatano, N. Asakura, T. Hayashi, M. Oyaidzu, J. Likonen, A. Widdowson. and M. Rubel, Overview of tritium retention in divertor tiles and dust particles from the JET tokamak with the ITER-like wall, Nuclear Fusion, 64 (2024), 016032.

10. S.S. Henderson, M. Bernert, D. Brida, M. Cavedon, P. David, R. Dux, O. Février, P. Jacquet, A. Järvinen, A. Kallenbach, J. Karhunen, K. Kirov, M. Komm, M. Lennholm, B. Lomanowski, C. Lowry, R. McDermott, A. Meigs, H. Reimerdes, H. Sun, B. Thomas, the EUROfusion Tokamak Exploitation, the ASDEX Upgrade Team, and JET Contributors, Comparison of reduced model predictions for divertor detachment onset and reattachment timescales in ASDEX Upgrade and JET experiments, Nuclear Fusion, **64** (2024), 066006.

11. J. Karhunen, S.S. Henderson, A. Järvinen, D. Moulton, S. Newton, and R.T. Osawa, First SOLPS-ITER predictions of the impact of cross-field drifts on divertor and scrape-off layer conditions in double-bull configuration of STEP, Nuclear Fusion, **64** (2024), 096021.

12. S. Wiesen, S. Dasbach, A. Kit, A.E. Järvinen, A. Gillgren, A. Ho, A. Panera, D. Reiser, M. Brenzke, Y. Poels, E. Westerhof, V. Menkovski, G.F. Derks, P. Strand, Data-driven models in fusion exhaust: AI methods and perspectives, Nuclear Fusion, **64** (2024), 086046.

13. E. Joffrin, M. Wischmeier, M. Baruzzo, A. Hakola et al., Overview of the EUROfusion Tokamak Exploitation programme in support of ITER and DEMO, Nuclear Fusion, **64** (2024), 112019.

14. C.F. Maggi et al., Overview of T and D–T results in JET with ITER-like wall, Nuclear Fusion, **64** (2024), 112012.

15. B.P. Duval et al., Experimental research on the TCV tokamak, Nuclear Fusion, **64** (2024), 112023.

16. C. Giroud, I.S. Carvalho, S. Brezinsek, A. Huber, D. Keeling, J. Mailloux, R.A. Pitts, E. Lerche, R. Henriques, J. Hillesheim, K. Lawson, M. Marin, E. Pawelec, M. Sos, H.J. Sun, M. Tomes, S. Aleiferis, A. Bleasdale, M. Brix, A. Boboc, J. Bernardo, P. Carvalho, I. Coffey, S. Henderson, D.B. King, F. Rimini, M. Maslov, E. Alessi, T. Craciunescu, M. Fontana, J.M. Fontdecaba, L. Garzotti, Z. Ghani, L. Horvath, I. Jepu, J. Karhunen, D. Kos, E. Litherland-Smith, A. Meigs, S. Menmuir, R.B. Morales, S. Nowak, E. Peluso, T. Pereira, V. Parail, G. Petravich, G. Pucella, P. Puglia, D. Refy, S. Scully, M. Sertoli, S. Silburn, D. Taylor, B. Thomas, A. Tookey, Ž. Štancar, G. Szepesi, B. Viola, A. Widdowson, E. de la Luna and JET Contributors, The core–edge integrated neon-seeded scenario in deuterium–tritium at JET, Nuclear Fusion, **64** (2024), 106062.

17. A. Chomiczewska, W. Gromelski, I. Ivanova-Stanik, E. Kowalska-Strzęciwilk, N. Wendler, P. Jacquet, A. Meigs, J. Mailloux, S. Menmuir, J. Karhunen, E. Lerche, I. Monakhov, R. Otin, B. Thomas, P. Dumortier, D. Van Eester, M. Barruzo, V. Bobkov, S. Brezinsek, L. Colas, D. Douai, D. Milanesio, E. Pawelec, E. Delabie, B. Lomanowski and JET Contributors, ICRH-related impurity source and control across experiments in H, D, T plasmas at JET-ILW, Nuclear Fusion, **64** (2024), 76058.

18. M. Zlobinski, G. Sergienko, I. Jepu, C. Rowley, A. Widdowson, R. Ellis, D. Kos, I., Coffey, M. Fortune, D. Kinna, A. Hakola, J. Likonen, et al., JET Contributors & EUROfusion Tokamak Exploitation Team, First results of laser-induced desorption - quadrupole mass spectrometry (LID-QMS) at JET, Nuclear Fusion, **64** (2024), 086031.

19. K. Verhaegh, J. Harrison, B. Lipschultz, N. Lonigro, S. Kobussen, D. Moulton, P. Ryan, C. Theiler, T. Wijkamp, A. Hakola., et al., EUROfusion Tokamak Exploitation Team & MAST Upgrade Team, Investigations of atomic and molecular processes of NBI-heated discharges in the MAST Upgrade Super-X divertor with implications for reactors, Nuclear Fusion, **64** (2024), 086050.

20. A. Hakola, M. Balden, M. Baruzzo, R. Bisson, S. Brezinsek, T. Dittmar, D. Douai, M. Dunne, L. Garzotti, M. Groth, J. Likonen, T. Tala, EUROfusion Tokamak Exploitation Team, ASDEX Upgrade Team & JET Contributors, Helium plasma operations on ASDEX Upgrade and JET in support of the non-nuclear phases of ITER, Nuclear Fusion, **64** (2024), 096022.

21. I. Jepu, A. Widdowson, G. F. Matthews, J. Coad, J. Likonen, S. Brezinsek, M. Rubel, G. Pintsuk, P. Petersson, E. Fortuna-Zalesna, J. Grzonka, C. Porosnicu, P. Dinca, O. Pompilian, B. Butoi, S. G. Moga, S. Silburn, S. Kuksenko, E. Alves, N. CatarinoR. A. Pitts, L. Chen and S. Ratynskaia, Overview of damage to beryllium limiters by unmitigated disruptions and runaway electrons in the JET tokamak with metal walls, Nuclear Fusion, 64 (2024), 106047.

