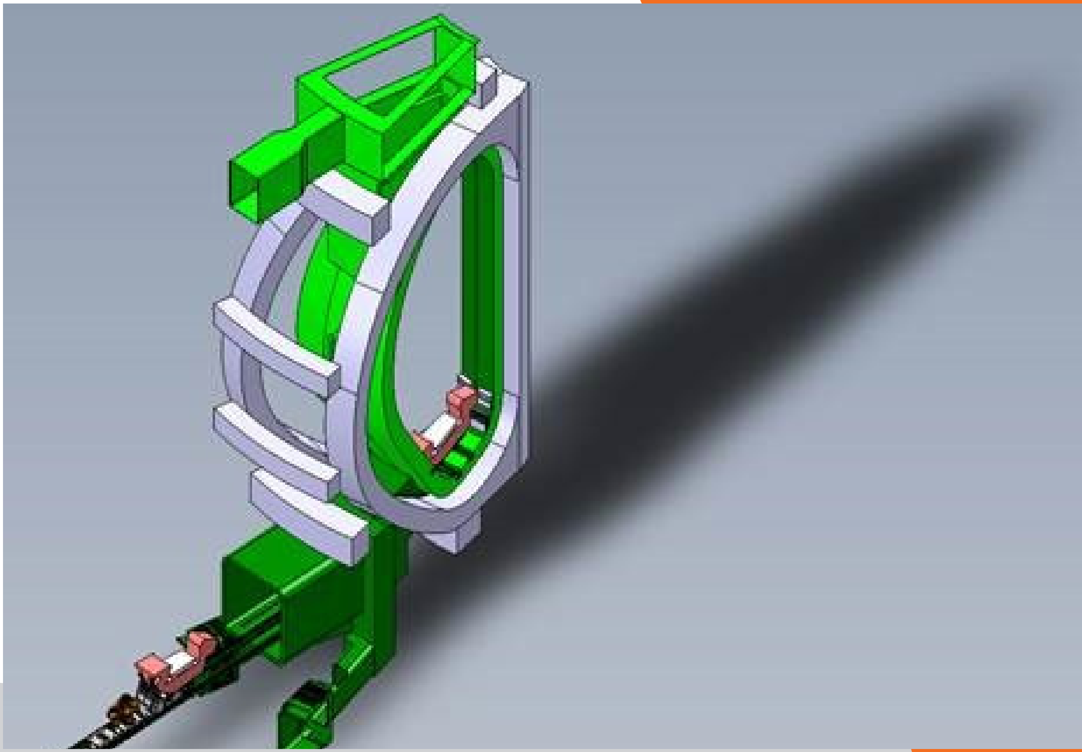

FinnFusion Yearbook 2022

Anu Kirjasuo | Jari Likonen (Eds.) |

VTT TECHNOLOGY 419

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VTT Technical Research Centre of Finland Ltd

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PunaMusta Oy, Helsinki 2023

Preface

Year 2022 can be considered as one of the most successful ones in fusion research in terms of various new fusion records. The most remarkable one was the new fusion energy production record of 59 MJ in JET DT campaign which was announced and published in February 2022 (the actual experiment took place in December 2021). In the record JET pulse, a total of 100 μg of tritium and 70 μg of deuterium was spent to generate 59 MJ of energy. The comparison to produce the same amount with fossil fuels would mean spending for example 1.06 kg of natural gas or 3.9 kg of lignite coal, resulting roughly a factor of 10 million in fuel mass ratio between the fusion fuel and fossil fuels.

Another fantastic record in its “laser-fusion class” took place in December at the National Ignition Facility (NIF) of Lawrence Livermore National Laboratory in California. They demonstrated so-called breakeven in their facility, i.e., obtained more heat out of the fusion reaction than was needed to start it. Achieving $Q > 1$ (producing thermal net energy) is a world-first and a landmark achievement in fusion. NIF did this by firing an intense laser pulse onto a frozen pellet of fusion fuel the size of a peppercorn, so that it compresses the pellet to the pressure and temperature necessary for fusion. One more fusion record was achieved in the ST40 tokamak at Tokamak Energy Ltd in Milton, UK, where they achieved more than 100 million degrees temperature, which is highest ever achieved in spherical tokamak geometry. Spherical tokamak is one of concepts that the private fusion enterprises are pushing toward a reactor scale.

There was a great media event in JET in Culham, UK, in early February to announce the new fusion energy record results. Worldwide in total 5218 news articles in 117 countries were published, and some 20 news and comprehensive articles were also published in Finnish media. I had the pleasure to represent the EUROfusion consortium when His Royal Highness, Prince of Wales, Prince Charles (recently crowned as King Charles), visited JET a week before the media event in February 2022. I explained to Prince of Wales that JET has played and is still playing a very important role for smaller European countries, which do not have a fusion device of their own, to have hands-on experience on fusion research and educate the new generation of scientists and engineers.

News from ITER is not only positive. The magnet program has been very successful as most of the toroidal field coils have been delivered, and the poloidal field coils are also almost complete. The magnets were thought to be one of the most challenging components in ITER, but it has turned out that building vacuum vessel sectors is on the critical path instead. The present Korean vacuum vessel sectors already delivered to the ITER site have non-conformity issues, and in addition, the thermal shields will have to be repaired, both these repairs taking more than a year. Furthermore, Europe/F4E is just about to deliver its first vacuum vessel sector with a delay from the original plan. ITER Council has also nominated a new director, Pietro Barabaschi, who came from F4E.

EUROfusion organised a political event, Horizon EUROfusion, to launch the work program in this framework programme 2021-2027 in Brussels on 4th of July. Several talks were given by the politicians acting in Brussels and the leaders of EUROfusion Consortium. Finland’s fusion program, FinnFusion, also received significant visibility, as I was invited to give a talk on “the History of Fusion Research in Finland” in the event. The scope of the talk was to demonstrate that both the birth of Association Euratom-Tekes in 1995 after having joined Euratom in 1995, and the birth of EUROfusion in 2014, have each become a very significant and distinct landmark in Finnish fusion research by all metrics. It is easy to state that Euratom and EUROfusion have given the form for the present Finnish fusion programme. One new aspect in EUROfusion, and also in FinnFusion, has been the work of “The Working Group Licensing for Fusion” (WGLF) that has a mandate to recommend the first principles of regulation adapted to a fusion facility in Europe. WGLF worked through 2022 and delivered early 2023 a report that will enable EUROfusion to contribute to the debate on the safety regulation of Fusion Power Plants (FPPs). From FinnFusion, Markus Airila is an active nominated member in that working group. Licencing of various future fusion DEMO and pilot plants has become an active and acute issue to be solved urgently, and some countries have already developed policies and legislation on how to licence a future fusion reactor practically and safely. It is evident that the licencing procedures should be much simpler than those of fission power plants.

The FinnFusion annual seminar 2022 was coupled with two other Nuclear Ecosystems (SMRs and Decommissioning) in an event called Nuclear Energy Ecosystems’ Open Business Day 2022. The event was organized by VTT in co-operation with FinNuclear and jointly funded by Business Finland co-innovation projects EcoSMR, dECOmm, ECO-Fusion and orchestration project FINUELS. The keynote speakers on the fusion side were Tony Donne, Program Manager of EUROfusion, Tim Luce, ITER Head of Operation Department, and Ana Belen, the Spanish ILO. This face-to-face event brought together companies interested in building nuclear energy business together. There were lively discussions on nuclear energy collaboration, co-innovation and business opportunities in Nordic countries, Europe and beyond among around 150 participants. The second day had the traditional FinnFusion annual seminar program.

With a great prospect for fusion thanks to all the great new fusion records, and with the fast-growing interest by the private sector on fusion energy, we are all enthusiastically looking ahead to year 2023, with the curiosity on the new opportunities and development it may bring to us.

Tuomas Tala

Tuomas Tala
Head of Research Unit
FinnFusion Consortium

Contents

List of acronyms and names

ACH	Advanced computing hub, hosted by UH
ADC	Alternative divertor configurations
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)
BB	Breeding blanket
BOP	Balance-of-plant
CCFE	Culham Centre for Fusion Energy
CFC	Carbon fibre composite
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
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)
FILD	Fast-ion loss detector
FP9	EUROfusion European Framework Program 9
FPP	Fusion power plant
GPU	Graphics Processing Unit
HCPB	Helium Cooled Pebble Bed
HEA	High entropy alloy
HHFM	High heat flux materials
HLCS	High level control system
HPC	High-performance computing
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 strong 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 30 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.

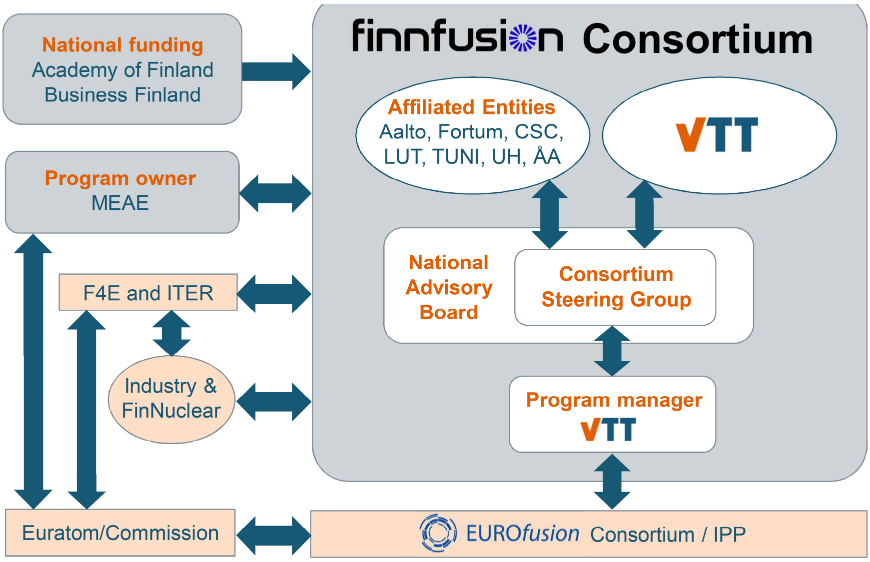


Figure 1.1. Organigram of Finnish Fusion Research Community in 2021–2025.

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 Dr. Tuomas Tala from VTT. The following institutes and universities participated in 2022:

VTT Tech. Research Centre of Finland

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

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

Activities: Materials modelling
Members: MSc. Timo Avikainen, Dr. Andris Freimanis, Dr. Anssi Laukkanen, MSc. Lassi Linnala, Ms. Johanna Lukin, Dr. Sami Majaniemi, Dr. Tatu Pinomaa, MSc. Rami Pohja, MSc. Tomi Suhonen

Activities: Hot cell analyses and experimental materials research
Members: MSc. Jouni Alhainen, MSc. Brahim Dif, Dr. Janne Heikinheimo, Mr. Jorma Hietikko, Mr. Mika Jokipii, MSc. Petteri Lappalainen, Mr. Jussi Leporanta, Mr. Kimmo Rämö, Mr. Jarmo Saarinen, Mr. Pekka Sinkkonen

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

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

Activities: Fire safety
Members: Dr. Tuula Hakkarainen, Dr. Timo Korhonen, MSc. Alexandra Viitanen

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

Activities: Remote maintenance
Members: MSc. Jarmo Alanen, Dr. William Brace, MSc. Kim Calonius, MSc. Jari Halme, MSc. Mika Hakkarainen, MSc. Tatu Harviainen, Jouko Heikkilä, MSc. Jani Hietala, MSc. Tero Jokinen, MSc. Petri

Kaarmila, MSc. Daniel Kaartinen, MSc. Kalle Kanervo, MSc. Kai Katajamäki, MSc. Pekka Kilpeläinen, MSc. Otto Korkalo, Lic. Tech. Jukka Koskinen, Dr. Marja Liinasuo, MSc. Janne Lyytinen, MSc. Timo Malm, MSc. Hannu Martikainen, MSc.Teemu Mätäsniemi, MSc. Matti Okkonen, Dr. Cheng Yuan Peng, MSc. Kari Rainio, MSc. Olli Rantanen, Msc. Kalle Raunio, Dr. Olli Saarela, MSc. Hannu Saarinen, MSc. Qais Saifi, MSc. Tuisku-Tuuli Salonen, MSc. Janne Sarsama, MSc. Teemu Sipola, MSc. Mika Siren, Lic.Tech. Mikko Siuko, MSc. Esko Strömmer, MSc. Mikko Tahkola, MSc. Antti Tanskanen, MSc. Petri Tikka, Msc. Van Dung Truong, Msc. Tapio Vaarala, MSc.Tero Välisalo, MSc. Arto Ylisaukko-oja

Aalto University (AU)

School for Engineering, Department of Mechanical Engineering

Activities: Physics
Members: Dr. Eero Hirvijoki

School for Science, Department of Applied Physics

Activities: Physics
Members: Prof. Mathias Groth (Group Leader), MSc. Francis Albert, Dr. Ray Chandra, MSc. Riccardo Iorio, Dr. Eero Hirvijoki, Dr. Andreas Holm, Dr. Timo Kiviniemi, MSc. Joona Kontula, MSc. Henri Kumpulainen, Dr. Taina Kurki-Suonio, Dr. Susan Leerink, MSc. Roni Mäenpää, MSc. Patrik Ollus, MSc. David Rees, Dr. Lucia Sanchis, Dr. Seppo Sipilä, Dr. Antti Snicker, MSc. Vladimir Solokha, MSc. Filippo Zonta, Suvi Niemelä (admin. support)

Students: Otso Hyvärinen, Petteri Lehti, Tommi Lyytinen (University of Jyväskylä), Luukas Myllynen, Heikki Simojoki, Vesa-Pekka Rikala, Pyry Virtanen

Activities: Materials physics
Members: Sara Bouarich (admin support), MSc. Ludovico Caveglia Curtil, Msc. Evgeniia Ponomareva, MSc. Rafael Nuñez, MSc. Iina Saunamäki, 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
Members: MSc. Qingfei Han, Prof. Heikki Handroos, Dr. Amin Hekmatmanesh, Dr. Changyang Li, Msc. Dongyi Li, Dr. Ming Li, BSc. Jesse Myller, MSc. Nikola Petikov, Dr. Guodong Qing, MSc. Qi Wang, Docent Huapeng Wu (Project manager), MSc. Zhixing Yao, MSc. Ruochen Yin

Tampere University (TUNI)

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

University of Helsinki (UH)

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

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

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
	Anna Kalliomäki, Academy of Finland
	Anssi Paalanen, Business Finland
	Veikko Puumala, Comatec
	Pilvi Ylander, EOS Electro-Optical Systems Finland
	Megumi Asano-Ulmonen, FinNuclear
	Harri Sairiala, Fluiconnecto
	Jaakko Ylätalo, Fortum
	Arto Timperi, IM Intelligent Machines
	Olli Naukkarinen, Luvata
	Sami Kiviluoto, Platom
	Juha-Matti Liukkonen, Reaktor
	Mika Korhonen, Suisto Engineering
	Timo Haapalehto, MEAE
	Jarmo Lehtonen, Tevolokomo
	Karoliina Salminen, VTT
FinnFusion Steering Group	*Mathias Groth, Aalto*
	Janne Ignatius, CSC
	Jaakko Ylätalo, Fortum
	Kai Nordlund, UH
	Heikki Handroos, LUT
	Jouni Mattila, TUNI
	Tommi Nyman, VTT
	Jan Westerholm, ÅA
Co-ordinator	Tuomas Tala, VTT
Secretary	Markus Airila, VTT

The FinnFusion advisory board had two meetings in 2022, April 28th at VTT Centre for Nuclear Safety, Espoo and December 8th at VTT, Visiokatu 4, Tampere.

1.5 Finnish members in the European Fusion Committees

1.5.1 Euratom Programme Committee, Fusion configuration

- Timo Haapalehto, MEAE

1.5.2 EUROfusion General Assembly

- Tuomas Tala, VTT

1.5.3 EUROfusion Scientific and Technical Advisory Committee

- Kai Nordlund, UH

1.5.4 EUROfusion HPC Allocation Committee

- Susan Leerink, AU
- Andrea Sand, AU

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 2022

- Markus Airila is the VTT representative in EUROfusion Communications Network (FuseCOM).
- Megumi Asano-Ulmonen is an Industrial Liaison Officer (ILO) for F4E.
- Flyura Djurabekova is the member of the international committees of the REI (Radiation Effects in Solids), ICACS (International Conference on Atomic Collisions in Solids), SHIM (Swift Heavy Ions in Matter) conferences, and PISC (Permanent International Scientific Committee) of ISDEIV (International Symposia on Discharges and Electrical Insulation in Vacuum) as well as one of the key members of the international committee of the Mechanisms of Vacuum Arcs (MeVArc) workshop series.
- Mathias Groth is a member of the programme committee of the Plasma Surface Interaction Conference (PSI) 2013-2022.

- Antti Hakola is a member of the programme committee for the EPS Conference on Plasma Physics 2023 and a member of the ITPA expert group on divertor and scrape-off layer.
- Timo Kiviniemi is a member of Scientific Users Selection Panel for HPC-Europa3.
- Taina Kurki-Suonio is the vice chair of the ESFRI energy SWG, and a member of the *Nuclear Fusion* Editorial Board, of the programme committee for the 17th IAEA Technical Meeting on Energetic Particles and Theory of Plasma Instabilities in Magnetic Confinement Fusion, of the scientific programme committee of the 19th European Fusion Theory Conference, and of the Scientific Advisory Committee for the 11th ITER International School.
- 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.
- 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.
- Arto Timperi is a member of the Fusion Industry Innovation Forum Management Board (FIIF MB) and the DEMO stakeholders’ group.
- Huapeng Wu has been appointed as a guest editor for MDPI Applied Sciences special issue “Remote handling techniques and applications”.

2. Fusion Science Workprogramme 2022

2.1 WP AC: Code development for integrated modelling

Research scientists:	M.Sc. Bruno Cattelan, Dr. Laurent Chôné, Dr. Fredric Granberg, Prof. Keijo Heljanko, Fran Jurinec, M.Sc. Oskar Lappi, Dr. Ilari Maarala, Prof. Kai Nordlund, Prof. Jukka Nurminen, Dr. Umberto Simola, UH Dr. Jan Åström, CSC Dr. Aaro Järvinen, VTT

In the Advanced Computing Hub (ACH) project, the tasks on 7 TSVVs, 1 MAT project and 1 ENR project were either started, continued, or finalized in 2022. The project started in mid-2021 and has continued in 2022 to support TSVVs and also other projects within EUROfusion. Our main topics are HPC-optimization, GPU enabling, AI utilization, data management, and Uncertainty Quantification. The project encompassed 6 ppy in 2022, meaning that there has been a quite large effort on this front, leading to several successful finalized projects as well as many ongoing projects.

The highlights of the completed tasks are the optimization and parallelization of MIGRANe and a new solver for DREAM. MIGRANe was first optimized to be approximately three times faster than before and the code was also parallelized, so that by utilizing many CPUs, the speed-up can be on the order of thousands easily, compared to the initial code. In the DREAM code a problem with the current solver was recognized, and within the ACH and collaborators a quadruple precision solver was found to solve the problem. In addition, the new solver was GPU enabled, making it more efficient for the use in the future.

During 2022 efforts have been placed on; utilizing AI in materials physics to determine defect formation energies; efficient data compression; general code-optimization and -correction; setup on Continuous Integration/Continuous Delivery (CI/CD); developing a testbed for future development of EIRENE. In addition to these the use of Bayesian Optimization to find optimal parameters for simulations has proven to be very efficient. Another large effort for us, that was started in 2022, was to provide a proof-of-concept solution for ML data processing, storage and access. This will be of outmost importance for future AI/ML techniques to be able to gather the needed data for the training.

2.2 WP TSVV: Theory-Simulation-Verification-Validation

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

Research scientists: L. Chôné, UH

As part of TSVV task 4, development of the particle-in-finite element code SymPiFE is ongoing. SymPiFE is solving the Vlasov-Maxwell system using geometric integration methods guarantying that the numerical solution faithfully captures fundamental aspects of the underlying model, such as conservation of energy and charge which remain bounded over simulation time. At the present stage, development is concentrated on enriching the set of relevant features of SymPiFE, as well as improving parallelisation. At present, SymPiFE is parallelised on distributed memory, and shows excellent scaling on CPU machines (see Figure 2.1). Parallelisation on shared memory (including GPU) is ongoing.

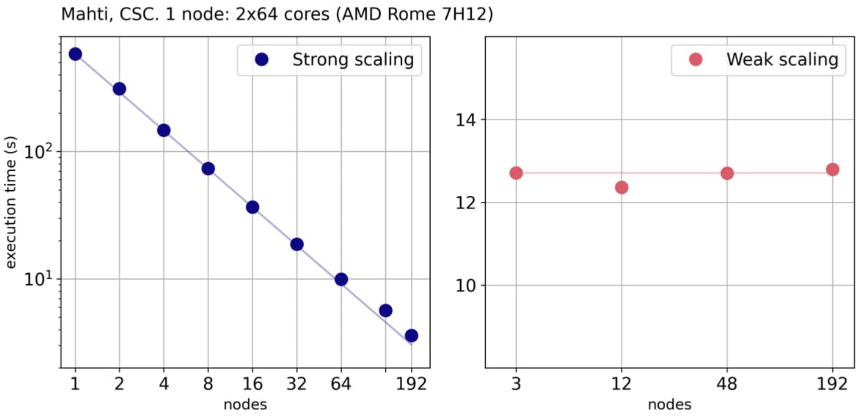


Figure 2.1: SymPiFE scaling on CPU machines.

2.2.2 TSVV Task 5 Neutral Gas Dynamics in the Edge

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

Divertor plasmas span a wide range of temperatures and densities, ranging from hot and tenuous plasmas, which achieve coronal equilibrium, to cold and dense plasmas, which may achieve local thermal equilibrium. Thus, modelling plasma processes in the divertor necessitating collisional-radiative (CR) modelling of the plasma species, which can accurately predict the plasma state populations throughout the relevant range of plasma density and temperature. The applied CR modelling considers a large set of species, states, and reactions and calculates effective rates for a smaller subset of species. The model accuracy and applicability dependent on atomic and molecular data included in the model: no unified CR model exists, as the relevant processes vary locally depending on the plasma conditions. Furthermore, CR models are inherently 0D and do not include transport effects on the local quasi-steady equilibrium of the plasma states. Kinetic neutral EIRENE simulations, individually following the different vibrationally excited hydrogen molecular states, were compared to YACORA CR simulations to assess the role of transport of excited states on the plasma conditions in fusion-relevant plasmas. The results indicated that transport effects may become significant under detached divertor conditions, the prospective operational regime for future fusion power plants. The effect could, however, not be evaluated due to the scarcity of the available molecular data in EIRENE. The work highlights the need to combine CR and kinetic neutral transport models explicitly, to correctly evaluate transport effects.