22. R. Ochoukov, R. Bilato, V. Bobkov, H. Faugel, A. Kappatou, P. Schneider, M. Weiland, M. Dreval, S. Sipilä, R. Dendy, T. Johnson, Y. Kazakov, K. McClements, D. Moseev, M. Salewski, Experimental and numerical investigation of the Doppler-shifted resonance condition for high frequency Alfvén eigenmodes on ASDEX Upgrade, Nuclear Fusion, **64** (2024), 126060.

23. DIII-D team et al., DIII-D research to provide solutions for ITER and fusion energy, Nuclear Fusion, **64** (2024), 112003.

24. H. Zohm, EUROfusion contributors et al., Overview of ASDEX upgrade results in view of ITER and DEMO, Nuclear Fusion, **64** (2024), 112001.

25. I. Borodkina, M. Groth et al., Modeling of plasma facing component erosion, impurity migration, dust transport and melting processes at JET-ILW, Nuclear Fusion, **64** (2024), 106009.

26. S. Rode, S. Brezinsek, M. Groth, A. Kirschner, D. Matveev, L. Moser, R. Pitts, J., Romazanov, A. Terra, T. Wauters, and S. Wiesen, Multi-staged ERO2.0 simulation of material erosion and deposition in recessed mirror assemblies in JET and ITER, Nuclear Fusion, **64** (2024), 086032.

27. J. Romazanov, S. Brezinsek, C.Baumann, S. Rode, A. Kirschner, E. Wang, F. Effenberg, D. Borodin, M, X. Navarro, H.Xie, M. Groth, H. Kumpulainen, K. Schmid, R.A., Pitts, A. Terra, A. Knieps, Y. Gao, M. Krychowiak, A. Pandey and C Linsmeier, Validation of the ERO2.0 code using W7-X and JET experiments and predictions for ITER operation, Nuclear Fusion, **64** (2024), 086016.

28. D. Matveev, C. Baumann, J. Romazanov, S. Brezinsek, S. Ratynskaia, L. Vignitchouk, P. Tolias, K. Paschalidis, D. Tskhakaya, M. Komm, A. Podolnik, J. Mougenot, Y. Charles, R. Delaporte-Mathurin, E. Hodille, C. Grisolia, F. Montupet-Leblond, K. Schmid, U. von Toussaint, F. Granberg, F. Kporha, F. Kovačič, and J. Costea, An integral approach to plasma-wall interaction modelling for EU-DEMO, Nuclear Fusion, **64** (2024), 106043.

29. T. Lyytinen, A., Snicker, J., Virtanen, I., Palermo, J., Alguacil, T., Bogaarts, and F. Warmer, Proof-of-principle of parametric stellarator neutronics modeling using Serpent2, Nuclear Fusion, **64** (2024), 076042.

30. M. Rud*, D. Moseev, F. Jaulmes, K. Bogar, Y. Dong, P. C. Hansen, J. Eriksson, H. Järleblad, M. Nocente, G. Prechel, B. C.G. Reman, B. Schmidt, Antti Snicker, L. Stagner, A. Valentini, M. Salewski, Orbit tomography in constants-of-motion phase-space, Nuclear Fusion, **64** (2024), 076018.

31. R. Calado, F. Nabais, S.E.. Sharapov, P. Schneider, Y. Kazakov, M. Garcia-Muñoz, A. Snicker, J. Ferreira, R. Coelho, M. Dreval, J. Fuertes, J. Galdon-Quiroga, J. Gonzalez-Martin, A. Karpushov, J. Stober, G. Tardini, M.A. Van Zeeland and ASDEX Upgrade Team, Modelling of energetic particle drive and damping effects on TAEs in AUG experiment with ECCD, Nuclear Fusion, **64** (2024), 016039.

32. X. Litaudon, U. Fantz, R. Villari, V. Toigo, M.H. Aumeunier, J.L. Autran, P. Batistoni, E. Belonohy, S. Bradnam, M. Cecchetto, A. Snicker, et al., EUROfusion Tokamak Exploitation Team, NBTF Team & JET Contributors, EUROfusion contributions to ITER nuclear operation, Nuclear Fusion, **64** (2024), 112006.

33. M. Rud, D. Moseev, F. Jaulmes, K. Bogar, J. Eriksson, H. Järleblad, M. Nocente, G. Prechel, B. C.G. Reman, B. S. Schmidt, Antti Snicker, L. Stagner, A. Valentini, M. Salewski, Diagnostic weight functions in constants-of-motion phase-space, Nuclear Fusion, **64** (2024), 036007.

34. E. Ponomareva, E. Pitthan, R. Holeňák, J. Shams-Latifi, G.P. Kiely, D. Primetzhofer and A.E. Sand, Local electronic excitations induced by low-velocity light ion stopping in tungsten, Physical Review B, **109** (2024), 165123.

35. A. Bruncrona, J. Wu, X. Jin, J. Byggmästar and F. Granberg, Understanding the RBS/c spectra of irradiated tungsten: A computational study, Computational Materials Science, **244** (2024), 113241.

36. Z. Chen, et al., Suppression of helium migration in arc-melted and 3D-printed CoCrFeMnNi high entropy alloy, Journal of Nuclear Materials, **599** (2024), 155238.

37. V. Lindblad et al., The effect of deuterium on defect production in irradiated tungsten, Journal of Nuclear Materials, **603** (2024), 155422.

38. M. Tokitani, M. Miyamoto, S. Masuzaki, Y. Hatano, S.E. Lee, Y. Oya, H. Kurotaki, N. Asakura, H. Nakamura, T. Hayashi, M. Rubel, A. Widdowson and J. Likonen, Co-deposited layers on gap surfaces of bulk tungsten divertor tiles in JET ITER-like wall: Directional effects and nanostructures, Nuclear Materials and Energy, 39 (2024) 101678.

39. T. Vuoriheimo, A. Hakola, J. Likonen, K. Krieger, M. Balden, I. Bogdanovic Radovic, G. Provatas, Z. Siketic, K. Ivankovic Nizic, M. Rasinski, S. Brezinsek, Divertor erosion at ASDEX Upgrade during helium plasma operations, Nuclear Materials and Energy, **41** (2024), 101766.

40. I. Jõgi, P. Paris, J. Ristkok, A. Marin Roldán, P. Ganapati Bhat, P. Veis, J. Karhunen, S. Almaviva, W. Gromelski, P. Dinca, C. Porosnicu, I. Bogdanović Radović, Z. Siketić, P. Gąsior, J. Likonen, A. Hakola, Laser-induced breakdown spectroscopy for helium detection in beryllium coatings, Nuclear Materials and Energy, **39** (2024), 101677.

41. T.Wauters, R. Bisson, E. Delabie, D. Douai, A. Gallo, J. Gaspar, J. Jepu, Y. Kovtun, E. Pawelec, D. Matveev, A. Meigs, S. Brezinsek, I. Coffey, T. Dittmar, N. Fedorczak, J. Gunn, A. Hakola, P. Jacquet, K. Kirov, E. Lerche & 25 others, Changeover between helium and hydrogen fueled plasmas in JET and WEST, Nuclear Materials and Energy, **38** (2024), 101587.

42. A. Gallo, P. Moreau, D. Douai, T. Alarcon, K. Afonin, V. Anzallo, R. Bisson, J. Bucalossi, E. Caprin, Y. Corre, M. De Combarieu, C. Desgranges, P. Devynck, A. Ekedahl, N. Fedorczak, J. Gaspar, A. Grosjean, C. Guillemaut, R. Guirlet, J.P. Gunn and 10 others, Wall conditions in WEST during operations with a new ITER grade, actively cooled divertor, Nuclear Materials and Energy, **41** (2024), 101741.

43. R. Chandra, D. Reiter, N. Horsten, M. Groth, Lyman line opacities in tokamak divertor plasmas under high-recycling and detached conditions, Nuclear Materials and Energy, **41** (2024), 101794.

44. A. Huber, M. Groth et al., Investigation of H-mode density limit in mixed protium–deuterium plasmas at JET with ITER-like wall, Nuclear Materials and Energy, **41** (2024), 101806.

45. A. Holm, M. Groth et al., Modeling a divertor with mid-leg pumping for high-power H-mode scenarios in DIII-D considering E × B drift flows, Nuclear Materials and Energy, **41** (2024), 101782.

46. J. Yu, M. Groth et al., Simulations of divertor designs that spatially separate power and particle exhaust using mid-leg divertor particle pumping, Nuclear Materials and Energy, **41** (2024), 101826.

47. M. Rees, M. Groth, S. Aleiferis, S. Brezinsek, M. Brix, I. Jepu, K.D. Lawson, A.G. Meigs, S. Menmuir, K, Kirov, P. Lomas, C. Lowry, B.Thomas, A. Widdowson, P. Carvalho, E. Delabie, E. and the JET contributors, Characterisation of the scrape-off layer in JET-ILW deuterium and helium low-confinement mode plasmas, Nuclear Materials and Energy, **39** (2024), 101657.

48. R. Nilsson, S. Choupanian, C. Ronning, K. Nordlund and F. Granberg, Investigation of surface orientation dependent sputtering of Ag, Journal of Physics: Condensed Matter, **36** (2024), 065002.

49. A. Panera-Alvarez, A. Ho, A.E. Järvinen, S. Saarelma, S. Wiesen, and JET Contributors and the ASDEX Upgrade Team, EuroPED-NN: uncertainty aware surrogate model, Plasma Phys. Control. Fusion, **66** (2024), 095012.

50. K.D. Lawson, M. Groth et al., He II line intensity measurements in the JET tokamak, Plasma Phys. Control. Fusion, **66** (2024), 115001.

51. H.A. Kumpulainen, M. Groth, S. Brezinsek, F. Casson, G. Corrigan, L. Frassinetti, D. Harting, J. Romazanov and JET contributors, Validated edge and core predictions of tungsten erosion and transport in JET ELMy H-mode plasmas, Plasma Phys. Control. Fusion, **66** (2024), 055007.

52. P. Ollus, S. Allan, J.R. Harrison, A.R. Jackson, T. Kurki-Suonio, K.G. McClements, C.A. Michael, D. Moulton, B.S. Patel, M. Robson, A. Snicker, J. Varje, C. Vincent and MAST Upgrade Team, Validating the simulation of beam-ion charge exchange in MAST Upgrade, Plasma Physics and Controlled Fusion, **66** (2024), 025009.

53. C.D. Stephens, J. Citrin, K.L. van de Plassche, C. Bourdelle, T. Tala, A. Salmi et al., Quasilinear modelling of collisional trapped electron modes, Journal of Plasma Physics, 90 (2024), 905900618.

54. A.E. Järvinen, A. Kit, Y.R.J. Poels, S. Wiesen, V. Menkovski, L. Frassinetti, M. Dunne, ASDEX Upgrade Team, and JET Contributors, Representation learning algorithms for inferring machine independent latent features in pedestals in JET and AUG, Physics of Plasmas, **31** (2024), 032508.

55. A. Kit, A.E. Järvinen, Y.R.J. Poels, S. Wiesen, V. Menkovski, R. Fischer, M. Dunne, and ASDEX Upgrade Team, On learning latent dynamics of the AUG plasma state, Physics of Plasmas, **31** (2024), 032504.

56. C.F.B. Zimmermann, C. Angioni, R.M. McDermott, B.P. Duval, R. Dux, E. Fable, A. Salmi, U. Stroth, T. Tala, G. Tardini, T. Pütterich, ASDEX Upgrade Team, Experimental validation of momentum transport theory in the core of H-mode plasmas in the ASDEX Upgrade tokamak, Phys. Plasmas, **31** (2024), 42306.

57. M. Ladygina, W. Gromelski, P. Gasior, A. Marín Roldán, J. Karhunen, P. Paris, I. Jõgi, A. Hakola, J. Likonen, S. Almaviva, J. Ristkok, P. G. Bhat, C. Porosnicu, C. Lungu, P. Veis, LIBS diagnostics of Be-based samples with different gas impurities, Phys. Plasmas, **31** (2024), 63501.

58. P. Vincenzi, M. Schneider and A. Snicker, Modelling of NBI shine-through in ITER non-nuclear phase to limit heat fluxes on first wall, Fusion Engineering and Design, **200** (2024), 114178.