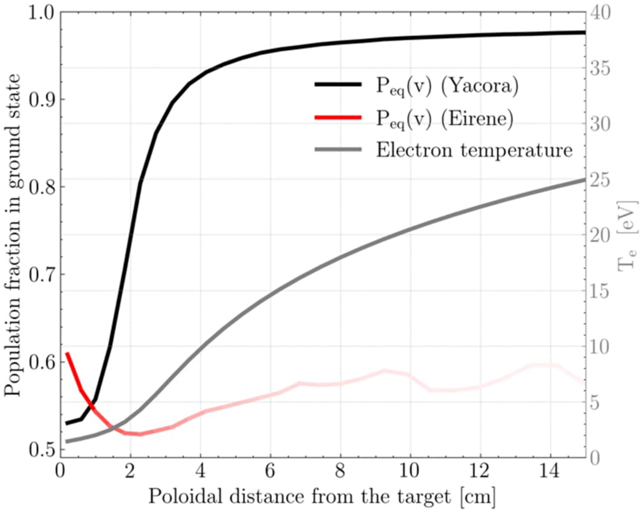


Figure 2.2: Fraction of H_2 molecules in ground state as calculated by Yacora (black) and Eirene (red) as function of poloidal distance from target plate. The electron temperature is given by the grey line and the right-hand y-axis. (From A. Holm et al., Contr. Plasma Phys., 2022.)

2.2.3 TSVV Task 6 Impurity Sources, Transport, and Screening

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

A combination of predictive edge and core simulations of tungsten (W) erosion and transport in JET-ILW plasmas ranging from L-mode to the highest-performance type-I ELMy H-mode scenarios, using the JINTRAC and ERO2.0 codes, consistently predict the experimentally inferred W density in the main plasma, within the combined uncertainty due to the uncertainty in the measurements of the deuterium plasma conditions and W content in the plasma. The simulation workflow consists of three main steps: 1) validation of the simulated background plasma conditions in each phase of the ELM cycle, 2) predictive ERO2.0 modelling of W erosion and edge transport, and 3) predictive modelling of W core transport using JINTRAC with NEO for neoclassical transport and a W boundary condition predicted by ERO2.0.

ERO2.0 predicts nearly complete screening of the largest gross W erosion sources at both divertor targets. Instead, the predicted W influx to the main plasma is mostly due to erosion by charge-exchange (CX) fuel atoms near the low-field side divertor entrance. Unlike earlier ERO2.0 modelling, which assumed a Maxwellian energy distribution of CX atoms, energy spectra predicted by kinetic EIRENE simulations were taken as the impact energy of the CX atoms at each surface location.

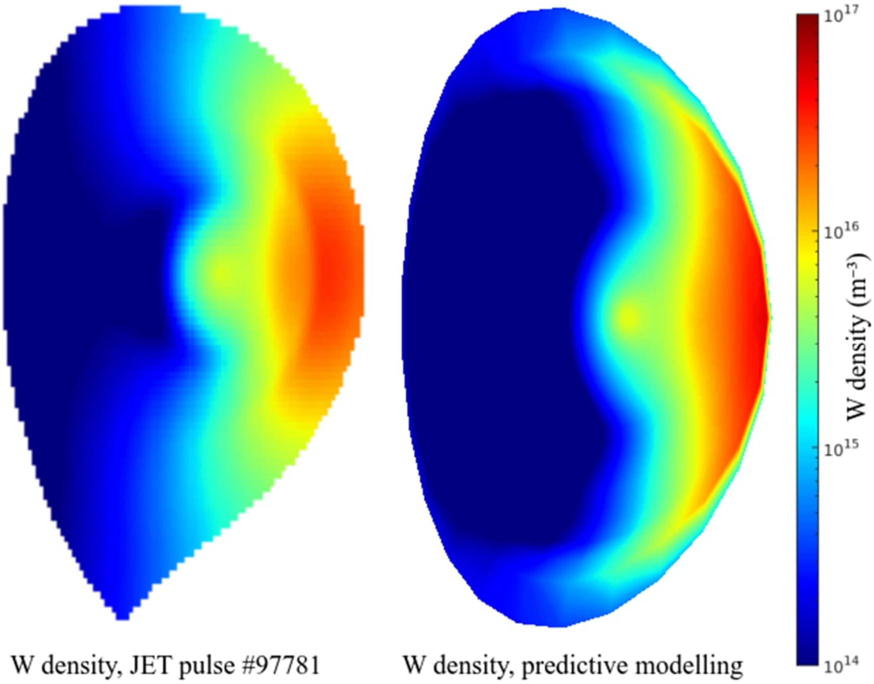


Figure 2.3: Measured (a) and JINTRAC-ERO2.0 predicted (b) W density in JET ELMy H-mode plasmas (from H. Kumpulainen et al., Nuclear Materials and Energy, 2022.)

Both the ERO2.0 and NEO simulations quantitatively reproduce the observed poloidal W asymmetry on the closed flux surfaces, driven mainly by the centrifugal effect due to toroidal plasma rotation (see Figure 2.3). TSVV task 6 includes the implementation and first ERO2.0 predictions with the centrifugal effect.

2.2.4 TSVV Task 7 Plasma-Wall Interaction in DEMO

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

The work is focusing on the sputtering of tungsten (W) surfaces under irradiation conditions in coming fusion power plants. The main topic of our project is to focus on the effect of deuterium (D) on the surface of tungsten and how it affects the sputtering of tungsten and the sputtering of the embedded deuterium. We have in 2022 looked at the sputtering of pure tungsten surfaces as well as tungsten surfaces with different concentrations of deuterium on the surface and in the surface layers. These surfaces were bombarded with different energy D and D_2 ions/molecules, and the W- and D-sputtering yields and D backscattering yields were determined. We found, as expected, that the energy affects all the parameters, and also that the D_2 sputtering was similar to that of two individual D ions. This is what is experimentally assumed, as D_2 is easier to handle. We also investigated different incoming angles to determine the effect, see Figure 2.4.

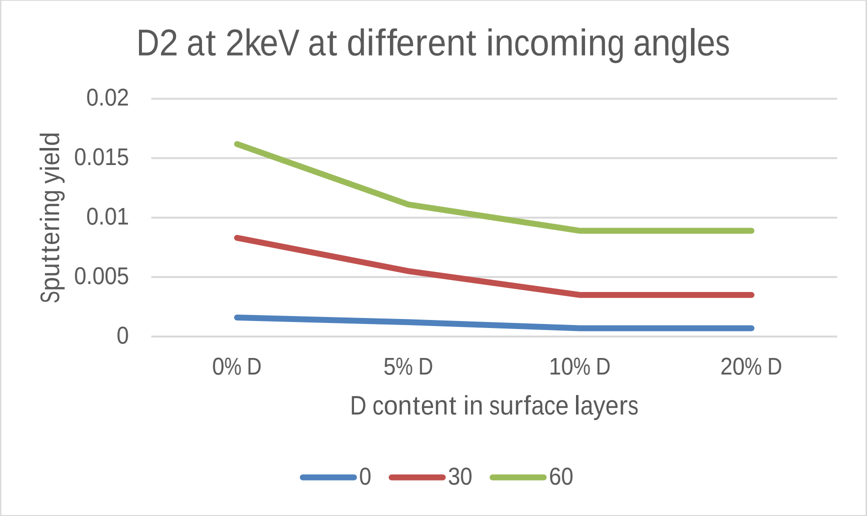


Figure 2.4: Impact of incoming angles on sputtering of D_2 ions.

We found that deuterium in the top layers will affect the sputtering, but not the reflection as much. The results at three different incoming angles for four levels on D concentration in the surface layers is seen in the figure. The more deuterium we have in the top layers the lower the sputtering was observed. In addition to the previous found results, we did also find out that the normally used simulations cells and approximations might not be so true for light ions like H and D, and we have started to look into this in more detail.

2.2.5 TSVV Task 12 Stellarator optimization

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

Code development related to ASCOT5 was pursued on two fronts: IMASifying and GPU performance-portability: In this work the ITER IMAS data structure was supplemented to accommodate specific stellarator specific features. The IMAS data structure is very flexible, and thus a convention is needed to fix a specific set of fields needed to interface fast ion codes with VMEC. Such a convention was prototyped in collaboration with an ACH. The IMAS data format is originally envisaged for 2D magnetic fields only. ASCOT5 can now take as input the magnetic field in the prototype convention as well as the 3D wall using the SMITER convention. Other ASCOT5 inputs have been previously implemented for ASCOT4 and ASCOT3 and porting them to ASCOT5 should be relatively straightforward.

The work on GPU support in ASCOT5 has concentrated on finding ways to make the code simultaneously portable and performant in multiple hardware platforms and compilers. The portability using the OpenMP offloading is in principle perfect, but unfortunately the different implementations require different choices for maximum performance. Furthermore, the performance for ASCOT5-GPU is good for some platforms, mainly Marconi-fusion. However, for most compilers the achieved performance has been so far insufficient to justify large-scale modifications to ASCOT5. Such changes are expected next year.

2.3 WP ENR: Enabling Research

FinnFusion participated in six Enabling Research projects in 2022:

- ENR-MAT.01.JSI: Detection of defects and hydrogen by ion beam analysis in channelling mode for fusion
- ENR-MAT.01.VR: Electronic interactions of slow ions and their influence on defect formation & sputter yields for plasma-facing components
- ENR-MOD.01.FZJ: Development of machine learning methods and integration of surrogate model predictor schemes for plasma-exhaust and PWI in fusion / Development of machine learning algorithms for data-driven pedestal models

- ENR-TEC.01.MPG: Novel methods for fast-ion tomographic reconstructions: Fast-ion tomography in 5D
- ENR-TEC.04.VTT: Silicon optics steady state magnetic field sensor

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

Research scientists: F. Djurabekova, V. Jantunen, I. Makkonen, T. Ahlgren, K. Mizohata, F. Tuomisto UH

Understanding the interaction of hydrogen with the host lattice of plasma-facing as well as structural materials is crucial since low hydrogen isotope (HI) retention is a stringent prerequisite. This enabling research project is focused on the development of a new characterization technique to explore the influence of structural defects on HI retention and vice versa. As a pilot case, we will study HI interaction with tungsten (W) that is considered as the main candidate for the wall material in future fusion devices. The existing experiments and state-of-the-art theory and modelling can neither satisfactorily describe the interaction of hydrogen with large structural defects in materials, nor consider the possible synergistic effects of the presence of HI on defects and material structure evolution. We combine state-of-the-art methods of HI retention studies with microstructure characterization. The main objective of the project is to set foundation for the evaluation of the interaction of structural defects with HI and the subsequent effect on HI retention and defect creation and evolution. We develop and use a novel ion channelling method – channeling-NRA – at the tandem accelerator laboratory in Ljubljana to characterize the produced structural defects and HI retention. Such an approach enables the direct correlation of the HI retention with the structural defects (from small structural defects, such as vacancies, to large defects such as voids) and determination of the lattice positions of hydrogen atoms around studied structures. Work at UH is focused on multiscale modelling and code development for channelling RBS interpretation, with a contribution to structural characterization by ion beam and positron annihilation techniques.

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

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

In a collaboration between Uppsala University, Aalto University, and TU Wien, we aim to elucidate the impact of electronic effects on energy partitioning from incident slow ions, and in particular on calculations of sputtering yields, to improve the fidelity of model predictions. Sputtering yields of deuterium (D) ions on iron (Fe) have been investigated with full molecular dynamics (MD) simulations.

Preliminary results confirm that the predicted yield is sensitive to the implementation of electronic stopping effects in simulations. A clear dependence on crystal surface orientation was also found, but surface irregularities, such as a step defect, had negligible effect on the yield. The penetration distance of low energy light ions causing sputtering is short, hence effects of local geometry on the instantaneous electronic energy losses of both ion and target atoms are expected to be important. Possible channeling effects on sputtering yields, seen experimentally as a minimum in the angular dependence of the measured sputtering yield at 30 degrees incidence angle, were also investigated with MD-based methods. Results indicate that channeling may occur at 30 degrees incidence angle if the irradiated Fe (bcc) surface has a dominantly <011>-oriented surface structure. These results are in good agreement with recent experiments performed within the project by our colleagues at TU Wien, and indicate the importance of accurately capturing the trajectory-dependence of electronic energy losses.

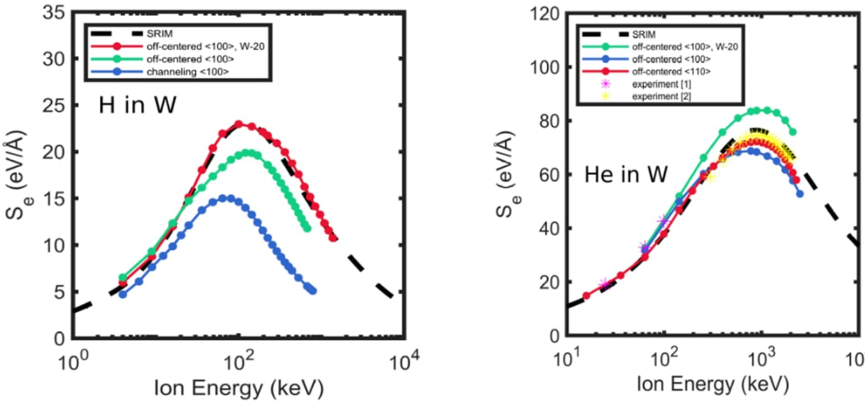


Figure 2.5: Electronic stopping of H and He in W.

To develop a model of local energy losses that can be implemented in MD, we have carried out real-time time-dependent density functional theory (rt-TDDFT) calculations of electronic stopping of H and He ions in pure Fe and W (Figure 2.5), for both channeling and random trajectories. In general, energy losses are higher for trajectories that pass through a higher average electron density, and core electron states contribute to energy losses and hence need to be explicitly accounted for in calculations. Interestingly, for He ions in W, much stronger energy losses are predicted by rt-TDDFT for an off-centered channel trajectory than that given by SRIM. The role of the core electrons in these off-channel trajectories is likely over-predicted, due to an excessive degree of close approach collisions in the simulation set-up. To obtain physically realistic values for the stopping power for direct comparison to experimental values, a method has been developed for sampling trajectories in a manner that reflects the average physical trajectories.

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

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

ENR-MOD.01.FZJ is focused on machine learning (ML) and artificial intelligence (AI) methods in fusion to facilitate predictions for exhaust and plasma-wall interaction (PWI). The team encomppasses more than 10 scientists from Germany, Netherlands, Sweden, and Finland. The project is divided into 4 subprojects (SP). Aaro Järvinen (VTT) is the leader of the SP 2, which is focused on developing ML/AI methods for core-edge integration and pedestal physics using both experimental as well as numerical (EUROPED/EPED [Saarelma et al. *Phys. of Plasmas* 2019, Snyder et al. *Phys. of Plasmas* 2012]) databases for training the models.

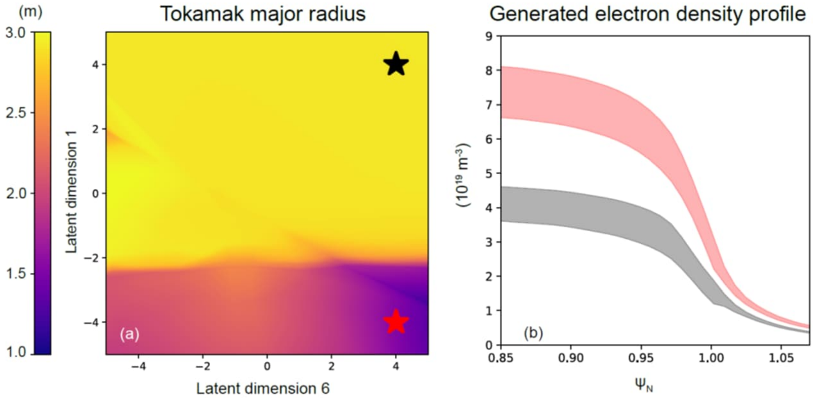


Figure 2.6. Illustration of the learned latent representation for two of latent dimensions and their relation to inferred tokamak major radius (a). (b) Illustration of generated, artifical electron density profiles that represent the latent space locations illustrated with black and red stars (Figure a). [Järvinen et al, Proceed. 4th Int. Conf. Data-Driven Plasma Science 2023]

In 2022, the focus has been on investigating the utility of latent variable based deep learning models for pedestal representation learning from experimental databases [Kit et al. *Nucl. Mat. Eng.* 2023]. A varational autoencoder (VAE) is used to learn a representation of the pedestal electron density, temperature, and pressure profiles in pedestal databases [Kingma and Welling, *ICLR* 2014]. A VAE is a probabilistic generative model that aims to model a dataset as a conditional distribution given a latent variable. In these studies, this is implemented using encoder and decoder distributions, parameterized by convolutional neural networks. Using an auxiliary regression for the machine control parameters and splitting the latent space to control parameter dependent and independent components, as described in the Domain Invariant Variational Autoencoder (DIVA) algorithm [Ilse et al. *MIDL* 2020], the latent representation is regularized to contain the machine control parameter information. Training such an algorithm using JET and AUG databases, the algorithm distentangles the latent representation between JET and AUG sized tokamak devices (Figure 2.6a). The learned representation can be used to generate artificial pedestal plasma profiles (Figure 2.6b).

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

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

During 2022, the ASCOT group contributed to the enabling research project to improve the tomographic reconstructions of fast-ion distributions using experimental data. In detail, the ASCOT code was used to generate the basis functions for the inversion problem. The basis functions consist of several 4D slowing-down functions. The idea is that since this information already has some physics of how each pixel in the 4D phase-space is connected to each other, this basis set would allow the inversion methods to find the solution more easily than the previously used basis functions. In order to run such simulations, python tools have been developed to run multiple ASCOT runs with different particle ensembles. The work continues in 2023 to find the optimal resolution needed for both in terms of the number of basis functions needed and in terms of test markers needed to estimate each slowing-down distribution function.

2.3.5 Silicon optics steady state magnetic field sensor

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

The work on developing the silicon-on-insulator (SOI) based magnetic field sensor has been advancing on multiple fronts. To allow accumulation of the Faraday rotation (as opposed to oscillating) the waveguide must be made of sufficiently isotropic (nearly zero birefringence). Due to the strict tolerance requirements for manufacturing we have set up COMSOL models for the straight waveguide sections of different kinds to gain insights how the birefringence depends on the geometry, material properties, temperature and wavelength of the incoming light (see Figure 2.7).

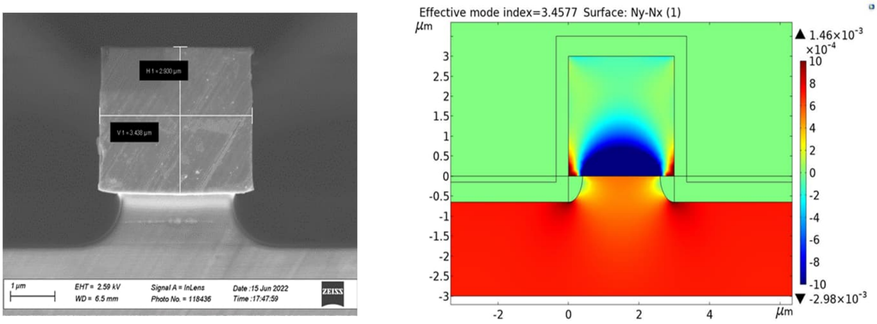


Figure 2.7: Scanning electron microscope (SEM) image of the square-ish waveguide (left) and COMSOL calculated effective index of TE polarized light for a similar waveguide.

These results have confirmed that by wavelength tuning a suitably shaped waveguide can be made with our manufacturing capabilities (±20nm) that essentially yields zero birefringence. We are currently making measurements with and without magnetic field to demonstrate this with 2cm long straight waveguides.

In parallel, we have verified that our design for the polarization splitter (to control the polarization just before the sensor) can yield a broadband attenuation ~15dB across 1500-1600nm wavelength range that is expected to be sufficient for accurate measurements. Furthermore, we have designed and manufactured two different designs for U-turns, that allow coiling the straight waveguide sections into a long and sensitive sensor. They utilise total internal reflection mirrors to make the turns wavelength independent and flip the polarisation either 3Pi on a single turn or use a compensation scheme that results in 2Pi shift over two consecutive turns. Choosing the better design will be done when the integrated circuits are available. So far we have been able to measure that the mirrors in our U-turns have a loss of <0.2dB per mirror allowing hundreds of mirrors to be used for the full sensor before attenuation becomes a problem. While significant progress has been made, there are still many hurdles to overcome before being able to demonstrate the capabilities (stability, accuracy, handling, etc.) of the sensor.

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

2.4.1 Overview

The 2022 scientific programme of WPPWIE concentrated on addressing key research topics in the fields of erosion, deposition, fuel retention, and surface modifications of plasma-facing components (PFCs). A new ingredient was the inclusion of post mortem analyses of PFCs coming from JET onto the agenda while modelling and design work for alternative divertor configurations was to a large extent brought to completion by the end of the year. As in the past, the Finnish focus areas were surface analyses of tokamak (JET, ASDEX Upgrade (AUG), WEST), stellarator (W7-X), and laboratory samples, numerical modelling of different plasma-wall-interaction (PWI) and scrape-off-layer (SOL) phenomena based on experiments carried out on AUG and JET, assessing retention and erosion characteristics of Be- and W-based plasma-facing components, as well as carrying out fluid simulations for alternative divertor configurations.

2.4.2 ADC: Advanced Divertor Solutions for Power Exhaust in DEMO

Research scientists: L. Aho-Mantila, A.E. Järvinen, VTT

Studies on alternative divertor configurations (ADCs) aim to provide a portfolio of potential exhaust solutions and to expand the operational regime of DEMO. Within this work, geometric variations of the conventional, ITER-like single-null (SN) divertor have been investigated. VTT has participated in these activities in 2022 by coordinating the work of the fluid modelling team, simulating the detailed exhaust processes in various DEMO divertor configuration, and analyzing the edge plasma properties in the various divertor configurations.