59. M. Li, H. Wu, C. Li, Z. Yao, Q. Wang, H. Handroos, T. Deighan, B. William and O. Crofts, Data driven modeling of heavy-duty joint system for DEMO manipulators: An initial study from MPD joint simulation. Fusion Engineering and Design, **202**, (2024) 114327.

60. V.D. Truong and W. Brace, Balanced-risk analysis in the engineering design of complex systems with extreme conditions. Fusion Engineering and Design, 208, (2024) 114690.

61. T. Pinomaa, J. Aho, J. Suviranta, P. Jreidini, N. Provatas and A. Laukkanen, OpenPFC: an open-source framework for high performance 3D phase field crystal simulations, Modelling Simul. Mater. Sci. Eng. **32** (2024) 045002.

62. R. B. Morales, A. Salmi et al, Improved accuracy and robustness of electron density profiles from JET's X-mode frequency-modulated continuous-wave reflectometers, Rev. Sci. Instrum., **95** (2024), 43501.

63. V.-P. Rikala, M. Groth, H. Kumpulainen, D. Rees, Comparison of OEDGE and EDGE2D-EIRENE predictions of the scrape-off layer conditions for attached plasmas, Contributions to Plasma Physics, **64** (2024), e202300107.

64. D. Rees, J. Sissonen, M. Groth, V-P. Rikala, H. Kumpulainen, D. Thomas and M. Brix, Comparison of the scrape-off layer two-point model for deuterium and helium plasmas in JET ITER-like wall low-confinement plasma conditions, Contributions to Plasma Physics, **64** (2024), e202300108.

65. J.L. Herfindal, E.A. Unterberg, K.M. Davda, E.W. Garren, M. Groth, F.Scotti, A.C. Sontag, D.D. Truong, R.S. Wilcox., Calibration improvements expand filterscope diagnostic use, Review of Scientific Instruments, **95** (2024), 023504.

66. V.-D. Truong and W. Brace, Function-Based Minimum Risk: Redesign of Robotic System in a Fusion Reactor, IEEE Transactions on Plasma Science, **52** (2024), 1-6.

67. H.Wu, Z. Yao, C. Li, M. Li, H. Handroos, A. Sinha and W. Brace, Concept Design and Development of the Multipurpose Deployer (MPD) for Large Port-Based Tokamaks. IEEE Transactions on Plasma Science, **52** no. 9,(2024), 3468-3473.

68. C. Li, Wu H., Eskelinen H., Li M., Brace W., Budden S., Crofts O., "Design and Development on the Remote Maintenance Tools and Strategy of the Port Closure Plate

in DEMO," in IEEE Transactions on Plasma Science, vol. 52, no. 9 (2024), pp. 3506-3510.

69. W. Brace, P. Tikka, J. Alanen, J. Lyytinen and H. Martikainen, Digital Thread Architecture: Coupling Requirements and 3-D CAD Models in an Iterative Closed Design Loop. IEEE Transactions on Plasma Science, vol. 52, no. 9 (2024), pp. 3549-3554.

70. A. Valentini*, B. C.G. Reman, M. Nocente, J. Eriksson, H. Järleblad, D. Moseev, M. Rud, A. Snicker, M. Salewski, Relativistic calculations of neutron and gamma-ray spectra from beam-target reactions in magnetized plasmas, Review of Scientific Instruments, **95** (2024), 083551.

71. E. Poli, L. Figini, E. Fable, M. Siccinio, A. Snicker, C. Wu and H. Zohm, ECCD studies for EU-DEMO plasmas, EPJ Web of Conferences, **313** (2024), 01005.

12.2 Conference presentations

1. N. Fakhrayi Mofrad and A. Sand, "Navigating Fusion Reactor Challenges: Correlations Between Surface Temperature, Plasma Particle Impact Angle and Erosion", Physics Days - Helsinki, Finland 4-6 March 2024. (Poster)

2. A. Hakola, J. Karhunen, J. Likonen, I. Jõgi, P. Paris, P. Veis, S. Almaviva, P. Gasior, G. Sergienko, UKAEA RACE Team and JET Contributors, “Development of LIBS as a tritium monitoring tool for the JET tokamak”, Nordic LIBS 2024, Tampere, Finland, 5.—6.3.2024.

3. T. Lyytinen, A. Snicker, J. Virtanen, I. Palermo, J. Alguacil, T. Bogaards, F. Warmer, Neutronics studies on parametric magnetic confinement fusion reactors using Serpent2 Monte Carlo code, 15th ITER Neutronics meeting and Fusion Neutronics Workshop, ITER Headquarters, France, 8-10 April, 2024.

4. T. Vuoriheimo, A. Hakola, J. Likonen, K. Krieger, M. Balden, I. Bogdanovic Radovic, G. Provatas, Z. Siketic, K. Ivanković Nizić, M. Rasinski, S. Brezinsek, ASDEX Upgrade Team, and the EUROfusion Tokamak Exploitation Team, Divertor erosion at ASDEX Upgrade during helium plasma operations, the 26th International Conference on Plasma Surface Interaction in Controlled Fusion Devices (PSI-26), 26th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Marseille, France, 13.—17.5.2024 (Poster).

5. J. Karhunen, B. Lomanowski, S. Aleiferis, P. Carvalho, M. Groth, A. Holm, K.D. Lawson, A.G. Meigs, A. Shaw, V. Solokha, JET Contributors, the EUROfusion Tokamak Exploitation Team, “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”, 26th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Marseille, France, 13.—17.5.2024 (P2-026)

6. R. Mäenpää, H. Kumpulainen, M. Groth, N. Horsten, D. Reiter, J. Romazanov, B. Lomanowski, S. Brezinsek, J. Karhunen, K. Lawson, A. G. Meigs, S. Menmuir, A. Shaw and JET Contributors, “Impact of nitrogen molecular breakup on divertor conditions in JET L-mode plasmas using SOLPS-ITER, EDGE2D-EIRENE and ERO2.0”, 26th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Marseille, France, 13.—17.5.2024 (P2-078).

7. V.-P. Rikala, M. Groth, A.G. Meigs, B. Lomanowski, A. Shaw, S. Aleiferis, G. Corrigan, I.S. Carvalho, D. Harting, N. Horsten, I. Jepu, J. Karhunen, K.D. Lawson, C. Lowry, S. Menmuir, B. Thomas, D. Borodin, D. Douai, A. Huber and JET contributors, “Characterization of detachment based on the Balmer line ratios in JET-ILW L-mode plasmas”, 26th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Marseille, France, 13.—17.5.2024 (P3-066)

8. P. Veis, J. Likonen, A. Hakola, A. Marín Roldán, M. Veis, P.G. Bhat, J. Karhunen, P. Paris, I. Jõgi, J. Ristkok, S. Almaviva, W. Gromelski, M. Ladygina, P. Gasior and JET contributors, “LIBS and SIMS comparison for impurities detection in JET limiter samples”, 26th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Marseille, France, 13.—17.5.2024 (P3-103)

9. C. Giroud, D.B. King, I.S. Carvalho, D. L. Keeling, L. Frassinetti, R. A. Pitts, S. Wiesen, G. Pucella, A. Kappatou, N. Vianello, M. Wischmeier, F. Rimini, M. Baruzzo, M. Maslov, M. Sos, X. Litaudon, R. B. Henriques, K. Kirov, C. Perez von Thun, H. J. Sun, M. Lennholm, J. Mitchell, A. Parrot, J. Bernardo, M. Zerbini, I. Coffey , K. Collie, J. Fontdecaba, N. Hawkes, Z. Huang, I. Jepu, D. Kos, K. Lawson, E. Litherland-Smith, A. Meigs, C. Olde, A. Patel, L. Piron, M. P. Poradzinski, Z. Stancar, D. Taylor, E. Alessi, I. Balboa, A. Boboc, S. Bakes, M. Brix, E. De la Cal, P. Carvalho, A. Chomiczewska, Z. Ghani, E. Giovannozzi, J. Foster, A. Huber, J. Karhunen, E. Kowalska-Strzeciwilk, K. Lawson, J. Maddock, J. Matthews, S. Menmuir, K. Mikszuta, R.B. Morales-Bianchetti, E. Pawelec, G. Petravich, E. Pinto, I. Voldiner, G. Sergienko, S. Silburn, G. Stankunas, J. Svodoba, M. Tomes, B. Thomas, A. Tookey, Y. Zayachuk, M. Valovic, A. Widdowson, L. Xiang, F. Auriemma, P. Innocente, S. Gabriellini, A. Mariani, M. Marin, I. Predebon, A. Thrysoe, V. Zoita, JET Contributors and the EUROfusion Tokamak Exploitation Team, “High current Ne-seeded ITER baseline scenario in JET D and D-T”, 26th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Marseille, France, 13.—17.5.2024 (Invited).

10. K. Verhaegh, J. R. Harrison, D. Moulton, B. Lipschultz, N. Lonigro, N. Osborne, P. Ryan, C. Theiler, T. Wijkamp, D. Brida, C. Cowley, G. Derks, R. Doyle, F. Federici, S. Kobussen, B. Kool, A. Hakola, S. Henderson, S. Newton, R. Osawa, H. Reimerdes, N. Vianello, M. Wischmeier, L. Xiang, the MAST Upgrade team and the EUROfusion Tokamak Exploitation Team, Understanding and predicting the benefit of long-legged divertors on MAST-U, 26th International Conference on Plasma Surface Interaction in Controlled Fusion Devices, 13 – 17 May 2024.

11. E. Tonello, G. Alberti, F. Mombelli, C. Tuccari, S. Brezinsek, T. Dittmar, M. Groth, A. Hakola, A. Kirschner, K. Krieger, M. Rasinski, J. Romazanov, A. Uccello, A. Widdowson, M. Passoni, the WPTE team, and the ASDEX-Upgrade team, Global modelling of helium Plasma-Wall Interaction experiments in ASDEX-Upgrade, 26th International Conference on Plasma Surface Interaction in Controlled Fusion Devices, 13 – 17 May 2024.

12. A. Uccello, A. Cremona, F. Ghezzi, M. Pedroni, E. Vassallo, G. Alberti, L. Bana, C. Tuccari, D. Vavassori, D. Dellasega, M. Passoni, E. Grigore, A. Hakola, M. Rasinski, J. Romazanov, and the GyM Team, Exploring the influence of morphology in the sputtering process of tungsten by GyM helium plasma, 26th International Conference on Plasma Surface Interaction in Controlled Fusion Devices, 13 – 17 May 2024.

13. A. Gallo, Ph. Moreau, D. Douai, T. Alarcon, K. Afonin, V. Anzallo, R. Bisson, J. Bucalossi, E. Caprin, Y. Corre, M. De Combarieu, C. Desgranges, P. Devynck, A. Ekedahl, N. Fedorczak, J. Gaspar, A. Grosjean, C. Guillemaut, R. Guirlet, J. P. Gunn,

J. Hillairet, T. Loarer, P. Maget, P. Manas, J. Morales, F. P. Pellissier, E. Tsitrone, K. Krieger, A. Hakola, A. Widdowson, the WEST team, and the EUROfusion TE team, Wall conditions in WEST during operations with a new ITER grade, actively cooled divertor, 26th International Conference on Plasma Surface Interaction in Controlled Fusion Devices, 13 – 17 May 2024.

14. A. E. Sand, Sputtering yields by slow light ions with molecular dynamics, Symposium on Plasma Materials Interactions and Diagnostics, Warsaw & hybrid, May 21–23, 2024 (invited talk).

15. A.E. Järvinen and EUROfusion ACH-05 and TSVV-09 teams, Machine learning acceleration of fusion model validation, FinnFusion Annual Seminar, University of Helsinki, Helsinki, 27 – 28 May 2024.

16. A.E. Järvinen, L. Acerbi, A. Bharti, T. Fülöp, M. Hoppe, E. Nardon, A. Kit, S. Silburn, and JET contributors, Update on developing efficient Bayesian inference methods for runaway electron model validation, Joint Runaway Electron Modelling (REM) and JET SPI Analysis meeting, Lausanne, Switzerland, 10 – 14 June 2024.

17. A. E. Sand, A. Tamm, A. A. Correa, COSIRES (16th Conference on Computer Simulation of Radiation Effects in Solids), Kingston, ON, Canada, June 16–21, 2024 (invited talk).