In 2022, investigation of parametric dependencies in these fluid modelling databases and comparisons to reduced Lengyel model was conducted [Järvinen, et al. Nucl. Mat. En. 2023]. The studies indicate that the Lengyel model overpredicts the necessary argon concentration for divertor detachment by a factor of 5 – 10 relative to the more complete fluid simulations. One of the key reasons for this is that the assumption of heat transport solely via heat conduction in the Lengyel model leads to a strong underprediction of argon radiation in low temperatures around 5 – 15 eV (Figure 2.8). The other transport processes in the more complete fluid models allow expansion of these low temperature regions, enabling significant enhancement of the radiated power for a given argon concentration in the plasma.

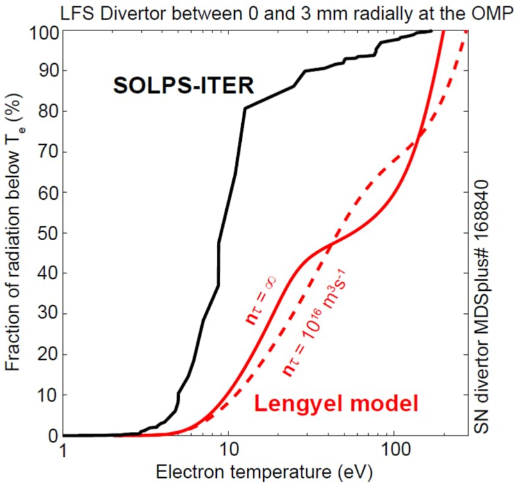


Figure 2.8. Fraction of argon radiated power below a certain electron temperature in the low field side (LFS), near-SOL in one of the SOLPS-ITER simulations and comparison to Lengyel model predictions.

2.4.3 Erosion of W PFCs upon exposure to He plasmas

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

In the field of experimental erosion and material migration studies, the largest share of efforts was put on preparations and analyses for an experiment that was carried out on AUG during its 2-week long helium campaign in July 2022. Here, different marker samples were exposed to L- and H-mode discharges in He using the AUG divertor manipulator to investigate the formation of nanostructures (so-called W fuzz) on them as well as the gross vs. net erosion balance in He (see Figure 2.9). For the latter goal, W-coated graphite samples with small Pt markers on top were applied. First results of the erosion profiles of the W and Pt markers show complete removal of all the layers in the strike-point zone and strong erosion rates, accompanied with the formation of thick co-deposited layers and indications of nanostructure growth on the W surfaces. Both erosion and deposition profiles are much more prominent than in the case of D plasmas.

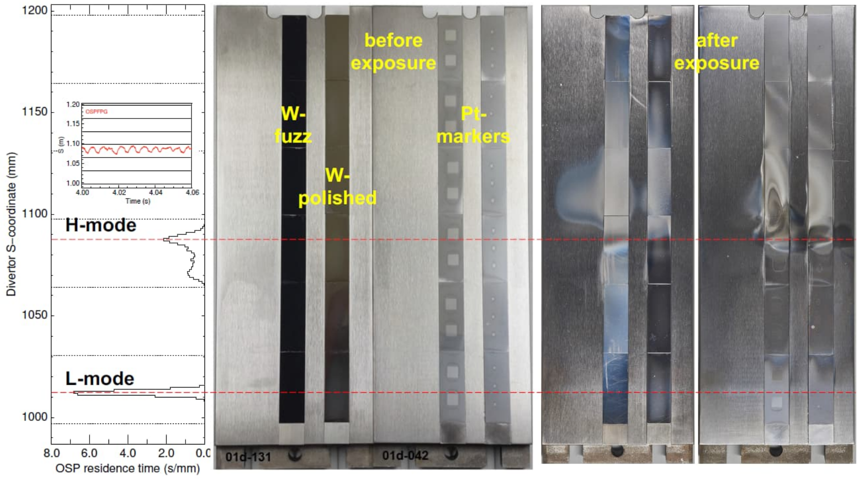


Figure 2.9: Photographs of marker samples (polished W, W with pre-formed fuzz, and Pt markers on W-coated graphite) exposed in a series of L- and H-mode plasma discharges in He on AUG before and after the experiment. On the left the distribution of plasma time on the markers in the L- and H-mode phase is shown.

2.4.4 Plasma-edge and plasma-wall interaction modelling

Research scientists: M. Groth, A. Holm, N. Horsten, H. Kumpulainen, R. Mäenpää, V. Solokha, AU

Comprehensive experimental data analyses and EDGE2D-EIRENE, ERO2.0 Be and W, and standalone EIRENE simulations were performed for JET-ILW and V5/C equilibria in Ohmic, L-mode and H-mode plasmas (pertaining to JET-ILW experiments Ex. 1.1.2, Ex. 3.1.2, Ex. 1.2.5, B15-09, M18-27, M21-15,). As part of these tasks, dedicated plasmas for (interpretative) edge fluid code validation, BeMP, isotope effect, nitrogen (recycling, transport), He, charge-exchange neutral, W sputtering, and ELMs. The isotope effect on the divertor plasma conditions at the low-field side was found to be small for attached conditions. However, tritium plasmas are more strongly detached and exhibit 30% higher divertor densities than hydrogen and deuterium plasmas. In addition, SOLPS-ITER simulations were performed for the L-mode plasmas, including $D+N_2+N$ simulations.

Predictive JINTRAC (EDGE2D-EIRENE) and ERO2.0 W simulations for high-performance H-mode plasmas in corner-corner (tile-3/tile-6 and tile-4/tile-6) configurations (JET-ILW hybrid experiments under M18-02, M21-01) predictive edge fluid code simulations, D vs T, W sputtering, and ELMs.

Dedicated experimental data analyses and OEDGE simulations of RISP (in lieu of EDGE2D-EIRENE) in support of Be migration/fuel retention experiments were conducted under JET experiments M18-30 and M21-27. 2D maps of the electron temperature, electron density and ion parallel-B flow velocity were generated based on the measured target profiles of electron temperature and density for a raised inner strike point divertor plasma configuration (Figure 2.10).

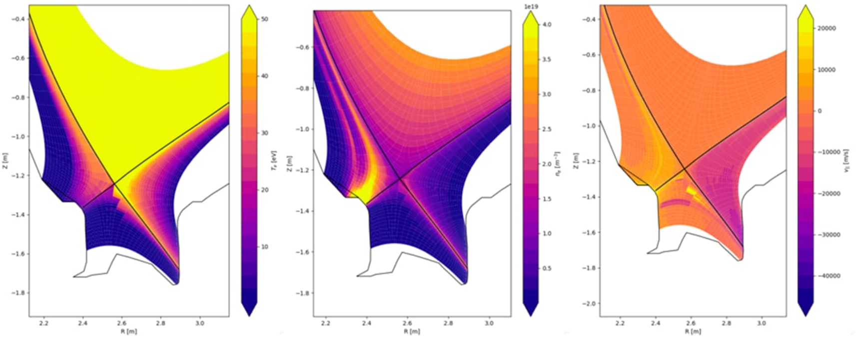


Figure 2.10: (left to right) 2D maps of the OEDGE predicted electron temperature, electron density and ion parallel-B flow velocity for a JET-ILW raised inner strike point divertor plasma configuration.

2.4.5 PWI with Be, T and neutrons: focus on JET post-mortem analysis its interpretation

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

The main aim in 2022 was to continue erosion/deposition and fuel retention studies on the divertor- and wall tiles as well as in-vessel erosion-deposition probes (EDP) exposed either in 2013-2016 or in 2011-2016, and removed during the 2016-2017 shutdown. In addition, comparison with individual campaigns was made to confirm linear/non-linear erosion/deposition. VTT used Secondary Ion Mass Spectrometry (SIMS), Time of Flight Elastic Recoil Detection Analysis (TOF-ERDA) and Thermal Desorption Spectrometry (TDS) for the analysis of divertor and wall components.

During the shutdown in 2009–2011, all the carbon-based plasma-facing components (PFC) were replaced with the ITER-like wall (JET-ILW). The divertor tiles of JET-ILW are made of tungsten-coated carbon fibre composites (CFC), except the load bearing tiles at the divertor base, which are made of solid tungsten. Limiters in the main chamber are manufactured from solid beryllium. JET has now completed three operating periods, ILW-1 (2011-2012), ILW-2 (2013-2014) and ILW-3 (2015-2016), giving an opportunity to make comparisons between tiles exposed for different operating periods.

Figure 2.11 shows SIMS depth profiles measured from a sample cut from the apron of inner divertor tile 14IWG1A exposed in 2011-2016.

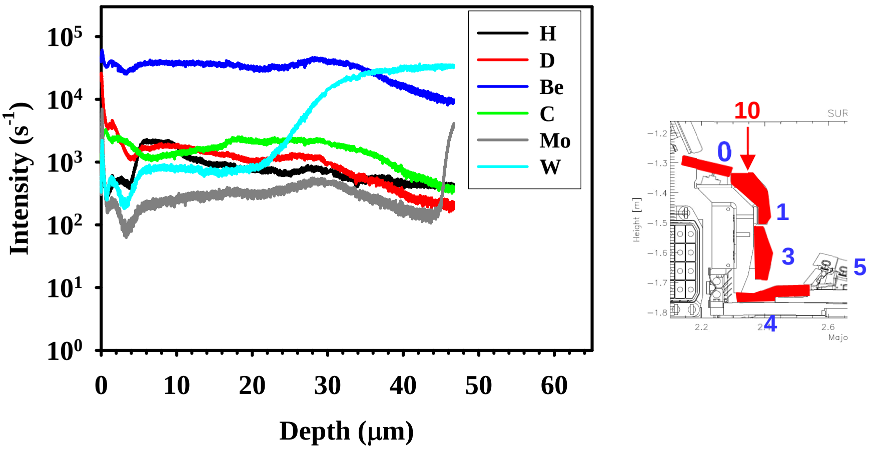


Figure 2.11. SIMS depth profiles for sample 14IWG1A/10 cut from the apron of inner divertor tile 14IWG1A (left) and JET inner divertor (right).

Tile 14IWG1A was coated with ~4 µm of W and ~3 µm of Mo on top of ~12 µm of W (and the thin Mo interlayer) to act as markers to measure the erosion/deposition during ILW campaigns. Depth profiling in Figure 2.11 was stopped at the interface between the Mo and W layers. It can be observed that the co-deposited layer (thickness ~30 µm) contains mainly beryllium in addition to hydrogen isotopes and carbon. The deuterium surface density determined from the SIMS depth profiles is ~2.8x10^{18} cm^{-2}. SIMS estimate for corresponding sample exposed in 2015-2016 is somewhat higher (5.4 x10^{18} cm^{-2}) indicating that deposition on the apron of tile 1 is not necessarily linear, i.e. the thickness of the co-deposited layer and deuterium amount do not increase as a function of the exposure time, but more investigations are required to confirm this observation.

In addition to fuel retention studies, transport to and from one of the Mo only markers (tile 14ING3B - a tile3 from the lower part of the inner divertor wall) to tile 14BNG4D (an innermost base tile4 with a standard Mo + W marker) has been extensively studied using SIMS and TOF-ERDA. Metallic elements are principally eroded by incident plasma ions as atoms or ions and most probably return to the surface a short distance further in the plasma field line direction where they may be eroded again: migration may thus occur by a series of “hops”. After both the ILW1 and the ILW2+3 campaigns significant amounts of Mo had been transferred to tile 14BNG4D and were located towards the top horizontal part of the tile.

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

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

ASCOT has been used to model the distribution function of the beam ions for energetic particle (EP) stability workflow, which will be utilized to study the stability of fast-ion driven modes in JT60-SA. In the past, a 4D distribution function was calculated by ASCOT and then used by the EP stability codes within the workflow as such. This year, based on discussions with the energetic particle modelers, it was decided to improve this workflow so that ASCOT would provide a list of markers sampled from the modelled distribution function. These markers can then be used to form a smooth distribution function using user-defined phase space variables (e.g. constants of motion space, which are used by the stability codes). This allows the calculation of the gradients of the distribution function with much lower statistics for the actual Monte Carlo simulation. The status of the developed tool is such that the ASCOT-calculated 4D distribution function can be sampled with a stand-alone separate program that generates a user-defined number of markers. This all happens in the IMAS infrastructure. The integration to the energetic particle stability workflow is still ongoing.

2.6 WP TE: Tokamak exploitation campaigns

2.6.1 Overview

Within the WPTE Task Force, the work performed on the AUG, TCV, and MAST-U tokamaks was a direct continuation of activities initiated in 2021. A new player in the team was JET from January 2022 onwards and there the most important individual operational periods were the second part of full tritium operations in January-March, the cleaning campaign in March-August, and the helium campaign in September-November. Helium experiments were also carried out on AUG during a period of two weeks in July. Due to various machine issues, no experiments could be done on WEST in 2022, however, the first plasma in the upgraded device was finally obtained just before Christmas. The main activity areas where the Finnish contribution was the most noticeable were studying erosion of plasma-facing components (AUG and JET), modelling of fast ions using the ASCOT code (AUG and MAST-U), as well as investigating particle and momentum transport (AUG and JET) and carrying out detailed camera analyses and numerical modelling for characterizing detachment (AUG, TCV, MAST-U, and JET).

2.6.2 Helium campaigns on AUG and JET

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

Helium campaigns were carried out on AUG and JET to assist ITER in deciding if their non-nuclear operational phases should be carried out in hydrogen or He. On both devices, H-mode operation could be achieved in helium but entering the type-I ELMy regime turned out to be more challenging than in H or D. On JET, the limited neutral-beam heating power (<14 MW) significantly restricted the parameter space of the possible He scenarios and in the end only in one scenario with the plasma current of 1.3 MA and the toroidal field of 1.3 T type-I ELMs were reached. Studies in mixed H/He plasmas showed that the features characteristic for helium emerge already once the He concentration (n_{He}/ne) exceeded 25-30% in the plasma. Transport analyses, for their part, revealed that there are no drastic differences in confinement between He and H, albeit some other changes were recorded such as the more peaked density profiles in He plasmas. In the field of plasma-wall interactions, creation of nanoscale structures (W fuzz) on plasma-facing components was unambiguously demonstrated on AUG (see section Erosion of W PFCs upon exposure to He plasmas) while on JET, no obvious signs of fuzz formation could be identified. The underlying reason may be connected to the strong migration of Be and W in the JET edge plasma, leading to the formation of thick co-deposited layers on the divertor surfaces. Finally, subsequent He→H and H→He changeover experiments were performed, with a combination of Ion Cyclotron Wall Conditioning (ICWC) and tokamak plasmas in varying configurations. The results indicate that the H→He changeover happens faster than the backtransition He→H and that both ICWC and tokamak plasmas are required to ensure the desired H or He plasma purity (see Figure 2.12).

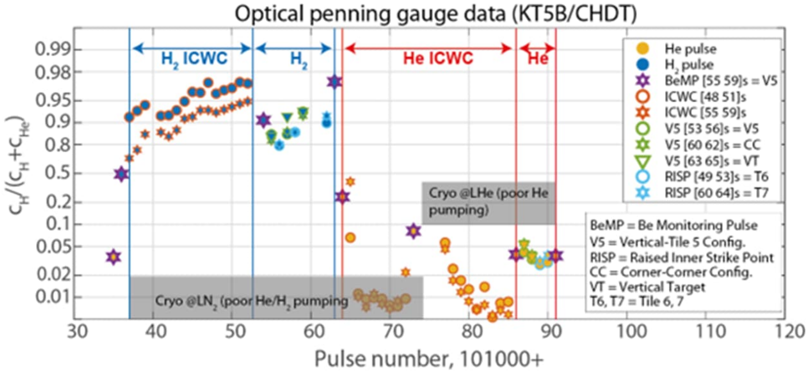


Figure 2.12: Measured H/(H+He) concentration during the He→H and H→He changeover experiments as a function of plasma discharges at JET

2.6.3 Helium detachment experiments in AUG and JET

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

Sets of He detachment experiments in ASDEX Upgrade L-mode and H-mode plasmas and in JET-ILW L-mode plasmas were successfully completed in July 2022 and October 2022, respectively. Due to the lack of NBI power and experimental time, H-mode experiments in JET-ILW were not performed as initially planned. In addition, the Divertor Thomson Scattering diagnostics was unavailable for the experiments in ASDEX Upgrade. The experiments show that the rollover of the ion currents in He plasmas (the sum of He^{+} and He^{++}) occurred at 15-20% lower electron density (as measured in the outer edge of the core plasma) than in otherwise identical hydrogenic plasmas (Figure 2.13). Generally, the recycling fluxes are 3 to 10 times lower in He than in hydrogenic plasmas.

In both ASDEX Upgrade and JET-ILW, the rollover of ion currents to LFS target plates were achieved at high core plasma density, accompanied with the peak radiation to move to X-point region. Similar signatures for onset and formation of detachment in He as in D plasmas. The reduction of $T_{e,OSP}$ below 5 eV coinciding with peak radiation established at X-point region.

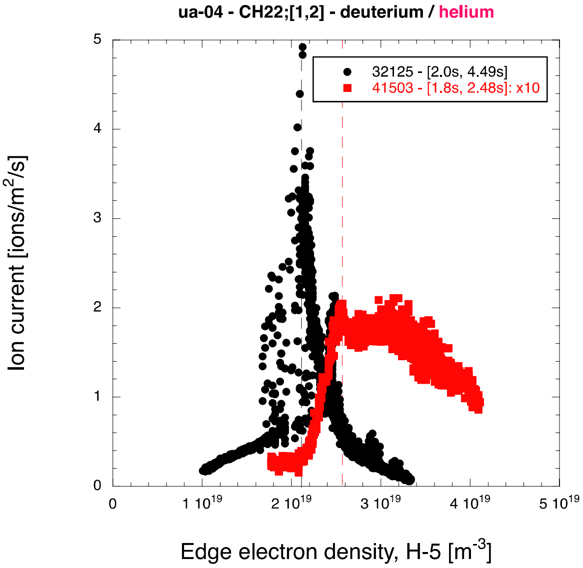


Figure 2.13: Ion saturation current measured near the low-field side strike point in ASDEX Upgrade otherwise similar deuterium (black) and helium (red) L-mode discharges as function of the edge electron density in the core plasma.

In JET-ILW, a 20% increase in rollover density when increasing NBI heating power fivefold. In comparison to vertical-vertical (VT) configurations, an approximately 10% higher rollover density at LFS plate for VT than in a vertical-horizontal (V5-C) configuration.

2.6.4 Spectroscopic camera analysis of the roles of molecularly assisted reaction chains during detachment in JET L-mode plasmas

Research scientists: J. Karhunen, VTT

Spectroscopic 2D estimates of plasma conditions and atomic and molecular densities in the divertor volume of JET were used to analyze the roles of molecularly assisted ionization, recombination and dissociation (MAI/R/D) in detachment in L-mode. MAD was found to act as a precursor for detachment at $T_{e,osp}$ = 1 - 2 eV by providing a significant source of atoms into the divertor plasma. The MAI/R reaction chains concentrated to the detachment onset phase at around $T_{e,osp}$ = 1 eV, while globally the divertor particle balance was dominated by electron-atom ionization and electron-ion recombination, the latter especially accounting for accessing deep detachment at $T_{e,osp}$ = 0.5 - 1 eV.

2.6.5 Impact of charge exchange on fast-ion confinement in MAST-U

Research scientists: P. Ollus, AU

Dedicated experiments were performed in the 2nd MAST-U campaign to investigate fast-ion charge-exchange losses. The density of ambient neutrals at the plasma edge was varied in a controlled manner by changing the plasma fuelling mid-shot, and the impact was measured with a range of fast-ion diagnostics. Different beam configurations were tested. The neutral density distribution was reconstructed using measurements of the neutral-gas pressure at the vessel wall.

Early analysis suggests a noticeable impact of an increase in ambient neutral density on the confinement of fast ions. Detailed modelling of the experiments is ongoing to determine the fast-ion transport and losses caused by charge exchange and other mechanisms, with the aim of better understanding the impact of charge exchange on fast ions in MAST-U.

2.6.6 Particle transport and sources in perturbation experiment (JET)

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

Particle transport and sources were investigated through analysis and modelling of a previous JET experiment, where periodic strike point sweeping was utilized to generate an edge perturbation. By altering the strike points, the recycled particle fluxes and other divertor and separatrix conditions were also altered. This resulted in an edge-localized perturbation in the particle transport channel, whose properties could be quantified by measuring the time evolution of the electron density. To enable analysis of the challenging plasma response, we improved the processing of the JET profile reflectometer data in several ways, resulting in high-quality data. Figure 2 shows the time averaged radial profile of the electron density (n_e) and its amplitude (A_{ne}) and phase (ϕ) response at the fundamental modulation frequency from the reflectometer measurements (shown in blue in figure 2.14). The complex response to the perturbation is evidenced by the strongly non-monotonic amplitude and phase profiles, whose features cannot be reconciled with traditional analysis that assumes time-independent background transport properties.

To reproduce the measurements qualitatively we have developed a simulation framework that uses a forward model for the time evolution of the electron density to fit the unknown transport (diffusion and convection, $\mathrm{D}(\rho, \mathrm{t}), v(\rho, \mathrm{t})$) and source ($S(\rho, \mathrm{t})$) parameters via optimisation. The forward model we selected is given by:

$$\frac{\partial \mathcal{V}}{\partial \rho}\frac{\partial \mathrm{n_e}}{\partial \mathrm{t}} = \frac{\partial}{\partial \rho}\frac{\partial \mathcal{V}}{\partial \rho}\left(\langle(\nabla\rho)^2\rangle \mathrm{D}\frac{\partial \mathrm{n_e}}{\partial \rho} - \langle\nabla\rho\rangle \mathrm{V}\mathrm{n_e}\right) + \frac{\partial \mathcal{V}}{\partial \rho}\left(\mathrm{S} - \frac{\mathrm{n_e}}{\tau_{||}}\right),$$

This model includes geometrical terms $\frac{\partial \mathcal{V}}{\partial \rho}$, $\langle(\nabla\rho)^2\rangle$ and $\langle\nabla\rho\rangle$, which are extracted from EFIT equilibrium reconstruction and a simple time-independent model for parallel confinement time $\tau_{||}$, which is active only in the Scrape-off-Layer. Although this model neglects the explicit coupling between particles, heat, and momentum and only solves for the electron density, it captures the coupling across the various transport channels and other non-linear phenomena through the time variation of the diffusion and convection profiles, making it capable of generating complex responses.