18. N. Verma, T. Korhonen and T. Hakkarainen, Fire analysis tools for DEMO fusion power plant. Nordic Fire and Safety Days, Lund, Sweden, 18–19 June 2024. Book of Abstracts, Nordic Fire and Safety Days, RISE Report 2024:49, pp. 114–115.

19. A.E. Järvinen, A. Kit, A. Bruncrona, Y. Poels, S. Wiesen, V. Menkovski, L. Frassinetti, M. Dunne, S. Saarelma, the ASDEX Upgrade Team and JET Contributors, State representation learning algorithms for data-driven predictions of tokamak pedestals, 50th EPS conference in Salamanca, Spain, 8 – 12 July 2024.

20. A Salmi, CFB Zimmermann, T Tala et al., TCV intrinsic torque in balanced NBI experiment, 50th EPS Conference on Plasma Physics (2024).

21. C. Reux, U. Sheikh, C. Paz-Soldan, O. Ficker, M. Lehnen, S. Jachmich, S. Silburn, P.J. Lomas, C. Lowry, N. Schoonheere, D. Craven, J. Wilson, M. Nocente, A. Dal Molin, G. Szepesi, D. Kos, A. Boboc, A. Lvovskiy, M. Baruzzo, A. Hakola, E. Joffrin, C. Sommariva, A. Battey, D. Brunetti, P. Buratti, H. Choudhury, J. Decker, N. Eidietis, M. Hoppe, H. Isliker, E. Kowalska-Strzeciwilk, G. Marcer, E. Nardon, V. Plyusnin, D. Rigamonti, L. Spolladore, E. Tomesova, M. Zerbini, JET contributors and the EUROfusion Tokamak Exploitation Team, 50th EPS Conference on Plasma Physics, 08 – 12 July 2024.

22. I.S. Carvalho, C. Giroud, D.B. King, D. L. Keeling, L. Frassinetti, R. A. Pitts, S. Wiesen, G. Pucella, A. Kappatou, N. Vianello, M. Wischmeier, F. Rimini, M. Baruzzo, M. Maslov, M. Sos, X. Litaudon, R. B. Henriques, K. Kirov, C. Perez von Thun, H. J. Sun, M. Lennholm, J. Mitchell, A. Parrot, J. Bernardo, M. Zerbini, I. Coffey, K. Collie, J.M. Fontdecaba, N. Hawkes, Z. Huang, I. Jepu, D. Kos, K. Lawson, E. Litherland-Smith, A. Meigs, C. Olde, A. Patel, L. Piron, M. P. Poradzinski, Z. Stancar, D. Taylor, E. Alessi, I. Balboa, A. Boboc, S. Bakes, M. Brix, E. De la Cal, P. Carvalho, A. Chomiczewska, Z. Ghani, E. Giovannozzi, J. Foster, A. Huber, J. Karhunen, E. Kowalska-Strzeciwilk, J. Maddock, J. Matthews, S. Menmuir, K. Mikszuta, R. B. Morales-Bianchetti, E. Pawelec, G. Petravich, E. Pinto, I. Voldiner, G. Sergienko, S. Silburn, J. Svodoba, M. Tomes, B. Thomas, A. Tookey, Y. Zayachuk, M. Valovic, A. Widdowson, L. Xiang, F.

Auriemma, P. Innocente, S. Gabriellini A. Mariani, M. Marin, I. Predebon, A. Thrysoe, V.K. Zotta, JET Contributors and the EUROfusion Tokamak Exploitation Team, “Neon seeded ITER baseline scenario experiments in JET D and D-T plasmas”, 50th EPS Conference on Controlled Fusion and Plasma Physics, Salamanca, Spain, 8.—12.7.2024 (O4.302).

23. E. Alessi, G. Pucella, E. Giovannozzi, C. Giroud, D.B. King, I.S. Carvalho, L. Frassinetti, S. Wiesen, A. Kappatou, N. Vianello, M. Wischemeier, D.L. Keeling, M. Baruzzo, M. Maslov, X. Litaudon, S. Gerasimov, R.B. Henriques, C. Perez von Thun, H.J. Sun, M. Lennholm, A. Parrot, M. Zerbini, I. Coffey, K. Collie, J. Fontdecaba, Z. Huang, I. Jepu, D. Kos, E. Litherland-Smith, M.P. Poradzinski, Z. Stancar, D. Taylor, M. Brix, P. Carvalho, A. Chomiczewska, Z. Ghani, J. Karhunen, E. Kowalska-Strzeciwilk, K. Lawson, S. Menmuir, R.B. Morales, E. Pawelec, G. Petravich, S. Silburn, B. Thomas, A. Tookey, Y. Zayachuk, A. Widdowson, A. Boboc, the EUROfusion Tokamak Exploitation Team and JET Contributors, “Impact of light impurities injection on n=1 core MHD activity at JET”, 50th EPS Conference on Controlled Fusion and Plasma Physics, Salamanca, Spain, 8.—12.7.2024 (P1.069).

24. Snicker, A., Särkimäki, K., Hyvärinen, O., Siccinio, M. & Bachmann, C., Fast ion transport and confinement in volumetric neutron source device, 50th EPS Conference on Plasma Physics (2024).

25. Rud, M., Hyvärinen, O., Järleblad, H., Snicker, A., Eriksson, J., Dong, Y., Hansen, P. C., Nocente, M., Reman, B., Schmidt, B. S., Valentini, A., Moseev, D. & Salewski, M., 4D reconstruction of JET DTE2 fast-ion distribution function based on synthetic data, 50th EPS Conference on Plasma Physics (2024).

26. J. Galdon-Quiroga, S. Sipilä, R. Bilato, M. Weiland, B. Simmendefeldt, V. Bobkov, M. Dreval, M. García-Muñoz, J. Hidalgo-Salaverri, Y. Kazakov, Ph. Lauber, J. Manyer, M. Mantsinen, J. Rueda-Rueda, M. Salewski, Ph. Schneider, S. Sharapov, A. Snicker, the ASDEX Upgrade Team and the EUROfusion Tokamak Exploitation Team, Mitigation of ICRH fast-ion losses induced by Alfven Eigenmodes using NBI: experiments and modelling in the ASDEX Upgrade tokamak, 50th European Conference on Plasma Physics, Salamanca, Spain, 8–12 July 2024.