Our optimization method only considers the fundamental harmonic oscillation, which allows for the use of D, v and S parametrization. These parameters are constructed from three radial profiles (steady state, amplitude, and phase):

$$X(t,\rho) = X_0(\rho) + X_1(\rho)\sin\big(\omega t - \varphi_X(\rho)\big).$$

This enables a limited number of degrees of freedom (10-20, depending on profile flexibility) for optimization, resulting in comfortable calculation time. Figure 2.14 illustrates the best fitting simulated profiles against the measurements and displays the resulting D_0 and v_0 profiles. The simulation can thus reproduce the main dynamics of the electron density with rather good accuracy. We discovered that the crucial factor in reproducing the measurements was the temporal variation of the transport, which is traditionally neglected in perturbation analysis. The magnitude of the temporal transport variation is demonstrated by the green bars, which is nonnegligible. Our belief is that this can be primarily attributed to the variation in the quality of the edge transport barrier, but it may also be influenced by changes in the temperature profile, which is caused by the propagation of cold particles into the plasma.

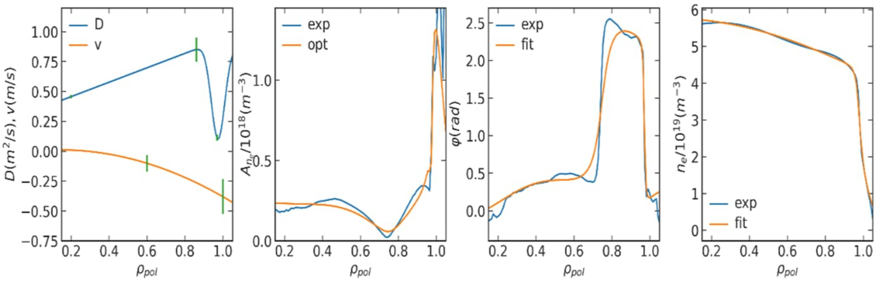


Figure 2.14: particle diffusion (D) and convection (v) profiles deduced by the optimisation, and best fitting simulated modulation amplitude (A), phase (ϕ) and steady state (ne) profiles against experimental measurement.

The experiment consists of three identical phases with varying sweep frequencies, enabling us to narrow down the possible solution space and confirm the robustness of our results. Interestingly, we observed that the edge transport barrier begins to degrade (D increases) 2-5 milliseconds before the particle source starts to increase, which holds true for all three frequencies. Further modeling by ourselves and others suggests that the movement of the strike points rapidly alters the radial electric field, leading to changes in the barrier, while the neutral leakage from the main chamber divertor, which results in particle source changes, is slightly delayed. Ongoing efforts involve incorporating new constraints into our models to make our results quantitative.

The same methodology or workflow to analyse density modulation experiment described above will be used to analyse gas puff modulation experiments in 100% Tritium plasma and in 100% He plasmas. Both the Tritium and Helium experiments were performed in 2022, but the particle transport analysis will take place in 2023.

2.6.7 RF heated plasmas (AUG)

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

As a first application of ASCOT4-RFOF to 3rd harmonic ion cyclotron resonance heating (ICRH), the effect of ICRH of neutral beam injected deuterium on high frequency Alfén eigenmode growth rate in the core region of ASDEX Upgrade discharge 39220 was studied. The derivatives of the simulated 4D fast ion distribution $f(R,z,\xi,E)$ were used in an analytic representation of the growth rate, and a good agreement with experimental observations was found. A manuscript reporting the findings was submitted to Nuclear Fusion.

Several new studies to explain observed mode responses and fast ion losses related to ICRH in ASDEX Upgrade were initiated.

2.6.8 Task Force Leadership activities

Research scientists: A. Hakola, VTT

Also in 2022, Antti Hakola acted as one of the Deputy Task Force Leaders (TFL) for WPTE, as part of the team of 9 TFLs. His main responsibility areas were (i) material erosion, migration, and fuel retention; (ii) detachment control; (iii) ELM suppression using resonant magnetic perturbations; (iv) characterization of runaway electrons and (v) 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 JET). Besides coordinating research activities, the deputy TFL duties included reporting of the scientific outcomes, and preparing new campaigns. Particular focus points in 2022 were executing the JET tritium campaign as well as organizing and coordinating helium experiments on AUG and JET.

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

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

The ASCOT code was used to evaluate the effect of different particle species on the fast-ion losses in W7-X. Ions from H and D-beams were simulated in H, D and He plasmas for the standard and high-mirror magnetic configurations. The results showed increased losses in D plasmas with respect to H plasmas in both configurations. Beam-ion losses go from 14% to 30% in the standard configuration, and from 15% to 32% in the high-mirror configuration.

3. Fusion Technology Work Programme 2022

3.1 WP BB: Breeding blanket

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

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

A 3D model of the tungsten shield mock-up has been implemented in Serpent2 using a realistic geometry and material composition. The model was used to calculate the neutron flux and reaction rates at the relevant measurement locations. The obtained results were benchmarked against the MCNP, showing a good agreement.

The experimental validation of the Serpent model was not possible due to a delay in the W-shield mock-up experiment, now rescheduled for the second quarter of 2023. This validation will be carried out as soon as the data becomes available.

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

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

A 3D model of the WCLL blanket mock-up has been implemented in Serpent2. The estimations of neutron flux and reaction rates were benchmarked against the MCNP code and compared to experimental data with good results. The discrepancy between the codes was below 10% and the comparison of the reaction rates with the experiment showed C/E values between 0.80-0.98 for most cases.

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

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

As part of the BOP efforts various Once-Through Steam Generator (OTSG) designs had been studied with Apros. A true OTSG without internal recirculation and another concept with internal economizer (IEOTSG) were benchmarked against RELAP5 reference data as part of the OTSG evolution. Based on the results, the true OTSG concept was adopted in subsequent sensitivity studies, focusing on the nodalization of the lower water port region in the riser of the OTSG. In addition to these activities the integral T/H model of the WCLL (Figure 3.1) and HCPB small ESS plants were revised, taking into account current energy balance maps. The transient analyses of these configurations are planned for 2023 with updates considering heat exchangers in the power conversion system (PCS). Concluding modelling activities of recent years with Apros, Serpent and ASCOT, Marton Szogradi defended his doctoral dissertation at Aalto University.

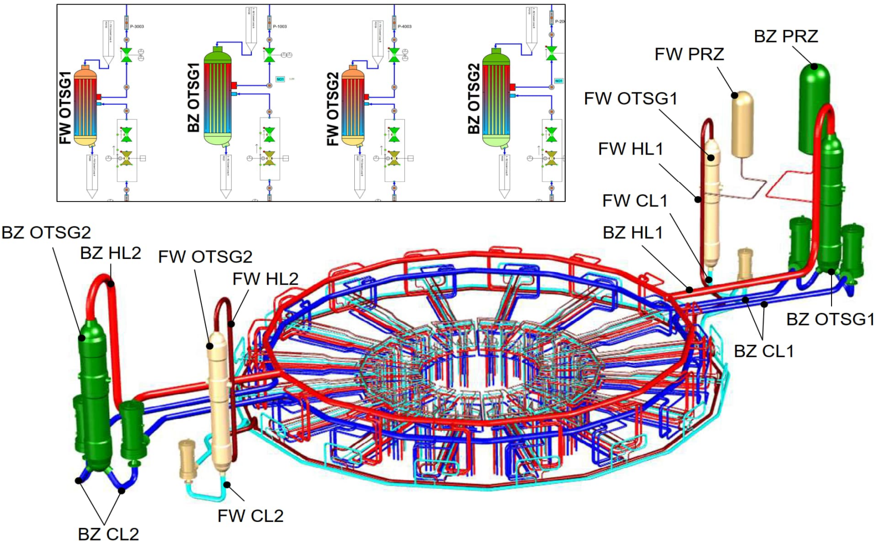


Figure 3.1: Integrated OTSGs in the WCLL concept.

3.3 WP ENS: Early Neutron Source definition and design

3.3.1 Project Level Analyses

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

International Fusion Material Irradiation Facility - DEMO Oriented Neutron 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 by providing probabilistic risk assessments (PRA) for IFMIF-DONES. The aim of the PRA is to give insights to the strengths and weaknesses of the design and operation of IFMIF-DONES.

In 2022, work at VTT has concentrated on the development of IFMIF-DONES internal events, design phase PRA model. The current PRA model for the design phase consists of 8 event trees on systems' transients and potential lithium leakages. Example of one event tree is presented in Figure 3.2.

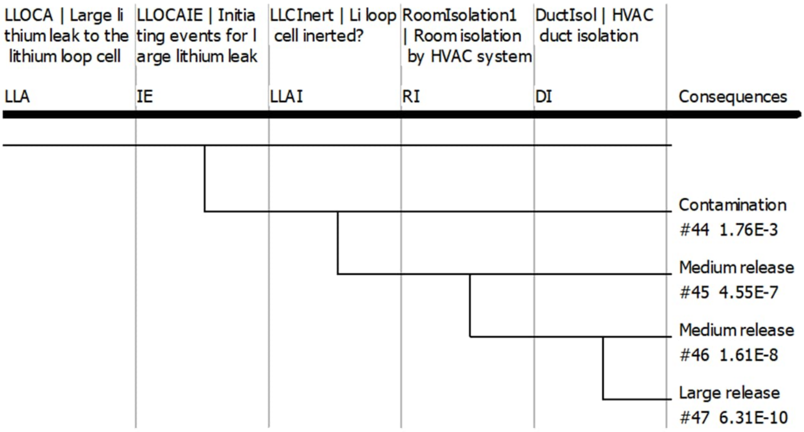


Figure 3.2: Large lithium leak event tree

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

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

The IFMIF-DONES facility investigates the effects of strong neutron radiation on materials. The facility is under construction in Granada, Spain. The results of IFMIF-DONES research will be vital when the future fusion reactors are being constructed.

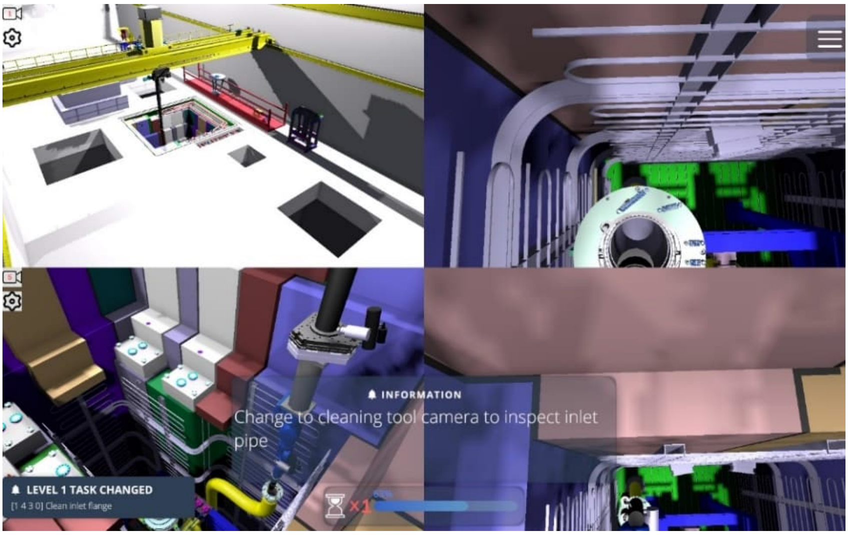
Some of the facility's facilities are under such strong radiation that maintenance procedures must be carried out by robots. The operation must be monitored remotely using radiation-resistant cameras. A few dozen cameras are needed to comprehensively monitor these maintenance procedures.

Until a few years ago, radiation-resistant (1 MGy) cameras were based on old analog black-and-white TV technology. Fortunately, color cameras based on semiconductor technology, which can withstand radiation just as well, have come onto the market in recent years. The price of the cameras is a few tens of thousands of euros, and they have Zoom-Pan-Tilt capabilities, and often lighting. They require a fixed cable (100 m or more) to the controller, which is in a radiation-protected space, often in a control room with human operators. VTT's responsibility is to give a recommendation on the camera model(s) to be used, as well as to plan the locations and wiring of the cameras.

The work used 3D animations created by Valeria VR Labs (Universidad de Granada), which show maintenance procedures in facilities under radiation. The characteristics of the cameras of the virtual model (e.g., Field of View) were set to be as similar as possible to the characteristics of the selected camera model.

At the time of this writing (April 2023), the recommended camera model has been selected, and a preliminary offer has been received from the camera manufacturer.

Recommendations have been made for most facilities subject to radiation regarding the locations of the cameras and the necessary wiring, the design of the remaining facilities is still being refined.



INFORMATION

Change to cleaning tool camera to inspect inlet pipe

LEVEL 1 TASK CHANGED

[1 4 3 0] Clean inlet flange

Figure 3.3: Screenshot of ValeriaLab's VR model with 4 partial images showing views from different cameras. The 3D model of the two cameras can be seen in the partial image below on the left: a whole consisting of a black and a white pipe. One of these is in the upper right corner of the partial picture, the other is attached to the same mast below. The images seen by these two cameras are on the right: the upper camera's view is the lower right partial image; the lower camera's view is the upper right one.

3.4 WP MAG: Magnet conductor/ insulator research

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

The performance of fusion magnets is strongly relying on the dielectric strength given by the electrical and mechanical robustness of the magnets insulation system. The dielectric and mechanical durability of the electrical insulation is in the focus of the WPMAG project related to the high voltage superconductive coils consisting of lots of cables. A dry glass fabric and polyimide film wrap type of insulation solution has traditionally been used. Now the manufacturing process step should be changed so that the implementation of the insulation solution takes place before the challenging heat – treatment and vacuum process cycle required by the Nb3Sn based superconductive cables. The step by step proceeding cycle goes up to the maximum of 650°C temperature. On the other hand, the insulation materials must faithfully withstand the significant forces when cooled down to the cryogenic temperatures, normal operation and in faults conditions in order to avoid the electrical breakdown in the coils.

VTT's role in the project is to chart some potential insulation solutions and choose the most promising further to be implemented in the practical demonstration system. In addition, target is to find a suitable subcontracting partner that could take a role in practical manufacturing (wrapping tapes, etc.) of the demonstration system and also support in choosing the most promising material components to the insulation composite. The electrical functionality and reliability will be tested by using the implemented demos together with the third company. VTT coordinates this co–operation and gives support e.g. by ProperTune material oriented skills. The multi–physics modeling containing e.g. dielectric features, heat transfer, thermal quench, insulation breakdown etc. is started by using the COMSOL simulation software. In addition, the mechanical strength, and elastic features of the composite type of insulation materials will be simulated and verified based on few ISO test setups.

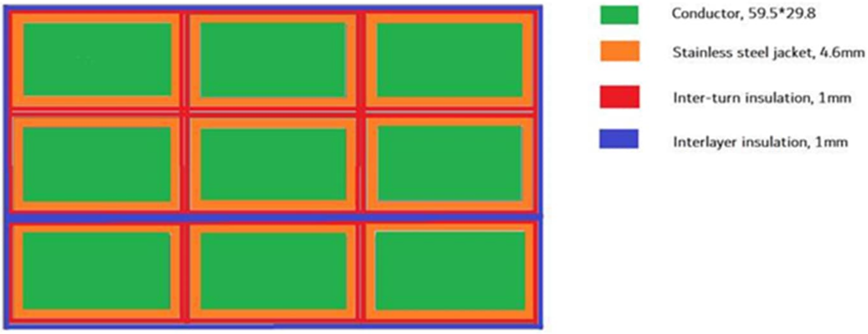


Figure 3.4: Simple 2D cross section sketch of the test demo, the length will be min. 1m for testing purposes.

3.5 WP MAT: Materials

Research scientists: P. Lappalainen, P. Arffman, J. Alhainen, J. Lukin, K. Rämö, P. Sinkkonen, J. Saarinen, J. Leporanta, VTT

The Materials Work Package (WPMAT) aims to develop and qualify three baseline materials, including EUROFER steel, tungsten, and copper chromium-zirconium (CuCrZr) alloy, for use in various components in fusion reactors. The EUROfusion WPMAT task specification PIE of LOT-II outlines the required mechanical testing for irradiated specimens, including the determination of mechanical properties for a CuCrZr alloy irradiated to 5 dpa. All validation tests, including the low cycle fatigue tests, were performed with a commercially available material Elmedur X, which has similar mechanical and chemical properties as the ITER grade CuCrZr alloy used in irradiated specimens.

The preliminary low cycle fatigue validation tests were performed at room temperature using a servo-hydraulic mechanical testing machine with an 8 mm gauge length dynamic axial extensometer to measure specimen deformation. The polished specimen was tested in strain control using a 3 Hz tapered sine wave signal with a cycle asymmetry of R_ε = -1.

The results of the low cycle fatigue strain-stress curve and the half-life hysteresis loop at room temperature in air are shown in Figure 3.5. The test results were compared with non-irradiated low cycle fatigue ITER-grade CuCrZr alloy testing results, and a good correspondence was achieved between the results. After the test, the tested specimen was analyzed to verify the initial crack location and exclude the influence of the extensometer contacts on the rupture location.

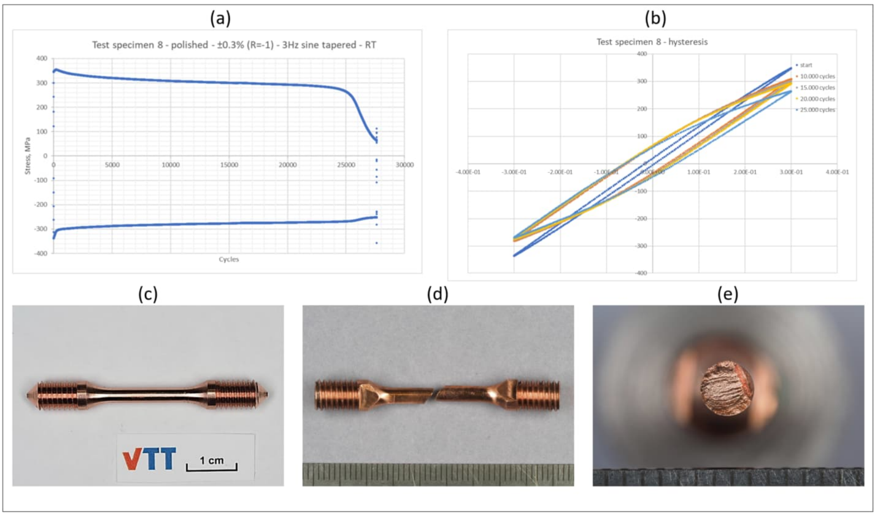


Figure 3.5: Cyclic stress response of applied stress (a), half-life hysteresis loops with the strain at different cycles of CuCrZr validation material for ε_a=0.3 % at room temperature in air (b), polished LCF specimen before testing (c), the tested center-broken specimen (d) and the fracture surface of the tested specimen for the crack initiation location determination (e).

3.6 WP PRD: Prospective R&D

3.6.1 HHFM High heat flux materials

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

The activities and work completed during 2022 focus on additive manufacturing (AM) of tungsten and the overall theme of supporting “manufacturability” by way of new and novel multiscale modeling capabilities. The work focuses on novel plasma-facing materials and on manufacturing technologies which are especially applicable to metal AM powder bed fusion (PBF), direct energy deposition (DED) and electron beam melting (EBM) technologies. This includes particularly work and development efforts towards:

- Rapid solidification of tungsten: solver for investigating solidification microstructures, defects etc. with atomistic resolution (phase field crystal, (PFC).
- AM process models for tungsten and alloys to form a multiscale workflow: melt pool scale (computational fluid dynamics), polycrystalline scale (cellular automata), single-to-polycrystalline scale (phase fields) in addition to the atomistic scale (phase field crystal, molecular dynamics).
- Driving the development with data-driven means to improve data analytics and introduce design and optimization capabilities (towards, e.g., process parameters, alloy chemistries, microstructures etc.): Deep learning methodology employing Bayesian and active learning strategies have been introduced.
- Benchmarking work across the main activities for tungsten comparing to available experimental and literature data.

3.6.2 IREMEV activities

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

At UH work focused on high dose simulations in tungsten (W) and tungsten with deuterium (D), to understand the effect of deuterium. Experimentally presence of deuterium is known to affect defect build-up, but the mechanism is not understood. Also kinks on screw dislocations were analysed in detail, to understand the dislocation mobility that ultimately affects macroscopical properties.

At AU, the effects of external loading on the damaged microstructure in the limit of high radiation dose in tungsten was studied by atomistic simulations of damage accumulation. A linear dependence on external strain was found for both the vacancy and dislocation line densities, which characterize the microstructure in the dynamically fluctuating steady state that the material attains in the high dose limit in the athermal regime.

3.6.3 Serpent2 neutron model for HELIAS stellarator

Research scientists: T. Lyytinen, L. Sanchis, A. Snicker, S. Äkäslompolo, AU

While EUROfusion mainly designs a fusion reactor based on the tokamak option, a research line to initiate the design activities for stellarators is also existing. Our role in that project is to use the Serpent2 code for the neutronics studies. During 2022, the work for the previous year continued to finalize the benchmark between Serpent2 and MCNP in the HELIAS 5B geometry. After the benchmark was satisfactory, Serpent2 was used to estimate the tritium breeding ratio (TBR) and fast-neutron flux at the superconducting coils. A scan was done to account for different thicknesses of the breeding blanket. The simulations showed that the design limit of TBR>1.15 can be obtained both with dual-cooled lithium lead (DCLL) and helium-cooled pebble ped (HCPB) breeding options. While the HCPB showed superior breeding capability (as demonstrated in Figure 3.6), the DCLL was observed to be much more effective in neutron shielding. In more detail, the threshold for the fast-neutron flux was easily obtained using DCLL material composition and suitable radial thickness of the geometry layers while for HCPB the threshold was barely reached within the statistical accuracy of the simulations.

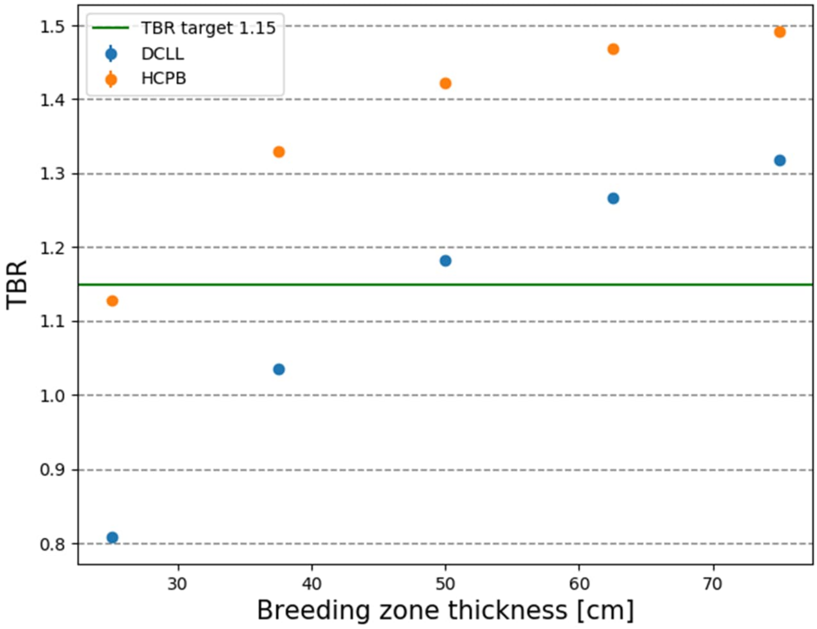


Figure 3.6: TBR as a function of breeding zone thickness using DCLL and HCPB blanket compositions.