27. A.E. Järvinen, L. Acerbi, E. Amnell, A. Bharti, R.M. Churchill, T. Fonghetti, C.S. Furia, T. Fülöp, A. Ho, M. Hoppe, E. Nardon, A. Kit, S. Silburn, and JET contributors, Simulation-based inference for validation of computationally demanding models in fusion energy applications, 5th International Conference on Data-Driven Plasma Science in Berkeley, California, USA, 12 – 16 August 2024.

28. T. Lyytinen, A. Snicker, I. Palermo, J. Alguacil, F. Warmer, Evaluation of divertor openings in HELIAS reactor neutronics, 33rd Symposium on Fusion Technology, 22 – 27 September 2024 (Poster).

29. W. Brace and V-D. Truong, V.-D. Optimal Design Drivers as a Rationale for a Bottom-Up Approach in DEMO Remote Maintenance Equipment Conceptualisation, 33rd Symposium on Fusion Technology (SOFT2024), Dublin, Ireland, 22 September 2024 (Poster).

30. A. Hekmatmanesh, Q. Xue, H. Wu, W. Brace, F. Milella and H. Handroos, Condition Monitoring in Human-in-the-Loop Remote Maintenance Systems: Advancements in AI Utilizing EEG and PPG Signals. 33rd Symposium on Fusion Technology (SOFT2024), Dublin, Ireland, 22 September 2024 (Poster).

31. A. Bousaid, M. Hora, J. Alanen, T. Tremethick, W. Brace and O. Crofts, Improving the Feasibility Analysis of Remote Maintenance Operations and Maintenance Duration. 33rd Symposium on Fusion Technology (SOFT2024), Dublin, Ireland, 22 September 2024 (Poster).

32. Q. Saifi, H. Wu, W. Brace and M. Li, Stochastic State Estimation in Digital Twins: Transforming Probability Densities. 33rd Symposium on Fusion Technology (SOFT2024), Dublin, Ireland, 22 September 2024 (Poster).

33. Z. Akhtar, P. Kokkonen, M. Tahkola, W. Brace, N. Milella, Advancing Remote Handling Capabilities in the Nuclear Industry: Integration of Machine Learning-Based Functional Mock-Up Units in Robotic Technologies. 33rd Symposium on Fusion Technology (SOFT2024), Dublin, Ireland, 22 September 2024 (Poster).

34. P. Tikka, J. Lyytinen, W. Brace, M. Staniforth and S. Budden, *In-Vessel Component Remote Maintenance Path Planning Methods for Plant Architecture Assessments*. 33rd Symposium on Fusion Technology (SOFT2024), Dublin, Ireland, 22 September 2024 (Poster).

35. P. Tikka, H. Saarinen, H. Martikainen and W. Brace, Simulated Installation of a Breeding Blanket Segment in a Two-Port Mover Context. 33rd Symposium on Fusion Technology (SOFT2024), Dublin, Ireland, 22 September 2024 (Poster).

36. D. Birlan, W. Brace, A. Bruschi, R. Chavan, O. Crofts, S. Garavaglia, J.P. Hogge, C. Marraco Borderas, A. Mas Sanchez, C. Li, H. Martikainen, A. Sinha, P. Spaeh, M. Torrance, A. Unt, C. Wu, H. Wu and A. Xydou, A., Conceptual Design Proposal for the EU DEMO EC Heating and Current Drive Ex-Vessel Waveguide System with Enhanced Remote Maintainability. 33rd Symposium on Fusion Technology (SOFT2024), Dublin, Ireland, 22 September 2024.

37. C. Li, H. Wu, M. Li, W. Brace, H. Eskelinen, Design and Development on the Remote Maintenance Equipment and Strategy of the Ports in DEMO. 33rd Symposium on Fusion Technology (SOFT2024), Dublin, Ireland, 22 September 2024.

38. V.-D. Truong, W. Brace and M. Hora, Design by Cataloguing – A Product-Driven Design Approach for the Conceptual Design of Fusion Remote Maintenance Systems. 33rd Symposium on Fusion Technology (SOFT2024), Dublin, Ireland, 22 September 2024 (Poster).

39. P. Spaeh, D. Birlan, W. Brace, C. Li, H. Martikainen, A. Sinha and H. Wu, Remote Maintenance Concept and Design Implications for the EU-DEMO EC Heating and Current Drive Launchers. 33rd Symposium on Fusion Technology (SOFT2024), Dublin, Ireland, 22 September 2024.

40. A. E. Sand, Environmentally dependent electronic energy losses in collision cascades, MMM (Multiscale Materials Modelling), Prague, September 22–27, 2024 (invited keynote lecture).

41. M. Zlobinski, G. Sergienko, I. Jepu, C. Rowley, A. Widdowson, R. Ellis, D. Kos, I. Coffey, M. Fortune, D. Kinna, M. Beldishevski, A. Krimmer, H. T. Lambertz, A. Terra, A. Huber, S. Brezinsek, T. Dittmar, M. Flebbe, R. Yi, R. Rayaprolu, S. Friese, Ph. Mertens, I. Ivashov, Y. Krasikov, K. Młynczak, J. Assmann, D. Castaño Bardawil, M. Schrader, Ph. Andrew, X. Jiang, J. Figueiredo, P. Blatchford, S. Silburn, E. Tsitrone, E. Joffrin, K. Krieger, Y. Corre, A. Hakola, J. Likonen, the EUROfusion Tokamak Exploitation Team, and the JET Contributors, In situ Tritium Retention Diagnostic using

Laser-Induced Desorption: JET results and ITER outlook, 33rd Symposium on Fusion Technology, 22 – 27 September 2024.

42. F. Kporha, Sputtering of Tungsten and Deuterium-Decorated Tungsten Surfaces, 11th International Conference on Multiscale Materials Modeling (September 22–27, 2024, Prague, Czech Republic).