The work continues in the coming years by removing some of the assumptions done so far. In particular, since the coil flux limit seems to be a critical component, the geometry of each coil is divided into cells and the neutron flux is calculated in each cell. This way, the neutron flux can be calculated at each poloidal location of the coil, while in 2022 only the average neutron flux over the coil was used.

3.7 WP PrIO: Preparation of ITER first experimental campaigns

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

During 2022, the ASCOT group contributed to the WPPrIO with simulations of ITER fast-ion loss detector (FILD). The main focus was to model the synthetic signal up to the pinhole of the detector for fusion-born alpha particles. Since ITER is going to be operated using various different scenarios, and it is not clear which will produce the highest losses to be measured, a new method was invented to allow faster iteration of simulations. Namely, the ASCOT simulations were used to estimate the 0D alpha particle flux at the pinhole, which was then compared to the background noise due to neutrons and gammas. Ultimately this 0D signal has a velocity space dependency but ignoring that allows us to use much lower statistics and, therefore, carry out more simulations.

Actual simulations were mainly carried out for the 15 MA baseline H-mode scenario. There, it was observed that the alpha particle flux at the pinhole was well above the threshold for the background noise. Moreover, it was observed that including a realistic plasma response model for the ELM correction coil fields will decrease the total losses but increase the losses at the location of FILD, as shown in Figure 3.7. In the near future, ASCOT simulations are used to estimate the signal of not only fusion-born alphas but also neutral beam ions. Moreover, higher-resolution ASCOT simulations are carried out to produce a velocity space coverage of the losses at the FILD pinhole and this is coupled with the FILDSIM code to arrive at a realistic synthetic FILD image.

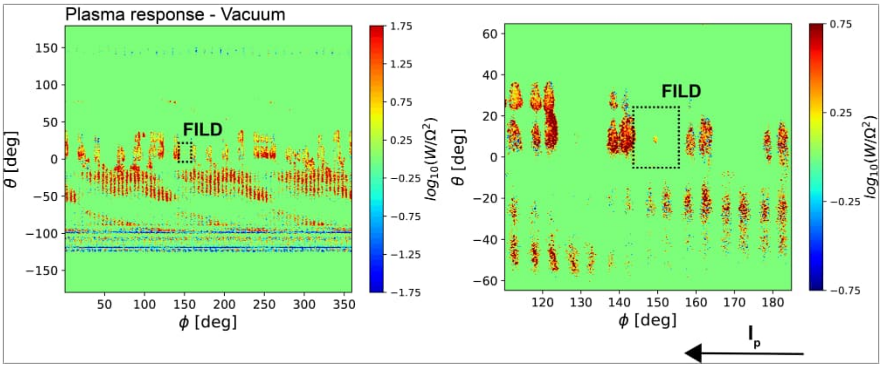


Figure 3.7: Alpha particle wall power load in the 15 MA ITER H-mode scenario, including n=3 RMP field due to ELM correction coils as a function of the toroidal and poloidal angles. Right: plasma response minus vacuum field. Left: Zoom at the FILD location.

3.8 WP RM: DEMO Remote maintenance

3.8.1 Overview

The European Research Roadmap acknowledges that the R&D activities for realising efficient DEMO remote maintenance equipment (RME) are critical in making the plant maintainable and maximising overall availability for a commercially viable Fusion Power Plant (FPP). Therefore, as part of the EUROfusion Framework Programme 9 (FP9) deliverable, Work Package Remote Maintenance (WPRM) is tasked with the parallel delivery of the RME design and supporting R&D Programme. In the roadmap, there is much emphasis on the proof-of-principle testing and validation of specific design concepts. Consequently, the main objective of WPRM FP9 is utilising Remote Maintenance Test Facilities (RMTF) as an integral part of the design and supporting R&D Programme to mitigate associated design and technology risks while generating the required knowledge to make informed decisions. Therefore, the focus of the WPRM design and R&D Programme has increased significantly. It now includes more extensive research activities from VTT, LUT, and TUNI and more participation from the industry, see Figure 3.8. The industry participants include Comatec, Qualifin, and Fulvisol, together with the research institutes we refer to as Finn RM-Group. The roadmap further includes delivering one or more test facilities to develop the critical technologies and designs that enable digitalisation in extreme conditions.

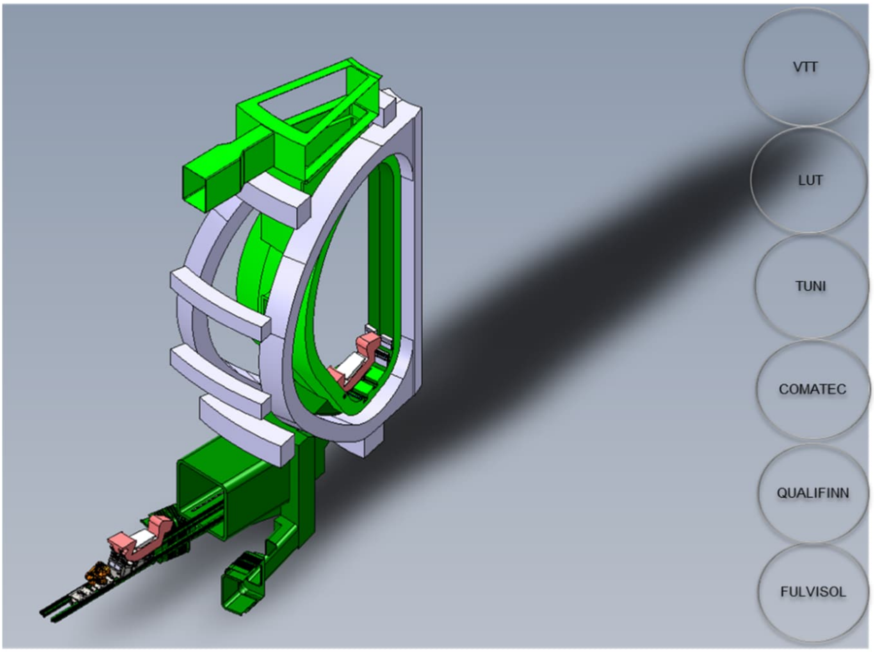


Figure 3.8: Finn RM-Group - Research institutes and companies participating in the DEMO fusion WPRM

The DEMO tokamak fusion power plant is an example of a system operating in extreme conditions. Therefore, maintenance is identified as mission-critical and design-defining to ensure a maintainable DEMO design from a conceptual stage. Maintenance through remote handling (RH) technology is one of the key issues of the DEMO Project. The neutron activation of the in-vessel components precludes manual maintenance within the bio-shield and many other plant areas. Under the FP9 design and supporting R&D programme, strategies are developed to ensure rapid maintenance such that several remotely controlled and autonomous systems can operate in parallel. The challenge is the careful combination of remote-controlled, autonomous, and man-in-the-loop due to stringent safety implications in nuclear power plant systems and operations. This calls for broader participation from the Finn RM-Group and a robust methodology. The approach combines traditional engineering design with R&D in advanced technologies, the development of automation and autonomous systems, and defining the human perspective in terms of Human Readiness Level (HRL) compared with Technology Readiness Level (TRL). Therefore, the participation of Finn RM-Group has exploded to include several tasks, such as research in sensors, communications, human factor perspective, systems engineering, modelling, and simulation combined with physical testing and experimentation (see Figure 3.9). These design and R&D

activities are divided under two programmes: Remote Maintenance System Design (RM-S) and Remote Maintenance Technology Research & Development (RM-T).

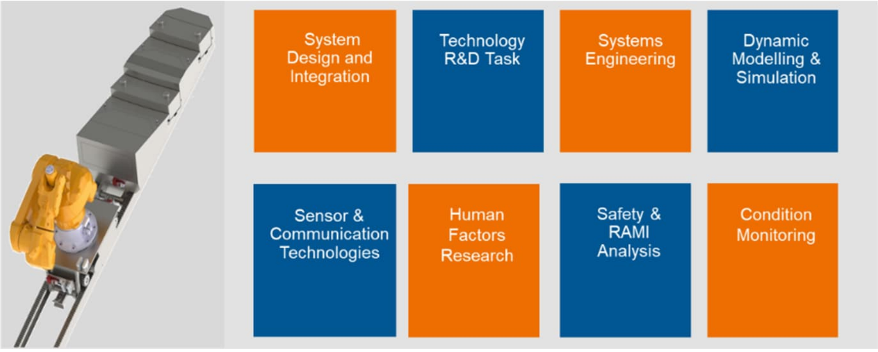


Figure 3.9: WPRM engineering design and supporting R&D programme.

3.8.2 RM System Design

Research scientists: J. Alanen, W. Brace, J. Heikkilä, T. Jokinen, A. Järvinen, P. Kaarmila, D. Kaartinen, K. Katajamäki, P. Kilpeläinen, P. Kokkonen, J. Koskinen, M. Liinasuo, J. Lyytinen, T. Malm, H. Martikainen, S. Qais, O. Rantanen, H. Saarinen, T. Salonen, J. Sarsama, T. Sipola, M. Siren, M. Siuko, E. Strömmer, M. Tahkola, B. Tammentie, A. Tanskanen, V. Truong, T. Vaarala, T. Välisalo, A. Ylisaukko-oja, VTT
K. Kund, S. Muhlig-Hofmann, V. Puumala, Comatec

Replacing the in-vessel components comprising heavy elements like the breeder blanket (BB) and divertor cassettes compounded by extreme conditions is a crucial maintenance operation for the DEMO FPP. The complexity of the handling operations, the precision with which the components must be handled, issues with recovery, and the speed with which the operations must be completed to meet maintainability requirements are issues to consider for developing RH equipment. Finn RM-Group has been involved since WPRM FP8 in designing and developing several RH equipment. In WPRM FP9, the design and development activities have increased to include RH equipment for the inbioshield and port components. Consequently, a new approach for the system design work using a developed integrated modelling methodology by producing reusable parametric 3D CAD models that allow the straightforward creation of alternative layouts and concepts for architectural and system analyses is researched and employed. The design work is further complimented by systems engineering, modelling and simulation on sensitivity, risk, safety, and RAMI (Reliability, Availability, Maintainability and Inspectability) analyses to reduce stress, risks, and payload limits, incorporating seismic mitigation strategies and enhance safety, rescue, and recovery. In addition, a System Test Programme will be set up to verify and validate design-specific prototypes, allowing the RH equipment design to be tested and optimised.

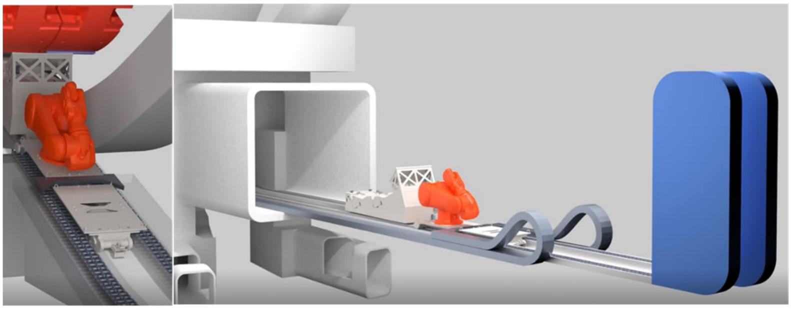


Figure 3.10: The new serapid chain single mover concept for gross movements in the lower access port

3.8.3 RM Technology R&D

Research scientists: J. Alanen, W. Brace, J. Heikkilä, T. Jokinen, A. Järvinen, P. Kaarmila, D. Kaartinen, K. Katajamäki, P. Kilpeläinen, P. Kokkonen, J. Koskinen, M. Liinasuo, J. Lyytinen, T. Malm, H. Martikainen, S. Qais, O. Rantanen, H. Saarinen, T. Salonen, J. Sarsama, T. Sipola, M. Siren, M. Siuko, E. Strömmer, M. Tahkola, B. Tammentie, A. Tanskanen, V. Truong, T. Vaarala, T. Välisalo, A. Ylisaukko-oja, VTT
K. Kund, S. Muhlig-Hofmann, V. Puumala, Comatec

In WPRM FP9, the Technology R&D (RM-T) activities focus on the research on existing and upcoming technologies, accessing the suitability for application in the FPP considering the extreme conditions. The researched technologies are diverse. Finn RM-Group involvement includes research on the human factors from the operation and control of remote maintenance systems (OCORMS) perspective; AI-based intelligent algorithms for model-based condition monitoring; twin condition monitoring - An integrated monitoring of the RM system and human operator; model-based advanced controls for remote operations (MACRO); and sensors and communication for MACRO. Sensors and communication research include determining the monitoring needs required for the in-vessel condition monitoring (CM) and RH equipment. The work further reviews the status and applicability of identified sensor technologies considering extreme conditions. Furthermore, there is a study on sensor fusion to combine different sensor data with MACRO. There is also research on communication architecture development for FPP, investigating the suitability of wired and wireless communication solutions to sensor data in extreme conditions. Particular emphasis is given to MACRO related to moving the breeding blanket segmentss and the divertor. Hence, a test platform shall be built to follow a technology test programme to conduct a series of trials to characterise the performance and limitations of the sensors that are critical to BB maintenance.

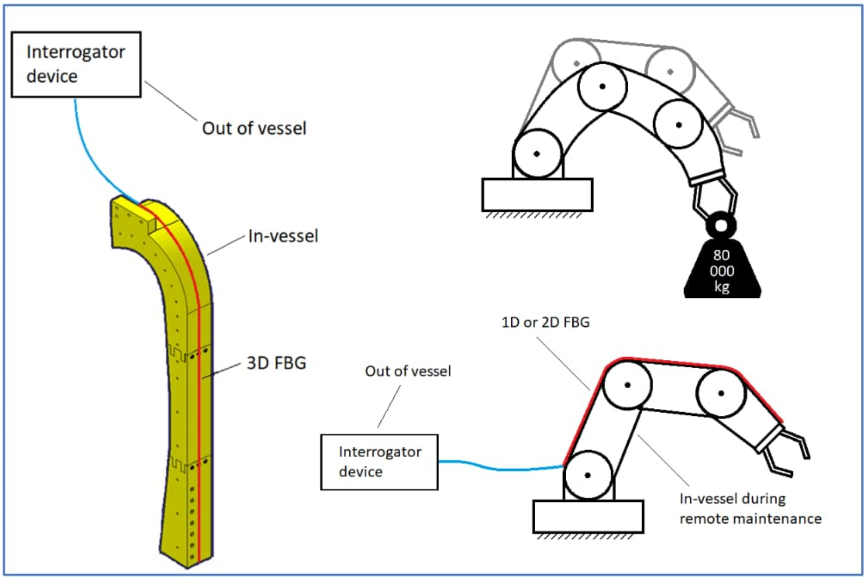


Figure 3.11: Sample test components for the technology test programme for sensors and communication. FBG = Fiber Bragg Grating optical fiber sensor. (The image on the left is based on a CAD model by the main designer of BB mock-up, Henri Durousseau from RACE-UKAEA.)

3.8.4 Remote Maintenance at LUT

Research scientists: L. Changyang, W. Huapeng, L. Ming, Y. Ruochen, Q. Guodong, H. Amin, LUT

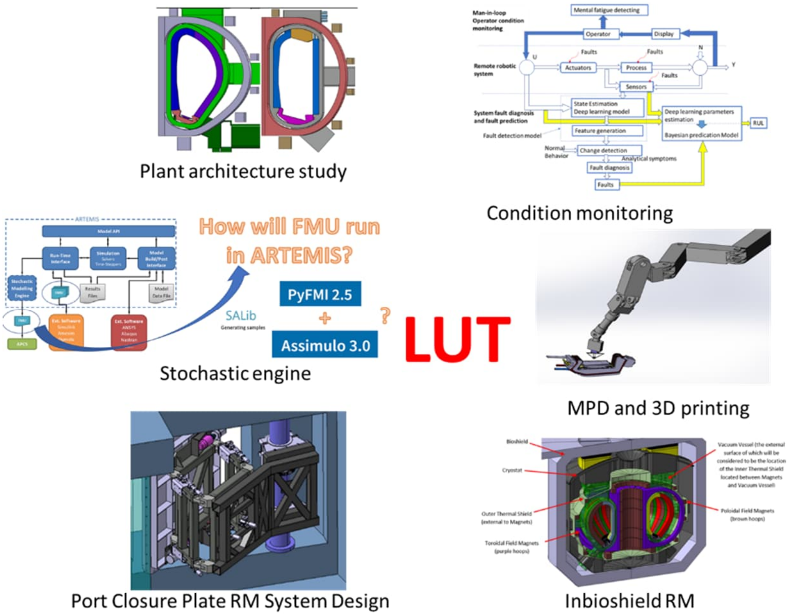
LUT participates the WP RM with 4 major areas: In-vessel maintenance system, condition monitoring, stochastic modelling, and In-BioShield Maintenance Systems. Overview of the LUT activities is in Figure 3.12.

1) Within the In-vessel maintenance system component, we have carried out a literature review and several other tasks: benefits of clearance behind the icv, further developments of integrated BB concepts, development of RM system for PCP, development of in-vessel maintenance-MPD and a study for 3D additive manufacturing for on-site maintenance.

2) In Condition monitoring AI algorithms (Data driven methods) are studied: Estimation of heath life of RM system; Fault diagnosis method for hydraulic RM system; Active Fault Tolerant Control Design for Actuator Faults Mitigation; Faults Mitigation in blanket transportation; Sensors (disturbance fault), and finally we focus on the methods of human condition monitoring in man-in-loop remote handling system.

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) In-BioShield Maintenance Systems the work aims to summarise works performed in AWP22, conduct a technical feasibility analysis of the potential In-BioShield RM systems/effectors in the EBOM list and propose corresponding deployment methods.



Plant architecture study

Condition monitoring

Stochastic engine

MPD and 3D printing

Port Closure Plate RM System Design

Inbioshield RM

Figure 3.12: LUT university activities on DEMO RM

3.9 WP SAE

3.9.1 Liquid operational waste expected from current DEMO design

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

The generation of radioactive waste, in terms of both volume, radioactivity content, and frequency of batches generated, must be considered before the construction of any nuclear facility like a fusion reactor. In 2022, VTT's scope in WP SAE covered the considerations about liquid radioactive wastes from the DEMO design.

We identified and classified the most important waste streams and listed process options identified so far, including a processing technology readiness estimate. Essential inputs for the work have been existing planning for future fusion facilities such as ITER, and experiences from current fusion operational facilities and the fission industry. The results will constitute part of the Generic Site Safety Report for DEMO, and in the future, they will be refined along the evolution of the technical design of DEMO.

3.9.2 Fire Hazard simulations

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

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

In 2022, the work in Fire accident analyses task concentrated on a preliminary proposal of fire sectorization. Fire loads, such as cables, that could be present in DEMO were described. The usability of analytical calculation methods and zone models were studied and validated with CFD simulations of selected fire scenarios. The use of different methods for screening fire hazards were demonstrated with vacuum pumping rooms as the main example. The work will continue in 2023 concentrating on the Tokamak building complex.

4. Communications

4.1 FinnFusion Annual seminar

The FinnFusion Annual Seminar was organised by VTT in co-operation with FinNuclear as Nuclear Energy Ecosystems’ Open Business Day 2022, “Building nuclear energy future together”, in Helsinki, Finland on 3 – 4 May 2022. The themes of the event included Small Modular Reactors (SMRs), fusion energy and nuclear decommissioning, including high-level keynote speakers on all topics. Fusion energy part of the program included presentations from Prof. Tony Donné, EUROfusion Programme Manager, Tim Luce, Head of ITER Science & Operation, and company presentations by Comatec, Platom, EOS Finland, and Luvata, and several scientific and technical presentations. The programme and presentations are available at www.openbusinessday.fi. The Annual Report, *FinnFusion Yearbook 2021,* VTT Technology **405** (2022) 103 p., was released during the meeting.

Figure 4.1: Tim Luce, Head of Science & Operation, ITER, delivering his presentation on ITER at Nuclear Energy Ecosystems’ Open Business Day 2022 conference.

4.2 Articles and public relations

During 2022, Finnish media published several articles and interviews on the fusion research activities in Finland:

- Antti Hakola: Will fusion energy finally be available in this century? Experiences from managing an international research programme (Onko fuusioenergiaa viimeinkin saatavilla tällä vuosisadalla? Kokemuksia kansainvälisen tutkimushankkeen vetämisestä) (in Finnish), Sytyke 1/2022, p. 16.
- Tuomas Tala: Media event presentation to His Royal Highness, Prince of Wales, Prince Charles (recently crowned as King Charles), who visited JET a week before the media event on 31 January 2022.