43. A.E. Järvinen, A. Bruncrona, D. Jordan, A. Kit, A. Niemelä, L. Acerbi, U. Braga-Neto, G.L. Derks, M. Dunne, I. Farcas, L. Frassinetti, T. Görler, D.R. Hatch, V. Menkovski, M. Minkowski, H. Nyström, Y.R.J. Poels, S. Saarelma, J. Schmidt, C. Stephens, S. Särkkä, S. Wiesen, L. Zanisi, ASDEX Upgrade Team, and JET Contributors, Developing machine learning facilitated pedestal models, 33rd ITPA Transport and Confinement Topical Group Meeting in Naka, Japan, 30 September – 3 October 2024

44. Z. Chen. Suppression of long-range helium migration in high-entropy alloys. NuMat 2024: The Nuclear Materials Conference Presentation, Singapore, 14-17 October 2024

45. Nima Fakhrayi Mofrad, Juri Romazanov, Andrea Sand, "Computational analysis of plasma-wall interactions: A detailed study of physical and chemically assisted physical sputtering, NuMat 2024: The Nuclear Materials Conference Presentation, Singapore, 14-17 October 2024

46. N. Vianello, M. Wischmeier, M. Baruzzo, A. Hakola, D. Keeling, B. Labit, E. Tsitrone on behalf of the EUROFusion Tokamak Exploitation Team, The EUROfusion Tokamak Exploitation Program in support of ITER and DEMO, 8th Asia-Pacific Conference on Plasma Physics, 04 – 08 November 2024.

47. S. Saari, A. Hakola, J. Karhunen, A. E. Järvinen, J. Likonen, C. Baumann, H. Kumpulainen, J. Romazanov, M. Balden, K. Krieger, ASDEX Upgrade Team, EUROfusion Tokamak Exploitation Team, Modelling marker erosion at the divertor, Conference on Plasma Physics, 04 – 08 November 2024.

12.3 Research reports

1. J. Likonen and T. Lyytinen (eds.), FinnFusion Yearbook 2023, VTT Technology 427 (2024).

2. V.-D. Truong, “RM-T.01.01 - Technical Report for Development of In-Bioshield Maintenance Equipment” (EFDA_D_2RM2C5)

3. V.-D. Truong, “RM-T.01.01 - Deliverable Report for Development of In-Bioshield Maintenance Equipment” (EFDA_D_2QNSX8)

4. A. Hakola, T. Lyytinen (Eds.), ECO-Fusion: Finnish Ecosystem for Industrial Fusion Technology, VTT Technology Report, 2024.

5. T. Hakkarainen, T. Korhonen and N. Verma, Fire accident analyses in DEMO plant focusing on cryostat, Deliverable SAE.S-04.03-T004-D004 (EFDA_D_2RN7XB)

12.4 Academic theses

1. Tomi Vuoriheimo, Irradiation-induced defects and hydrogen retention in fusion reactor plasma-facing materials, PhD thesis, University of Helsinki, 2024.
2. Riccardo Iorio, Particle scattering in magnetized plasmas: a theoretical and numerical approach, PhD thesis, Aalto University, Espoo, 2024.
3. Henri Kuivasniemi, Two-point model and OEDGE simulations of the scrape-off layer for attached JET-ILW L-mode plasmas, B.Sc. thesis, Aalto University, Espoo, 2024.
4. Samuli Saari, ERO2.0 modelling of divertor marker erosion in ASDEX Upgrade L-mode experiments, M.Sc. thesis, Aalto University, 2024.

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Title	**FinnFusion Yearbook 2024**
Author(s)	Tommi Lyytinen and Jari Likonen (Eds.)
Abstract	This Yearbook summarises the 2024 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. The members of FinnFusion are VTT Technical Research Centre of Finland Ltd., Aalto University, Comatec Ltd., CSC - IT Center for Science Ltd., EOS Finland Ltd., Fortum Power and Heat Ltd., Lappeenranta-Lahti University of Technology, Luvata Ltd., Platom Ltd., Tampere University, University of Helsinki and Åbo Akademi. FinnFusion participates in several EUROfusion work packages, the largest being remote maintenance, advanced computing, materials research, plasma-facing components and experimental campaigns at ASDEX Upgrade and related analyses also at JET. F4E projects in 2024 focused on the development of 3D machine vision, HLCS modules and GENROBOT at DPT2. In addition, DigiValve development continued under the same grant. EUROfusion supports post-graduate training through the Education work package that allowed FinnFusion to partly fund 39 PhD students in FinnFusion member organizations. In addition, one EUROfusion Researcher and Engineering Grant was running in 2024. The FinnFusion annual seminar 2024 was organised by the University of Helsinki at both Downtown and Kumpula campuses in May 2024. This seminar was the first one "FinnFusion only" annual seminar since 2018 as we have had two Nordic Joint seminars and one combined with Business Finland SMR and Decommissioning Ecosystem seminar in between.
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Nimeke	**FinnFusion vuosikirja 2024**
Tekijä(t)	Tommi Lyytinen ja Jari Likonen (toim.)
Tiivistelmä	Tähän vuosikirjaan on koottu FinnFusion-konsortion vuoden 2024 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, Platom Oy, Tampereen yliopisto ja Åbo Akademi. FinnFusion-konsortio osallistuu useisiin EUROfusion-projekteihin. Suurin työpanos kohdistuu etäkäsittelyyn, kehittyneen tietojenkäsittelyn keskukseen, materiaalitutkimukseen, ensiseinämäkomponentteihin ja ASDEX Upgrade -koelaitteissa tehtäviin kokeisiin ja analyyseihin myös JET-koelaitteissa. 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 39 jatko-opiskelijan työtä jäsenorganisaatioissaan. Lisäksi vuoden 2024 aikana oli käynnissä yksi EUROfusionin rahoittama tutkijatohtorin projekti. Helsingin yliopisto järjesti fuusioalan vuosiseminaarin sekä Keskusta- että Kumpulan kampuksella toukokuussa 2024. Tämä vuosiseminaari oli ensimmäinen "FinnFusion only" seminaari v. 2018 jälkeen sillä sen jälkeen on järjestetty kaksi yhteispohjoismaista vuosiseminaaria ja v. 2022 vuosiseminaari yhdistettiin Business Finland:n SMR ja Decommissioning ekosysteemien seminaariin.
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