- Tuomas Tala: Saako ihmiskunta hylätä vuosisadan puolivälissä ydinvoiman? Tuore ennätystulos tuo uskoa fuusioenergian tulevaisuudelle (Can humanity abandon nuclear power by mid-century? A recent record result gives hope for the future of fusion energy). Iltalehti 9.2.2022. https://www.iltalehti.fi/talous/a/a80f54c5-183a-4f13-a60d-c4832b28364d
- Tuomas Tala: Fuusiovoiman kehittämisessä edistysaskel: tutkimusryhmä onnistui tuottamaan enemmän fuusioenergiaa kuin koskaan aiemmin (Step forward in fusion power development: research group succeeded in producing a record amount of fusion energy). YLE 9.2.2022. https://yle.fi/uutiset/3-12309916
- Tuomas Tala: Fuusioenergiassa uusi ME 25 v jälkeen (World record in fusion energy after 25 years). Tekniikka & Talous 9.2.2022. https://www.tekniikkatalous.fi/uutiset/fuusioenergiassa-uusi-me-25-v-jalkeen-eurooppalainen-reaktori-toimi-6-sekuntia-10-mw-teholla-170-parannus-loputon-energianlahde-taas-hieman-lahempana/2299aa8c-ced2-4734-b914-a8ae3a3c1626
- Tuomas Tala: Tutkijoilta läpimurto uuden ajan ydinvoimassa (Scientists make a breakthrough in modern nuclear power). Ilta-Sanomat 10.2.2022.
- Tuomas Tala: Energiantuotanto voi mullistua (Energy production could be revolutionized). Ilta-Sanomat 10.2.2022. https://www.is.fi/kotimaa/art-2000008601898.html

- Tuomas Tala: Fuusioenergiassa saavutettiin uusi ennätys, jossa mukana suomalaistutkijat (A new record in fusion energy, involving Finnish researchers). Turun Sanomat 10.2.2022. https://www.ts.fi/uutiset/5565247
- Tuomas Tala: Loputon energianlähde on taas hieman lähempänä (The endless source of energy is a little closer again). Talouselämä 12.2.2022. https://www.talouselama.fi/uutiset/loputon-energianlahde-on-taas-hieman-lahempana-fuusioenergiassa-uusi-maailmanennatys/cedcc26c-d61c-4abf-a347-8f4f67916c49
- Tuomas Tala: Fuusioenergiassa uusi maailmanennätys (New world record in fusion energy). Kauppalehti 12.2.2022. https://www.kauppalehti.fi/uutiset/fuusioenergiassa-uusi-maailmanennatys-loputon-energianlahde-taas-hieman-lahempana/09393ac4-6f10-467e-911b-39b930ca6b3d
- Tuomas Tala: Loputon energianlähde taas hieman lähempänä: Fuusioenergiassa tehtiin uusi maailmanennätys (Infinite energy source a little closer again: a new world record in fusion energy). Uusisuomi 13.3.2022. https://www.uusisuomi.fi/uutiset/loputon-energianlahde-taas-hieman-lahempana-fuusioenergiassa-tehtiin-uusi-maailmanennatys/a214cc25-6807-465d-ac6d-72a8ba880677
- Tuoma Tala: Englannissa syttyi keinoaurinko: 150 000 000 °C reaktorin sisältä kuvattiin huikea video, jota on vaikea uskoa todeksi (An artificial sun ignites in England: a stunning video from inside a 150 000 000 °C reactor is hard to believe). Tekniikka & Talous 16.2.2022. https://www.tekniikkatalous.fi/uutiset/englannissa-syttyi-keinoaurinko-150-000-000-c-reaktorin-sisalta-kuvattiin-huikea-video-jota-on-vaikea-uskoa-todeksi-niin-kuumaa-ettei-valoakaan-enaa-nay/2bf814db-c859-4a57-aea7-073da704efce
- Tuomas Tala: Keinoauringossa on 150 000 000 °C pätsi mutta säkkipimeä: ”Liian kuumaa valolle” (The artificial sun has a 150 000 000 °C core but is pitch-black: "Too hot for light"). Tekniikka & Talous 17.2.2022. https://www.tekniikkatalous.fi/uutiset/keinoauringossa-on-150-000-000-c-patsi-mutta-sakkipimea-liian-kuumaa-valolle-professori-vastaa-enta-oikean-auringon-ytimessa-15-000-000-c/2c2c2c4d-3c95-4627-8de1-7f7f058a6bd9
- Tuomas Tala: Fuusioenergiassa uusi maailmanennätys (New world record in fusion energy). Tekniikka & Talous 18.2.2022.
- Tuomas Tala: Fuusiovoimassa tehtiin uusi maailmanennätys, mutta miksi siinä kesti 24 vuotta? Suomalaistutkija selittää syyt (A new world record was set in fusion power, but why did it take 24 years? Finnish researcher explains why). Tekniikka & Talous 24.2.2022.
- https://www.tekniikkatalous.fi/uutiset/fuusiovoimassa-tehtiin-uusi-maailmanennatys-mutta-miksi-siina-kesti-24-vuotta-suomalaistutkija-selittaa-syyt/79fb4ba3-1d3d-42e9-9f4a-4c71670062fd
- Sampo takomaan sähköä (limitless electricity). Editorial by Jukka Ruukki in Tiede 2.3.2022.

- Tuomas Tala: Keinoaurinko tuottaisi puhdasta energiaa (Artificial sun would produce clean energy). Tekniikan Maailma 16.3.2022.
- Tuomas Tala: Fuusio on puhdas ja ikuinen energianlähde, mutta tiesitkö: Ei 100,00 % puhdas, vaan siitäkin syntyy vähän ydinjätettä (Fusion is a clean and eternal source of energy, but did you know: not 100.00% clean, but it also produces some nuclear waste?). Tekniikka & Talous 12.4.2022. https://www.tekniikkatalous.fi/uutiset/fuusio-on-puhdas-ja-ikuinen-energianlahde-mutta-tiesitko-ei-100-00-puhdas-vaan-siitakin-syntyy-vahan-ydinjatetta-juuri-nyt-kukaan-ei-mene-sinne-muutamaan-kuukauteen/9b6d96b2-91a1-48fa-bb86-f4e5dfe1c6af
- Tuomas Tala: Loikka kohti fuusiovoimaa (leap towards fusion power). Tekniikan maailma 5/2022.
- Tampere University: Tampereen yliopistolle palkinto 3D-konenäköjärjestelmästä (Tampere University wins award for 3D machine vision system). Ostologistiikka.fi 24.10.2022. https://www.ostologistiikka.fi/kategoriat/teknologia/tampereen-yliopistolle-palkinto-3d-konenakojarjestelmasta
- Jaakko Leppänen, Tuomas Tala: Tiedeykkösen aiheena on ydinvoima (Science-one programme topic: nuclear power). YLE radio 28.10.2022.
- Tuomas Tala: Historiallinen fuusioläpimurto tehtiin laserilla (Historic fusion breakthrough made with laser). Tekniikka & Talous 13.12.2022. https://www.tekniikkatalous.fi/uutiset/historiallinen-fuusiolapimurto-tehtiin-laserilla-suomalaistutkija-kertoo-miksi-eri-tekniikalla-toimiva-iter-voi-silti-olla-parempi/a6c74487-8760-47c4-96f2-456c6a53b337
- Tuomas Tala: Tätä kaikkea tarkoittaa fuusioenergiassa tehty läpimurto: "Geopoliittisesti neutraali, turvallinen ja päästötön" (This is what a breakthrough in fusion energy means: "Geopolitically neutral, safe and emission-free"). MTV 14.12.2022. https://www.mtvuutiset.fi/artikkeli/tata-kaikkea-tarkoittaa-fuusioenergiassa-tehty-lapimurto-geopoliittisesti-neutraali-turvallinen-ja-paastoton/8591918
- Tuomas Tala: Yhdysvalloissa läpimurto fuusioenergian tuotannossa (US breakthrough in fusion energy production). YLE news 14.12.2022.
- Tuomas Tala: Näin läpimurto fuusioenergian tuotannossa käytännössä tehtiin (How the breakthrough in fusion energy production was made in practice). YLE 14.12.2022. https://yle.fi/a/74-20008627
- Tuomas Tala: Fuusioenergiaan liittyvä läpimurto on merkittävä askel kohti turvallista ja saasteetonta energiantuotantoa (Fusion energy breakthrough is a major step towards safe and pollution-free energy production). MTV news 14.12.2022.
- Antti Hakola: Interview on topical global fusion science news with Radio Suomen iltapäivä – Helsinki 16.12.2022.

4.3 Courses on Fusion studies

Lecture courses at Aalto University, School of Science:

- *Fusion Energy Technology (M. Groth, spring 2022).*
- *Introduction to plasma physics for fusion and space applications (T. Kurki-Suonio, autumn 2022).*
- *Special Course in Advanced Energy Technologies 2 V D: Radiation damage in metals and semiconductors (A. Sand, spring 2022)*

Lecture course at University of Helsinki:

- *Plasma Physics (Prof. Minna Palmroth, autumn 2022)*

MOOC course at University of Helsinki:

- *Radiation damage in materials (Prof. Kai Nordlund, Prof. Flyura Djurabekova, Adj.Prof. Antti Kuronen)*

5. Education and training

5.1 WP EDU: FinnFusion student projects

5.1.1 Overview

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

During 2022, five Doctoral dissertations, one Master's thesis and five Bachelor's theses were completed (see Section 10.4).

5.1.2 Doctoral students

Student: Francis Albert Devasagayam (AU)
Supervisor: Mathias Groth (AU)
Instructor: Timo Kiviniemi (AU), Susan Leerink (AU)
Topic: *Effect of toroidal particle sources on SOL physics in the FT-2 tokamak*
Report: Research activity was focused on understanding the GAM intermittency in the FT-2 tokamak using GENE simulations. Bicoherence analysis was done for finding the non-linear coupling between turbulence and GAMs. The results of this research activity will be published as a paper in the year 2023.

Two dimensionally matched JET discharges namely ICRH and NBI discharges are studied using gyrokinetic simulations for studying the discrepancy obtained between experiments and simulations. This research is still ongoing and will continue during the year 2023.

Student: Ludovico Caveglia Curtil (AU)
Supervisor: Andrea Sand (AU)
Instructor: Andrea Sand (AU)
Topic: *Modelling of electronic energy losses and sputtering events in fusion-relevant materials*
Report: In the past year we studied low energy sputtering of deuterium on low-index Fe surfaces using LAMMPS molecular dynamics (MD) simulations. We focused on the dependence of sputtering yield on ion incidence angle and surface orientation, as well as on the role of electronic stopping, and found good compatibility with results

from experiments and channeling theory. In parallel, we used ab-initio Time Dependent Density Functional Theory to extract the electronic stopping power of hydrogen in Fe along channeling trajectories, for various impact parameters. This stopping power will be integrated in the near future into MD codes for erosion and damage analysis.

Student: Riccardo Nicolo Iorio (AU)
Supervisor: Mathias Groth (AU)
Instructor: Timo Kiviniemi (AU), Eero Hirvijoki (AU)
Topic: *Collisional bracket for the guiding-center Vlasov-Maxwell-Landau model*
Report: ELMFIRE simulations of improved core confinement in FT-2 tokamaks and analysing deviations of the radial electric field from the Hazeltine-Hinton value when turbulent effects are considered was finished and published.
An additional numerical analysis on the effects of impurity density variation in a tokamak pedestal has been performed to validate new theoretical models which depart from the conventional neoclassical results. The presence of steep radial gradient both for temperature and density translates in higher degree ratio of poloidal gyroradius to gradient scale length. Numerical simulations were carried out to test the corrections to the radial electric field in the presence of impurities for main ions in the plateau regime.

Student: Henri Kumpulainen (AU)
Supervisor: Mathias Groth (AU)
Instructor: Mathias Groth (AU)
Topic: *Impurity transport in tokamak edge plasmas*
Report: A combination of predictive edge and core simulations of W erosion and transport in JET-ILW plasmas ranging from L-mode to the highest-performance type-I ELMy H-mode scenarios, using the JINTRAC and ERO2.0 codes, is found to be consistent with the experimentally inferred W density in the main plasma, within the combined uncertainty due to the uncertainty in the measurements of the deuterium plasma conditions and W content in the plasma. ERO2.0 predicts nearly complete screening of the largest gross W erosion sources at both divertor targets. Instead, the predicted W influx to the main plasma is mostly due to erosion by charge-exchange fuel atoms near the low-field side divertor entrance.

Student: Roni Mäenpää (AU)
Supervisor: Mathias Groth (AU)
Instructor: Mathias Groth (AU)
Topic: *Nitrogen transport and chemistry in divertor plasmas*

Report: EDGE2D-EIRENE simulations of nitrogen-seeded partially detached JET L-mode plasmas reproduce the peak intensities of N I to N V as measured by vertically viewing divertor spectrometers to within 50 %. The predicted profiles are narrower than the measured ones. If nitrogen is assumed to recycle exclusively as molecules instead of atoms in these plasmas, ERO2.0 predicts that the N III and N IV intensities in the divertor increase by up to a factor of two, improving agreement with experiment.

Student: Rafael Nuñez (AU)
Supervisor: Andrea Sand (AU)
Instructor: Andrea Sand (AU)
Topic: *Core increased pseudopotentials for electronic stopping calculations in radiation-exposed materials.*
Report: Accurate electronic stopping calculations are important for the radiation damage process, of particular interest in fusion materials. The state-of-the-art technique to calculate the energy losses to the electronic system comes from the rt-TDDFT formalism. It allows us to explore in real-time the non-adiabatic stages of the radiation damage process, and even more, to depict the role of the different electron orbitals involved. In some cases, to get accurate results, it is necessary to increase the number of explicit electrons considered. Since this increases the computational cost of the calculations, it is crucial to study the regions and scenarios where increased-core pseudopotentials are needed.

Student: Patrik Ollus (AU)
Supervisor: Mathias Groth (AU)
Instructors: Antti Snicker (AU)
Topic: *Modelling fast ions in current and future fusion devices under the effect of charge exchange reactions*
Report: Predictions based on ASCOT and TRANSP modelling of fast ions in plasmas of the 1st MAST-U campaign were compared to Fast Ion Deuterium-Alpha measurements and neutron-rate measurements in a fission chamber to validate the ASCOT model for fast-ion charge-exchange. The ambient neutral density was reconstructed based on radially resolved bulk-particle deuterium-alpha measurements. The analysis was made difficult by uncertainties in the calibrations of the bulk-particle deuterium-alpha and fission-chamber measurements. The deuterium-alpha emissivity was scaled based on comparison to emissivity predictions based on neutral-pressure measurements from the 2nd MAST-U campaign. The measured neutron rates were scaled by a temporary scaling factor calculated by experts at MAST-U. Assuming the measurements were scaled correctly, fast-ion deuterium-alpha and

neutron-rate predictions are quantitatively more consistent with the measurements when charge-exchange reactions are accounted for in the fast-ion distributions calculated by ASCOT.

Student: Evgeniia Ponomareva (AU)
Supervisor: Andrea Sand (AU)
Instructor: Andrea Sand (AU)
Topic: *Trajectory dependence of the light ions electronic stopping in plasma-facing components*
Report: The energy losses of slow light ions propagating in plasma-facing components were investigated using time-dependent density-functional theory. Apart from comparing the projectile dynamics in the channeling directions, we analyzed a statistically averaged electronic stopping by studying random trajectories. The latter can be considered the most physically generalized case, relevant when compared to the SRIM data and the most common experiments. By exploiting the correlation between the electronic energy loss and the average electron density the projectile is experiencing on its way, we implemented a pre-sampling algorithm that allows for a relatively fast converging to the averaged electronic stopping value. The next stage of the research project will utilize the advanced understanding of the electronic stopping data through application in molecular dynamics simulations.

Student: David Rees (AU)
Supervisor: Mathias Groth (AU)
Instructors: Mathias Groth (AU)
Topic: *The impact of main ion species on divertor plasma detachment in tokamaks*
Report: Langmuir probe measurements of NBI-heated, L-mode plasmas in JET-ILW show that recycling in He is significantly lower than in otherwise identical D plasmas. In high-recycling conditions, the ion currents were a factor of five lower in He than in D and atomic He pressure were equally lower than molecular D. Experiments were performed in two divertor configurations. Below 5MW ion currents reduced and nearly bifurcated, along with a move of He radiation from the divertor to the core. At 5MW, reduction in ion currents is more gradual, as seen with previous observations of D plasmas. Bolometry shows a move of peak radiation from HFS divertor to LFS divertor/X-point region, with increasing core density.

Student: Iisa Saunamäki (AU)
Supervisor: Andrea Sand (AU)
Instructor: Andrea Sand (AU)

Topic: *Effects on strain on high dose damage state in W, including effects on mechanical properties*

Report: During reactor's lifetime, structural materials experience an environment of complex mechanical stresses and strains which can impact on the gradual accumulation of radiation damage over time This research work aims to investigate the effect of strain on high-dose damage state in W. We have studied by MD simulations the combined effects of external mechanical loading application and cascade overlap on the defect morphology of BCC W, to ultimately mimic the irradiation damage accumulation induced by high-dose ion irradiation. We have studied both tensile and compressive loading conditions with an initial configuration of pristine BCC W crystal, and a pre-damaged W system, where Frenkel pairs are artificially introduced together with an additional 1500 overlapping cascades. The results of this work will provide an understanding of the effects on mechanical properties of damage accumulation under strain in the high-dose irradiation limit.

Student: Filippo Zonta (AU)
Supervisor: Mathias Groth (AU)
Instructor: Eero Hirvijoki (AU)
Topic: *Study of action principles and metriplectic dynamics in plasma physics and their discretization*

Report: A Multi Species structure-preserving numerical scheme for the Landau collision operator has been developed. The scheme is a marker-based discretization of the collisional operator and is able to preserve energy and momentum to machine precision. The scheme has been tested with a highly GPU parallelized code against inhomogeneous temperature relaxation, isotropization, and thermalization examples. This work will help building future structure-preserving schemes for the complete Vlasov-Maxwell-Landau system. The resulting paper has been presented at the Numkin 2022 conference in Munich and included in the PhD thesis that has been written in the second part of the year.

Student: Qingfei Han (LUT)
Supervisor: Heikki Handroos (LUT)
Instructor: Huapeng Wu (LUT)
Topic: *Wall-climbing robot for internal detection of nuclear fusion device*

Report: This research aims to develop a wall-climbing robot, which can carry out surface detection and flaw detection on the surface of the vacuum vessel with a snake-shaped manipulator (equipped with detection equipment at the end). In nature, geckos can stably adhere to and crawl freely on surfaces made of different materials, which depend on the cross-scale regulation mechanism of high stable adhesion and fast and easy detachment. Based on this, the gecko-like multi-level adhesive paws have been designed innovatively and applied to the biomimetic design of wall-climbing robots. Aiming at the working space under vacuum vessel, the snake-shaped manipulator and the end detection equipment are studied. Finally, the integrated design of the wall-climbing robot and the snake-shaped manipulator is completed, which integrates the wall-climbing structure, the snake-shaped manipulator, the drive control and the autonomous detection into one, and combines the advantages of the adaptive control, the crawling gait planning and the autonomous defect detection algorithm to realize the stable crawling and autonomous detection of the wall-climbing robot on the surface of the vacuum vessel.

Student: Changyang Li (LUT)
Supervisor: Huapeng Wu (LUT)
Instructor: Huapeng Wu (LUT)
Topic: *Development and multi-optimization of robot systems in a fusion reactor*
Report: Fusion is the energy source of the sun and stars, a fusion reactor is a machine to harness the fusion energy, where the heat absorbed during the operation is used to produce steam, and then electricity just like in the conventional power plant. Worldwide, fusion reactors are being designed, built, and tested. Currently, the progress of the fusion reactor is still in experimental stage, which will be forward to demonstration stage and commercial stage systematically. In recent years, with the developing of different configurations of the fusion reactor, different robot systems concepts are becoming more and more attractive to perform different tasks in such hazardous environment. Thus, two robot systems for divertor remote handling and vacuum vessel assembly are proposed in this dissertation, among which the robot system for vacuum vessel assembly is manufactured and tested. The simulation and analysis results reveal that the proposed robot systems can carry out their tasks in the fusion reactor, and they show better performance compared with similar or previous robot system proposed by other researchers. Apart from this, multi-objective optimization of parallel mechanism was carried out to optimize the parallel mechanism structure to better fit its specific tasks, the results show the robust of the proposed optimization method, and it can be further adopted in the future robot system design. In addition, a summary of optimization on parallel mechanism was concluded, which can be a guideline for other researchers in the future.

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

Student: Guodong Qin (LUT)
Supervisor: Huapeng Wu (LUT)
Instructor: Huapeng Wu (LUT)
Topic: *Research on Key Technology of Snake Arm Maintainer in CFETR Remote Maintenance System*
Report: The objective of this project was to develop SAM as one of the key subsystems of the CFETR remote handling maintenance system for tasks such as visual inspection and dust removal in the complex pipeline areas of the upper window and the bottom of the divertor in the vacuum chamber. By analyzing the skeleton characteristics of the snake and its geometric form of sinuous movement, an under-actuated SAM design method is proposed. Mounting it on the quick-change interface at the end of the CFETR multipurpose overload robot (CMOR) enables many types of maintenance operations in complex and confined spaces inside the vacuum chamber. The main research content of this dissertation includes (1) A SAM structure design method, (2) A SAM dynamic decoupling algorithm, (3) A SAM adaptive trajectory control algorithm, and (4) A SAM rigid-flexible coupling deformation position error compensation algorithm. The results of the research will be used to meet the practical maintenance requirements of the CFETR vacuum chamber in the divertor and upper window complex pipeline area.

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

Student: Zhixin Yao (LUT)
Supervisor: Huapeng Wu (LUT)
Instructor: Huapeng Wu (LUT)
Topic: *Research on the motion planning and precision control algorithm of the CFETR maintenance manipulator*
Report: The robot system, called CMOR (CFETR multipurpose overload robot), adopts the long cantilever with nine link combination; The main research topics are as follows: 1. Investigate and analyze the current status of multipurpose manipulators for fusion remote handling applications worldwide. 2. Set objective functions; 3. Form training datasets for NN. 4. Vibration control and deformation estimation; 5. Construct the control software; 6. Conduct experiments and analyze results. The experimental results show that the deformation prediction model can quickly calculate the deformation of the manipulator. The precision control algorithm can correct the motion error of the manipulator in real time and ensure the accurate position of the end effector.

Student: Ruochen Yin (LUT)
Supervisor: Huapeng Wu (LUT)
Instructor: Huapeng Wu (LUT)
Topic: *Learning based peg-in-hole Assembly Task for Fusion Application*

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

Student: Laura Maria Goncalves Ribeiro (TUNI)
Supervisor: Atanas Gotchev (TUNI)
Instructor: Atanas Gotchev (TUNI)
Topic: *Vision enhancement in safety critical applications*
Report: The recognition of optical markers on operational targets allows for the accurate estimation of the target’s pose to be used as an aid for remote handling operations. During this year we have worked towards a general marker detection and recognition framework that can be straightforwardly applied to different use cases at ITER. We have built realistic prototypes and tested the developed strategies on two use cases: the knuckle, fitted with the previously developed optimized retro reflective markers; and the pipe flange, using smaller diffuse markers. We have also tested the application of this approach to the bridging link use case on synthetic data and analyzed on a conceptual level it’s use in the cask and plug and neural beam remote handling systems.

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, related to ITER heavy-duty RH operations*
Report: In the ITER vacuum vessel, precise motion and force control of the slave devices are a necessity in order 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 from limited available data. This study focuses on developing feasibility-aware identification and adaptation methods for serial manipulators with arbitrary topology, easing commissioning of nonlinear model-based controllers for such systems.

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

Student: Pejk Amoroso (UH)
Supervisor: Filip Tuomisto (UH)
Instructors: Jonatan Slotte (UH)
Topic: *Characterization of Novel Ge-based Materials for Advanced Radiation Sensors*
Report: Ge-based materials are used for a wide range of radiation detection and sensor applications. Introducing other elements to the germanium lattice enables control of the photonic and electronic properties. The objective of the project is to characterize novel types of doped Ge and Ge-based compound semiconductors, and thus expanding existing research in the field of materials for advanced radiation sensors. Our research is focused on defect characterization in GeSi, GeSn and Ga-doped Ge, as understanding defect behavior is crucial for controlling material properties. The main experimental methods used are Positron Annihilation Spectroscopy (PAS) and Ion Beam Analysis techniques (IBA).

Student: Zhehao Chen (UH)
Supervisor: Filip Tuomisto (UH)
Instructors: Filip Tuomisto (UH)
Topic: *Irradiation damage on high entropy alloys*
Report: High Entropy Alloys (HEAs) are composed of five or more elements with concentrations ranging from 5 to 35 atomic percent. These alloys exhibit excellent irradiation resistance, making them suitable for nuclear material applications. In a reactor irradiation environment, hydrogen and helium are produced through neutron activation reactions of (n, p) and (n, α) within structure materials, respectively. Helium's most significant impact on materials includes void swelling, which leads to degradation. To investigate the effects of helium in HEAs, we utilized arc-melted CoCrFeMnNi (Cantor alloy), 3D-printed Cantor alloy, and 304 stainless steel (as a reference) for conducting the experiments. All samples were irradiated with 3 MeV Ni at a concentration of 1E16 and 500 keV He at 5E17, sequentially. Following irradiation, the samples were annealed at 873K to study helium migration. Helium bubbles or cavities were characterized using Transmission Electron Microscopy (TEM).

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 are going to study radiation damage in FCC high-entropy alloys. Work on single element ML potentials was presented with a poster at the conference of COmputer Simulation of IRradiation Effects in Solids (22 - 26 May 2022, Porquerolles, France) with the title of "Machine learning potentials for FCC materials". In addition, two articles were published during 2022.

Student: Faith Kporha (UH)
Supervisor: Kai Nordlund (UH)
Instructors: Fredric Granberg (UH)
Topic: *Effect of surface morphology on tungsten sputtering and reflection yields*
Report: To better understand how the surface morphology of the plasma wall membrane will affect tungsten sputtering and reflection yields,

work commenced with the development of various levels of supersaturated tungsten surfaces, testing of potentials, performing Molecular Dynamics simulations on pristine and supersaturated surfaces by bombarding them with atomic deuterium ions and molecular deuterium ions at different incident angles and different depths of the simulation cell. A faster and more accurate potential was discovered, and it was seen that the atomic deuterium will be best for further simulations.

Student: Oskar Lappi (UH)
Supervisor: Keijo Heljanko (UH)
Instructor: Jan Åström (CSC)
Topic: *Software quality and performance in large-scale HPC*
Report: This work concentrates on improving computational science tools which struggle to scale to new problem sizes. Performance must improve, but root causes are often issues in software quality. One project is parallelizing the core algorithm of EIRENE, a neutral particle transport solver used by computational fusion scientists. Changes in EIRENE would require fundamental changes in the implementation, we therefore started a new software project: Eiron. Eiron is functionally equivalent to EIRENE for a subset of EIRENE's functionality. Eiron will support multiple designs which will be compared with the intent of providing direction for EIRENE development. The project is still in development.

Student: Victor Lindblad (UH)
Supervisor: Kai Nordlund (UH)
Instructors: Fredric Granberg (UH)
Topic: *Studying kink formations on screw dislocation lines, using MD*
Report: The mechanical properties of metals are partly determined by their screw dislocations and the mobility of these dislocations. It has been shown that the mobility of screw dislocations is greatly dependent on the formation energy of kinks along the dislocations. Thus, being able to determine the formation energies of double-kinks in metals/alloys is an important step in establishing the macroscopic mechanical properties of the material. Determining the formation energy can be done by computational means, using molecular dynamics (MD). For pure elements, the task is trivial, but for alloys, the situation becomes increasingly complex and requires a more elegant approach. Our task has therefore been to design an machine-learning (ML) model that can predict the double-kink formation energy in an arbitrary alloy. The model is still being tested, but preliminary findings seem promising.

Student: Anna Liski (UH)
Supervisor: Filip Tuomisto (UH)
Instructors: Filip Tuomisto (UH), Tommy Ahlgren (UH)
Topic: *High entropy alloys as first wall materials*
Report: High entropy alloys are a novel class of metal alloys with promise towards applicability for extreme environments such as fusion first wall. Our work investigates the alloys from the perspective of their interaction with isotopes of hydrogen. By introducing deuterium into material, the retained quantities and energy of trapping can be measured with ion beam analysis tools and thermal desorption spectrometry. The samples studied are pre-irradiated to achieve the scope of damage ranging from light to heavy prior to the deuterium implantation to investigate possible effects of irradiation damage on retention and interactions.

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 work we focus on the study of using machine learning for efficient energy binding estimation in material dislocations. This involves studying the effects of vacancies in the binding energy of different materials, and using advanced machine learning methods for predicting their impact. For that, we make use of state of the art descriptors as well as machine learning techniques. Once this step is concluded, we want to extend the research to involve more complex dislocations and use not only vacancies but also different atom types, so we can study the binding energy in 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: Ultrawide bandgap semiconductors such as gallium nitride (GaN) and aluminium gallium nitride (AlGaN) are the key elements to development of opto- and power-electronic devices. Routinely, n-type conductivity of such devices can be improved by silicon doping. We combine positron annihilation and near edge x-ray absorption spectroscopies to study the nature of formation of acceptor-like defects in semiconducting nitrides.

Student: Tomi Vuoriheimo (UH)
Supervisor: Filip Tuomisto (UH)

Instructors: Kalle Heinola (IAEA), Tommy Ahlgren (UH)
Topic: *Irradiation-induced defects and their effect to fuel retention in the next step fusion plasma armour materials*
Report: Work during 2022 included finishing experiments on hydrogen isotope exchange in high entropy alloy WMoTaNbV and preparing an article on it. Hydrogen isotope exchange was found to work more efficiently near the surface in this HEA material than in pure W but high hydrogen retention was found to be a major problem. In addition, deuterium retention in W was studied experimentally by TDS and PAS with partially-filled trap sites in self-irradiated W. Further analysis of the results continues in 2023.

Student: Jintong Wu (UH)
Supervisor: Fredric Granberg (UH)
Instructors: Fredric Granberg (UH)
Topic: *High dose irradiation simulation of tungsten*
Report: Our aim is to determine the effects of irradiation on the mechanical properties of tungsten by obtaining atomistic details. Classical molecular dynamics interatomic potentials have been used to validate and benchmark the speed-up method. The exact defect morphology and structure behind the experimental signal is determined through state-of-the-art simulations to provide important information on how different defect morphologies can affect the material's mechanical properties. The results will be verified against experiments to obtain the accurate realistic dose rate irradiation response of tungsten, a fusion relevant material.

Student: Iuliia Zhelezova (UH)
Supervisor: Filip Tuomisto (UH)
Instructors: Filip Tuomisto (UH)
Topic: *Point defect and radiation hardness of beta-Ga_2O_3 semiconductor crystal*
Report: The understanding of vacancy-type defects in Ga_2O_3 crystals is crucial for the development of radiation-resistant materials for fusion reactors. In contrast to earlier experiments in n-type and undoped Ga_2O_3, the proton irradiation was found to dramatically change the positron lifetime in Fe-doped Ga_2O_3. In addition, 3D Doppler experiments show that the overall anisotropy has reduced. Together, these are a clear sign that unrelaxed vacancy-type defects are created in the irradiation, and that the overall defect density before irriadation is significantly lower than in Sn- and Mg-doped Ga_2O_3 crystals. Interestingly, initial data in Mg-doped Ga_2O_3 suggest similar behavior to n-type and undoped Ga_2O_3. These results are exceptionally exciting as they allow for the first time to

determine the nature and densities of vacancy-type defects in Ga_2O_3 crystals.

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

Student: Tom Andersson (VTT)
Supervisor: Hannu Hänninen (AU)
Instructors: Anssi Laukkanen (VTT), Matti Lindroos (VTT)
Topic: *Deformation and Damage Mechanics of Metallic Materials*
Report: The existing crystal plasticity (CP) framework for simulating the mesoscale deformation and damage is extended to be compatible with the copper microstructure. The aim is to introduce a sufficient number of plastic deformation mechanisms and to develop a failure model capable of depicting damage in the material. The effect of local variations in material are evaluated and the model response is compared with experiments and characterization. The basis of this work is a CP material modelling including grain orientation distribution and size, obtained using electron backscatter diffraction (EBSD) and experimental mechanical test data.

Student: Anu Kirjasuo (VTT)
Supervisor: Filip Tuomisto (UH)
Instructors: Antti Salmi (VTT), Tuoma Tala (VTT)
Topic: *Particle and momentum transport in tokamaks*
Report: Understanding particle and momentum transport in tokamaks is very important, because they have a major role on plasma

confinement and density profiles, which are important in fusion energy generation capability of the plasma. Study on source impact in particle transport was continued, database of JET experiments was expanded to cover a large number of pulses from JETPEAK and a smaller database from ASDEX Upgrade was analysed for comparison purposes. Further analysis is needed. Study of intrinsic torque in ohmic JET plasmas was started. The aim is to describe the intrinsic torque profiles required for explaining the experimentally observed intrinsic rotation profiles by performing Jetto analysis.

Student:	Marton Szogradi (VTT)
Supervisor:	Andrea Sand (AU)
Instructor:	Antti Snicker (AU)
Topic:	*The multiphysics calculation chain of DEMO*
Report:	The work entailed the assembly and development of a calculation chain, composed of the ASCOT plasma-physics package, the Serpent Monte Carlo code and the Apros thermal-hydraulic code. ASCOT is utilized to generate source terms for flat-top and transient scenarios, afterwards Serpent uses this data to derive power deposition schemes across the blanket. The heating profiles will be adopted by the integral Apros model of given DEMO configuration, ultimately constituting the full-cycle simulation of DEMO from the plasma chamber to the switchyard of the power plant. The doctoral thesis titled “Multidisciplinary fusion engineering” was defended 4th October 2022 at Aalto University.

5.2 WP TRA: EUROfusion Researcher and Engineering Grants

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

Research scientist: A. Freimanis, VTT

Radiation damage leads to material hardening and embrittlement. Moreover, radiation damage in fusion reactors is expected to be by a magnitude larger than in the current fission reactors. Therefore, novel material and fracture modelling techniques are required to assess the safety of reactor designs made from EUROFER97 structural steel.

The project’s first year focused on studying the basics of radiation materials engineering, surveying literature for available data sets, and developing crystal-plasticity material model that could adequatly describe material behaviour at wide temperature and irradiation damage range

The next year will focus on identifying relevant fracture mechanisms, developing a fracture model, and implementing the material model and the damage model in finite-element and peridynamic modelling software (see Figure 5.1).

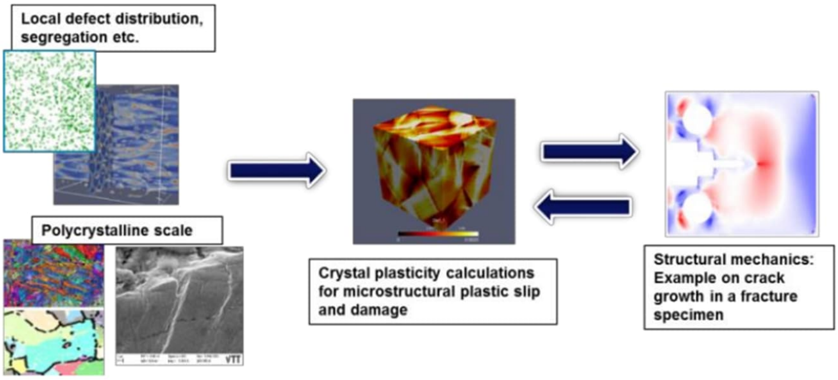


Figure 5.1: Assessment of fracture toughness through multiscale modelling

5.2.2 Insights into fast ion losses and neutron production

Research scientist: L. Sanchis, AU

Isotope effect in W-7X stellarator: The ASCOT code was used to evaluate the effect of different particle species on the fast-ion losses in W7-X. Ions from H and D-beams were simulated in H, D and He plasmas for the standard and high-mirror magnetic configurations. The results showed increased losses in D plasmas with respect to H plasmas in both configurations. Beam-ion losses go from 14% to 30% in the standard configuration, and from 15% to 32% in the high-mirror configuration.

AFSI-Serpent: A tool chain was built to provide a self-consistent neutron model. AFSI, capable of calculating the neutron production in plasmas, has been coupled with Serpent to estimate the neutron transport in fusion devices. The complete chain was applied to a test case using AUG parameters and it is now ready to be validated with JET DT/DT2 campaign data.

Serpent2 neutronics simulations for the DEMO WCLL tritium-breeding mock-up: A 3D model of the WCLL blanket mock-up has been implemented in Serpent2. The estimations of neutron flux and reaction rates were benchmarked against the MCNP code and compared to experimental data with good results. The discrepancy between the codes was below 10% and the comparison of the reaction rates with the experiment showed C/E values between 0.80-0.98 for most cases.

Backward Monte Carlo (BMC) method for improved resolution of wall loads: A method to estimate fast-ion losses based on the BMC scheme was developed and benchmarked against the common Forward Monte Carlo. The two methods were found to agree, and the BMC was shown to increase the statistics of the wall heat load signals by up to x400.

6. International collaborations

6.1 DIII-D tokamak

6.1.1 Comparisons of Electron Temperature, Density and Pressure Profiles in DIII-D Discharges with EDGE2D-EIRENE Predictions

Research scientists: M. Groth, AU

Comparisons of profiles of the electron temperature (T_e), density (n_e) and pressure (p_e) measured with Divertor Thomson Scattering in DIII-D low-confinement mode discharges to predictions from the edge fluid code EDGE2D-EIRENE show that the models implemented in EDGE2D-EIRENE predict the measurements within their collective uncertainties if the T_e at the separatrix ($T_{e,sep}$) is 10 eV, or higher. The simulations do not predict, however, the peaked T_e and n_e profiles measured adjacent to the target plate when $T_{e,sep}$, is below 10 eV, i.e., for the plasma downstream from the region of ionization of deuterium atoms. Inclusion of cross-field drifts and a five-fold reduction of radial transport cannot reconcile the discrepancy between the measurements and predictions.

6.1.2 DIII-D Experiments Shed Light on Particle Transport in H and D Plasmas

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

In collaboration with local experts, we carried out gas modulation experiments on DIII-D to better understand isotope scaling of particle transport in the core and plasma edge. This Deuterium gas experiment was carefully designed to allow comparison with a previous Hydrogen experiment, offering insights into the differences in transport between these isotopes.

Much like the earlier Hydrogen experiment, we utilized both neutral beam heating and electron cyclotron heating to modify the electron to ion temperature ratio. To ensure comparable density and temperature profiles between the isotopes, we scaled the heating and fuelling levels from the Hydrogen discharge, even as we operated at different magnetic field strengths as needed for the identity experiment.

The experiment was a success, in the view of our key diagnostics, such as Thomson scattering, functioned smoothly, displaying clear density modulation, but the dimensional match with the earlier Hydrogen experiment was not perfect. The preliminary analysis of the data has generated enthusiasm for the potential of more detailed studies in the future.

6.2 CFETR tokamak

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

Double doctor degree program with ASIPP on the remote maintenance for CFETR is extended to 2027. The research topics include: 1) The motion planning and precision control algorithm of the CFETR maintenance manipulator. 2) Motion Control of Blanket Remote Maintenance Robot Based on Model Predictive Control Algorithm, 3) Research on fault diagnosis method for hydraulic system of CFETR blanket transfer device based on CNN-LSTM. 4) Parameter identification of CMOR manipulator for the maintenance of CFETR.

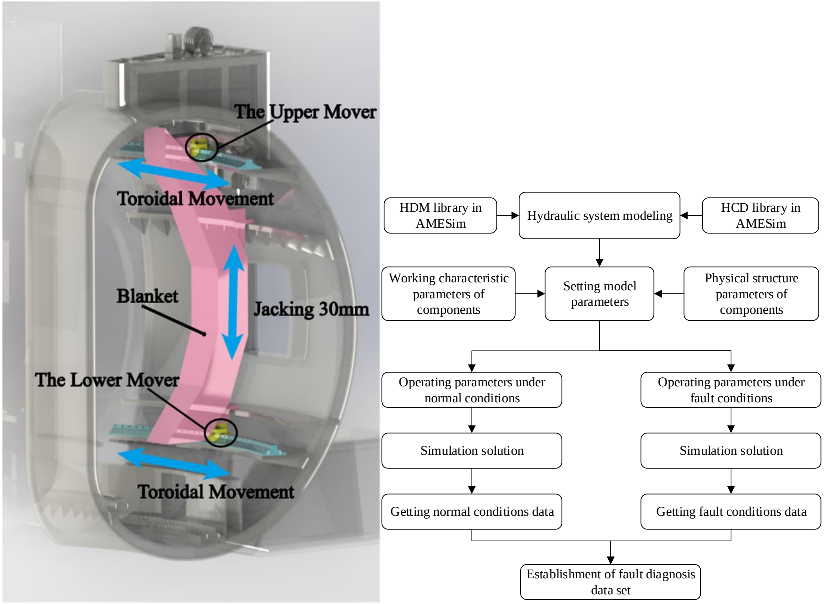


Figure 6.1: Schematic diagram of blanket transportation of CFETR and Simulation of typical faults and dataset establishment.

6.3 KSTAR tokamak

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

Currently the ITPA Multi-machine scaling of intrinsic torque with normalized gyro-radius is based on data from JET, AUG and DIII-D. Experiments were planned at KSTAR to expand the experimental range of ρ* scaling of intrinsic torque and momentum transport. This is expected to increase understanding on whether the ρ* scaling of the intrinsic torque is positive or negative, which in turn is a critical issue for ITER extrapolation.

A 4-point scan in L-mode with beam modulation was completed in July 2022. The scan ranged from Bt/Ip 1.6T/0.43MA to 3.0T/0.8 MA. The initial analysis showed a clear modulation signal in toroidal rotation at 5 Hz modulation frequency and using NBI in 1/8 duty cycle at 55kV. The detailed analysis is ongoing. TRANSP runs have been jointly prepared, adding to the diagnostic data. In the next phase the momentum transport and the intrinsic torque will be analysed in more detail.

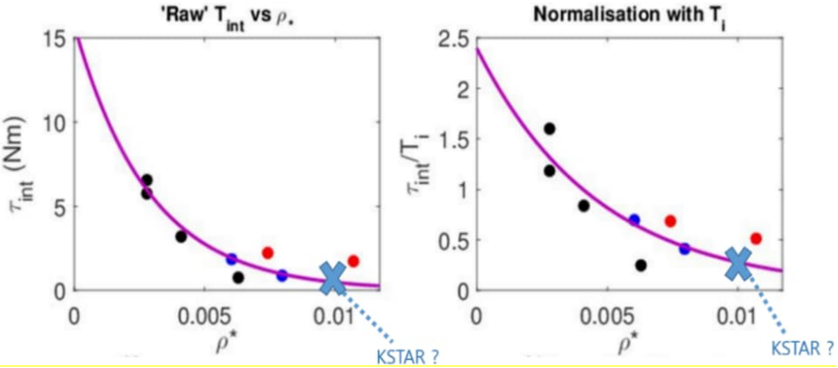


Figure 6.2: Total intrinsic torque τ_{int} integrated from centre up to r/a=1.0. For comparison, ITER NBI torque will be ~35 Nm.

7. Fusion for Energy activities

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

F4E grant: F4E-GRT-0901

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

The development of the High Level Control System (HLCS) subsystems for ITER Remote Handling System (RHS) consists of tasks to develop and integrate Remote Diagnostics System (RDS), Command & Control (C&C) and Virtual Reality (VR). During 2022, the main activity was to run and test the C&C and GENROBOT robot control middleware (both implemented by GTD, a Spanish system and software engineering company), and a water hydraulic digital valve by Tamlink and Fluidconnecto, and the VR application (by VTT) at the Divertor Test Platform (DTP2, hosted by VTT) by performing Central Cassette (CC) remote maintenance operations.

Development of yet another HLCS subsystem, Computer Assisted Teleoperation, was coordinated by Tampere University (TUNI). The 3D Node system uses camera images to detect targets, e.g. the Remote Handling (RH) Equipment, and determine their position and orientation in relation to the environment or instruments such as robotic manipulators (see Figure 7.1). The second round of iterations on the 3D Node was finalized during 2022 by designing an improved retro-reflective marker, developing more robust detection algorithms and extending the system to work with laser markings in order to address additional use cases. Also, the first version of a software stack to interface the 3DNode with HLCS was completed.

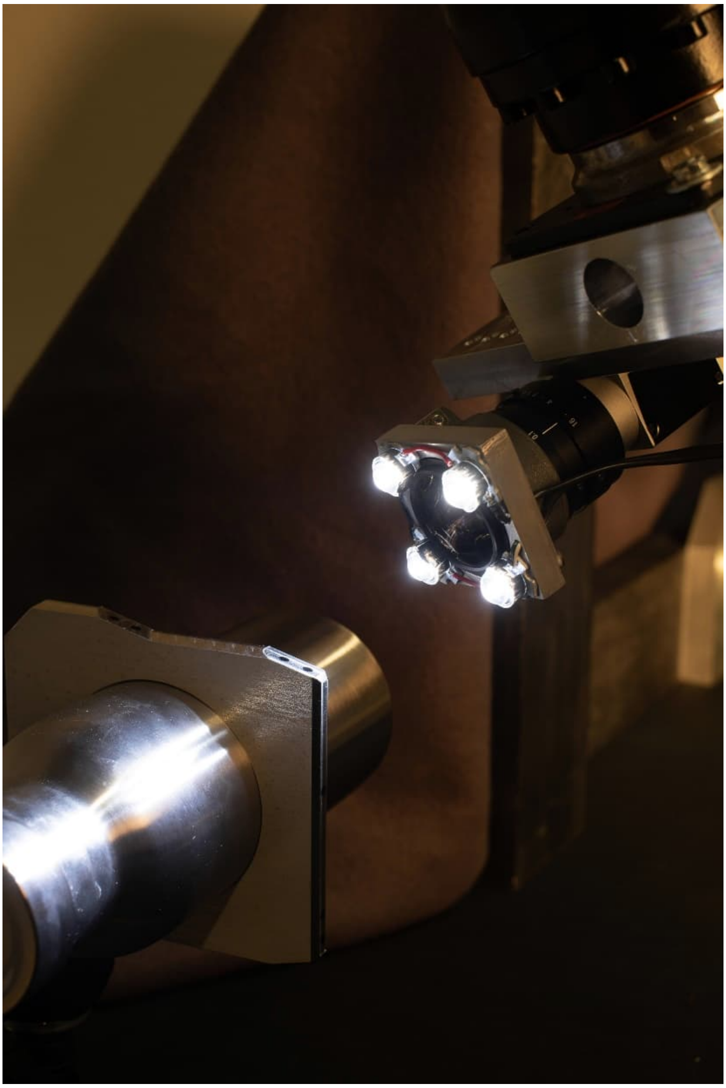


Figure 7.1: 3DNode camera system calculates the pose of an object

8. Completentary research in Finnfusion

8.1 ECO-Fusion activities (VTT)

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

In the ECO-Fusion project, one enabling and cross-cutting topic is to understand better and communicate the needs and activities of the Finnish fusion ecosystem. The aim is to gather and share information about the European fusion ecosystem as one of the Big Science ecosystems and connect this with the knowledge about the Finnish companies and supporting organizations.

This research will help Finnish companies, especially SMEs with limited resources, better understand and evaluate the opportunities that Big Science ecosystems as research and business networks have (see Figure 8.1). On the other hand, through interviews and workshops, views and needs are gathered from the companies, with the help of which supporting organizations can create new and more efficient services for these companies.

The ECO-Fusion project will collaborate with entities like Business Finland, Finnuclear, VTT and ILO to co-innovate new activities, support Finnish companies and connect business and research. Big Science fusion should not be unobtainable out there but a daily opportunity for all.

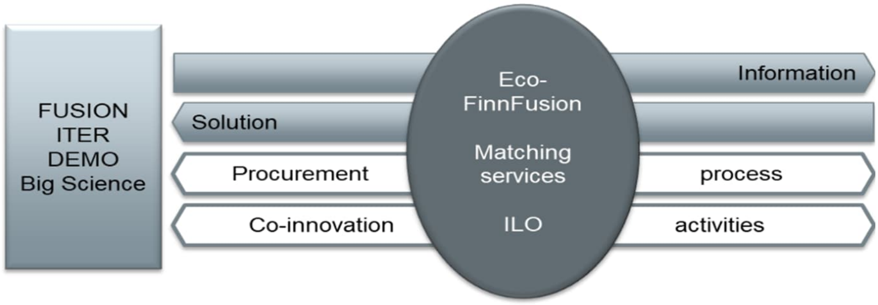


Figure 8.1: Connecting BigScience and Finnish actors

8.2 ECO-Fusion activities (UH)

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

The ECO-Fusion project at UH is a collaboration between the ACH in Finland and Quanscient Ltd, with the goal to transition fusion simulation codes to the quantum era. The Sparselizard open-source C++ finite element library provides a framework for numerical implementation of multiphysics systems and domain-decomposition capabilities for high-performance computing. The collaboration aims to take advantage of these for numerical simulation of models describing the scrape-off layer (SOL) plasma. As a first step, the one-dimensional isothermal fluid approximation for SOL plasma was implemented and successfully validated with analytical solutions. Successively, a diffusive neutral model was implemented so that the neutral and particle source are determined in a self-consistent manner. The self-consistency was further extended by implementing the energy conservation equation to calculate the plasma temperature profile in the SOL. Currently, verification and validation of the energy equation is underway. Subsequently the implementation will be extended to include two-dimensional SOL plasma and parallel computing of the same.

8.3 Partner activities

8.3.1 Comatec Oy, remote maintenance

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

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

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

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

Research scientists: J. Ottelin and P. Ylander

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

8.3.3 Luvata Oy, Heat resistant coppers for fusion reactors

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

Luvata Pori has built the first casting moulds utilizing a calculated solidification model. First series of casting trials have been made with promising results and the work continues to develop parameters further for the production scale.

VTT has continued material research, which bases on the structural model made earlier. Heat resistant copper to be used in fusion reactors has to have a certain grain structure. This structure has to be obtained in all product shapes and forms manufactured with different metallurgical processes. Most advanced material models can simulate these processes and suggest best parameters to achieve the required structure. With these in background the remaining work is to implement this grain structure with the new extrusion press installed in Pori.

8.3.4 Platom Ltd, International Licensing Framework in Challenging Environments

Research scientists: K. Hassinen, S. Kiviluoto, T. Kivirinta, M. Nordlund, S. Sihvola, Platom Ltd

Platom is a company providing expert services in the nuclear field focusing on the main areas of safety, engineering, operability, and licensing, quality, and project management. Platom has joined the Business Finland co-innovation project ECO-Fusion to develop a licensing framework, which can be applied to fusion (as well as other potential new technologies) both internationally and in Finland.

The goal is to create a new model for diligent management of various relations between authority requirements, quality management and other central aspects of licensing processes. This work has started by creating a tool for identifying necessary licensing documentation while also developing ways to manage requirements efficiently. However, during the project it has become clear that in order to maintain such framework it is not enough to focus on technical and quality details. Therefore, as a development project aimig to produce a usable living framework, the efforts have been extended to e.g. competence management and compiling operation experiences from earlier projects. At the same time work is done to survey the licensing practices abroad while actively creating contacts to gain practical knowledge by getting to work within those environments directly.

8.4 STEP collaboration

8.4.1 Scrape-off layer plasma simulations with cross-field drifts for STEP

Research Scientists: A. Järvinen, J. Karhunen, VTT

Spherical Tokamak for Energy Production (STEP) project of UKAEA aims to demonstrate the ability to generate net electricity from fusion. The first phase of the programme is to produce a concept design by 2024, followed by detailed engineering design in second phase, and construction of the prototype power plant in third phase. The aim is to complete the construction of the prototype plant around 2040.

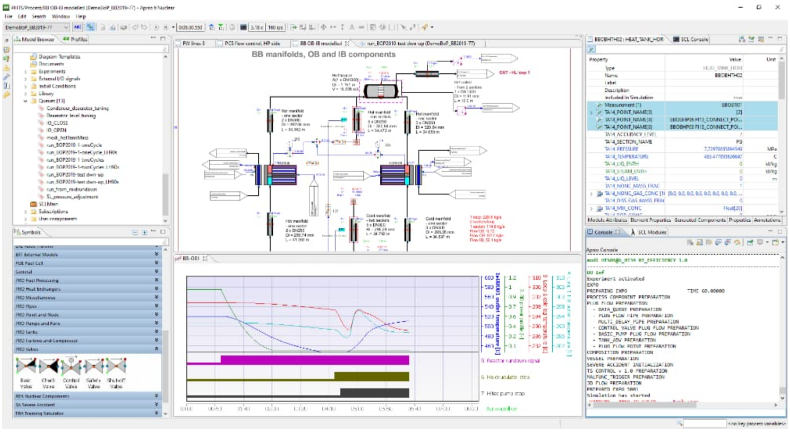
In 2022, VTT has started a project in collaboration with UKAEA to investigate the role of cross-field drifts on the power exhaust properties of the scrape-off layer (SOL) plasmas and on the resulting heat deposition profiles at the wall components of the various STEP designs. These drift terms lead typically to numerically very challenging SOL simulations. The progress made in the first part of the project has indicated previously unaddressed notable changes in the plasma solutions due to effects associated with drifts. The observations will be presented in the 29th IAEA Fusion Energy Conference 16 – 21 October 2023 in London, UK.

8.5 Code development in FinnFusion

8.5.1 Apros

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

Apros is a commercial software platform, owned by VTT and Fortum, for system-wide modelling and dynamic simulation of process, automation and electrical systems. The scope of applications varies from small computational experiments to full-scope training simulators of industrial plants, both in the conventional and nuclear fields. The thermal hydraulic (T/H) model library features different sets of governing equations for one dimensional water/steam/gas flow (homogeneous and 6-eq.) and for a wide range of other fluids (homogeneous). T/H models have been validated against a set of separate effect tests and integral tests. A simulation model is built and configured with a graphical user interface (see Figure 3). Within EUROfusion, several alternatives of Balance-of-Plant (BoP) configurations have been developed and investigated during the Pre-conceptual Design Phase of DEMO by means of dynamic simulations of normal operation of the plant. This work continues in the Conceptual Design Phase.



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  - CONTROL_VALVE PLUG FLOW PREPARATION
  - BASIC_PUMP PLUG FLOW PREPARATION
  - TANK_ADW PREPARATION
  - PLUG FLOW POINT PREPARATION
COMPOSITION PREPARATION
VESSEL PREPARATION
SEVERE ACCIDENT INITIALIZATION
TS CONTROL v 1.0 PREPARATION
MALFUNC_TRIGGER PREPARATION
3D FLOW PREPARATION
PREPARED EXPO 5001
Simulation has started
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Figure 8.2: Apros user interface.

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

Research Scientists: E. Hirvijoki, J. Kontula, T. Kurki-Suonio, P. Ollus, L. Sanchis, S. Sipilä, F. Zonta, AU

AFSI-Serpent: A tool chain was built to provide a self-consistent neutron model. AFSI, capable of calculating the neutron production in plasmas, has been coupled with Serpent to estimate the neutron transport in fusion devices. The complete chain was applied to a test case using AUG parameters and it is now ready to be validated with JET DT/DT2 campaign data.

Backward Monte Carlo (BMC) method for improved resolution of wall loads: A method to estimate fast-ion losses based on the BMC scheme was developed and benchmarked against the common Forward Monte Carlo. The two methods were found to agree and the BMC was shown to increase the statistics of the wall heat load signals by up to x400.

With the IMAS support and ICRH capability of ASCOT5 under development, support for ICRH simulation capable ASCOT4-RFOF and basic ASCOT4 in the IMAS environment was continued. Requested code changes were made to further improve bookkeeping and input/output of simulated distributions from multiple marker species and different sources.

8.5.3 Full-f gyrokinetic turbulence code ELMFIRE

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

New subroutine to take into account ionization loss of electrons was implemented to gyrokinetic full-f particle-in-cell plasma simulation code ELMFIRE by generating locations for the ionization events, selecting nearby electrons to be responsible for the ionization of the neutral, and finally decreasing the kinetic energy of that electron.

The validity of the code was demonstrated by running two identical simulations of a limiter tokamak with and without the electron loss subroutine enabled and comparing the total kinetic and potential energies of the plasmas in each simulation. The subroutine was found to work as expected, although the limitations of the model are beginning to show when using high ionization costs.

8.5.4 Molecular Dynamics

Research Scientists:	J. Byggmästar, F. Granberg, A. Kuronen, K. Nordlund, UH

Molecular dynamics is the most widely used technique to investigate the atomistic evolution of systems under irradiation. To describe the system with sufficient accuracy, a good interatomic potential is needed. We have focused on developing and generating new interatomic potentials with the Gaussian Approximation Potential (GAP) formalism, and the much more efficient tabulated version (tabGAP). The accuracy of these potentials is close to DFT, but the efficiency is not much lower than traditional potentials, especially the tabulated version. Interatomic potentials for fusion relevant materials such as W, Fe and different HEAs have been developed and tested during 2022.

9. Other activities

9.1 Missions and secondments

Tuomas Tala to JET facilities, Culham, United Kingdom, 31 January – 2 February 2022 (WPTE).

Antti Hakola to JET facilities, Culham, United Kingdom, 21 February – 2 March 2022 (WPTE).

Anu Kirjasuo and Tuomas Tala to Max-Planck-Institut für Plasmaphysik (ASDEX Upgrade tokamak), Garching, Germany, 3 – 7 April 2022 (WPTE).

Tuomas Tala to JET facilities, Culham, United Kingdom, 5 – 9 June 2022 (WPTE).

Antti Hakola to JET facilities, Culham, United Kingdom, 6 – 9 June 2022 (WPTE).

Fredric Granberg, Victor Lindblad, Andrea Sand, and Iisa Saunamäki attended IREMEV monitoring meeting, Garching, Germany, 7 - 9 June 2022.

Tuomas Tala participated in F4E Governing Board meeting in Brussels, Belgium, 13 June 2022.

Tuomas Tala to JET facilities, Culham, United Kingdom, 20 June – 2 July 2022 (WPTE).

Antti Hakola to CEA Cadrache (WEST tokamak), Saint-Paul-Lez-Durance, France, 29 June – 6 July 2022 (WPTE).

Antti Hakola and Anu Kirjasuo to Max-Planck-Institut für Plasmaphysik (ASDEX Upgrade tokamak), Garching, Germany, 17 – 21 July 2022 (WPTE).

Tuomas Tala to Max-Planck-Institut für Plasmaphysik (ASDEX Upgrade tokamak), Garching, Germany, 18 – 22 July 2022 (WPTE).

Mathias Groth to ASDEX Upgrade, IPP Garching, Germany, 18 - 28 July 2022 (WPTE).

Aaro Järvinen to Culham Centre for Fusion Energy, UKAEA, United Kingdrom, 5 – 9 September 2022.

Juuso Karhunen to STEP facilities, UKAEA, Culham, United Kingdom, 5 – 16 September 2022.

Andrea Sand participated in Eurofusion HPC Short Allocation Committee Meeting on 6 September 2022.

Antti Hakola to JET facilities, Culham, United Kingdom, 11 – 15 September 2022 (WPTE).

Anu Kirjasuo and Tuomas Tala to JET facilities, Culham, United Kingdom, 25 – 30 September 2022 (WPTE).

Mathias Groth to FZ Juelich, Germany, 26-27 September 2022 (WPPMIE).

Juuso Karhunen to JET facilities, Culham, United Kingdom, 29 September – 21 October 2022.

Antti Hakola, Anu Kirjasuo and Tuomas Tala to JET facilities, Culham, United Kingdom, 9 – 14 October 2022 (WPTE).

Tuomas Tala to JET facilities, Culham, United Kingdom, 16 - 19 October 2022 (WPTE).

Mathias Groth to DIII-D, General Atomics, San Diego, USA, 16 October – 14 November 2022 (WPTE, International Missions).

Antti Hakola to JET facilities, Culham, United Kingdom, 2 – 5 November 2022 (WPTE).

Juuso Karhunen to STEP facilities, UKAEA, Culham, United Kingdom, 7 - 11 November 2022.

Tuomas Tala to JET facilities, Culham, United Kingdom, 13 - 23 November 2022 (WPTE).

Anu Kirjasuo to JET facilities, Culham, United Kingdom, 15 - 22 November 2022 (WPTE).

Juuso Karhunen to STEP facilities, UKAEA, Culham, United Kingdom, 18 - 25 November 2022.

Tomi Vuoriheimo to IPP, Garching, Germany, 21 - 25 November 2022 (WPTE).

Antti Hakola to Max-Planck-Institut für Plasmaphysik, Garching, Germany, 23 – 25 November 2022 (WPTE).

Antti Salmi to JET facilities, Culham, United Kingdom, 24 - 28 November 2022 (WPTE).

Antti Hakola to JET facilities, Culham, United Kingdom, 27 November – 4 December 2022 (WPTE).

Jari Likonen to JET facilities, Culham, United Kingdom, 4 – 9 December 2022 (WPPWIE).

Patrik Ollus to MAST-U, Culham, UK, 12 – 21 December 2022 (WPTE).

9.2 Conferences, seminars, workshops, and meetings

Markus Airila participated in the 4th EUROfusion FSD Tokamaks Board meeting (virtual), 14 March 2022.

Antti Hakola and Tuomas Tala participated in the Nordic ITER Business Forum, Copenhagen, Denmark, 29 – 30 March 2022.

Francis Albert participated remotely in 2022 Joint US-EU Transport Task Force workshop, 5 – 8 April 2022.

William Brace, Andris Freimanis, Fredric Granberg, Amin Hakamenish, Tuula Hakkarainen, Antti Hakola, Tatu Harviainen, Aaro Järvinen, Petteri Lappalainen, Changyang Li, Ming Li, Jari Likonen, Alexandra Viitanen, Huapeng Wu, Ruochen Yin participated in the Nuclear Energy Ecosystems – Open Business Day 2022, Helsinki, 3 – 4 May 2022.

Aaro Järvinen participated in 9th Runaway Electron Modelling Meeting in Garching, Germany, 5 – 6 May 2022. (WPAC).

Fredric Granberg participated in Spring MRS, Honolulu, Hawaii, USA, 8-13 May 2022.

Antti Snicker participated in ITER Scientist Fellow visit to ITER, France, 16 – 26 May 2022.

Aslak Fellman, Fredric Granberg and Jintong Wu participated in The 15th conference of COmputer Simulation of IRradiation Effects in Solids, Cosires, Porquerolles, France, 23 – 26 May 2022.

Aaro Järvinen participated in the Fair4Fusion final meeting in Gothenburg, Sweden, 24 – 25 May 2022. (WPAC)

Victor Lindblad attended IREMEV monitoring meeting, IPP Garching, Germany, 7 – 9 June 2022.

Mikko Siuko participated in DONES project meeting, Granada, Spain, 6 – 11 June 2022.

Ray Chandra, Mathias Groth, Andreas Holm, Antti Hakola, Aaro Järvinen, Juuso Karhunen, Adam Kit, Henri Kumpulainen, Jari Likonen, Roni Mäenpää and Tomi Vuoriheimo participated in the 25th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Virtual Conference, 13 – 17 June 2022.

Fredric Granberg, Victor Lindblad and Jintong Wu participated in 29th international conference on atomic collisions in solids & 11th international symposium on swift heavy ions in matter, ICACS-SHIM, Helsinki, Finland, 19-24 June 2022.

Olli Soppela participated in Fusion Industry School Week 1 in York, UK, 19 - 22 June 2022.

Timo Kiviniemi and Francis Albert participated remotely in 48th EPS conference 27 June to 1 July 2023.

Tuomas Tala participated in General Assembly meeting in Brussels, Belgium, 3 – 5 July 2022.

Francis Albert participated in FuseNet PhD event in Padova, Italy, 4-6 July 2022.

Markus Airila participated in the 46th Fusion for Energy Governing Board Meeting, Barcelona, Spain, 9–10 July 2022.

Anu Kirjasuo participated in Summer school on microwaves in York university, UK, on 11 - 15 July 2022.

Aaro Järvinen and Adam Kit participated in the ENR-MOD.01.FZJ progress meeting hosted by the Advanced Computing Hub at the University of Helsinki, 29 August – 2 September 2022. (WPENR).

Laura Goncalves Ribeiro participated in 10th European Workshop on Visual Information Processing (EUVIP) in Lisbon, Portugal, 11 - 14 September 2022.

Janne Lyytinen and Petri Tikka participated in SOFT 2022, the 32nd Symposium on Fusion Technology in Dubrovnik, Croatia 18 – 23 September 2022.

Olli Soppela participated in Fusion Industry School Week 2 in Oxford and Culham, UK, 25 - 28 September 2022.

Fredric Granberg participated in the 10th International Conference on Multiscale Materials Modeling, Baltimore, Maryland, USA, 2-7 October 2022.

Olli Soppela participated in Big Science Business Forum in Granada, Spain, 4 - 7 October 2022.

Antti Hakola participated in the 2nd DEMO WPPRD Workshop, Lausanne, Switzerland, 5 – 7 October 2022.

Lionel Hulttinen participated in the 2022 IEEE Global Fluid Power Society PhD Symposium in Naples, Italy on 12-14 October 2022.

Antti Hakola participated in the 32nd ITPA meeting of TG SOL and divertor physics, Saint-Paul-Lez-Durance, France, 23 – 29 October 2022.

Tuomas Tala participated in the 32nd ITPA meeting of TG Transport, Saint-Paul-Lez-Durance, France, 23 – 29 October 2022.

Fredric Granberg and Jintong Wu participated in NUMAT, Ghent, Belgium, 24-28 October 2022.

Markus Airila participated in the 1st EUROfusion FSD Board meeting, Garching, Germany, 26 October 2022.

Antti Hakola, Atte Helminen, Essi Immonen, Seppo Sipilä, Antti Snicker, Olli Soppela, Tuomas Tala and Tero Tyrväinen participated in the Nuclear Science and Technology Symposium 2022 (SYP2022), Helsinki, 1 – 2 November 2022.

Aaro Järvinen participated in the 4th IAEA Technical Meeting on Divertor Concepts in Vienna, Austria, 7 – 10 November 2022. (WPPWIE)

Filippo Zonta and Eero Hirvijoki participated in NumKin workshop in Garching, Germany, 7-10 November 2022.

Petteri Lappalainen participated in the WPMAT IRRAD Monitoring of EUROfusion meeting, Garching, Germany, 14 November 2022.

Juuso Karhunen and Roni Mäenpää participated in SOLPS-ITER workshop on extended grid version workshop at KU Leuven, Belgium, 14 – 18 November 2022.

Aaro Järvinen and Adam Kit participated in the FCAI AI Day in Espoo, Finland, 16 November 2022. (WPENR).

Andris Freimanis participated in EUROfusion meeting and presented the progress of engineering grant, Garching, Germany 16 – 18 November 2022.

Fredric Granberg participated in Finlandssvenska Fysik och Kemidagarna, Finland, 18 - 20 November 2022.

Fredric Granberg, Victor Lindblad, and Andrea Sand attended IREMEV monitoring meeting, Garching, Germany, 21 - 23 November 2022.

Ray Chandra participated in TSVV-5 Workshop, KU Leuven, 21 - 24 November 2022.

Patrik Ollus and Antti Snicker participated in ITPA-EP meeting at ITER, France, 21 – 25 November 2022.

Anssi Laukkanen participated in WPPRD monitoring meeting, IPP Garching, Germany 29 November – 1 December 2022.

Tuomas Tala participated in F4E Governing Board meeting in Barcelona, Spain, 1 – 2 December 2022.

Markus Airila participated in the 8th EUROfusion Working Group for Licensing of Fusion meeting, Garching, Germany, 5 December 2022.

Seppo Sipilä participated in the 3rd Fusion High Performance Computing Workshop (online event), 15 – 16 December 2022

Markus Airila participated in the six virtual meetings of the EUROfusion Working Group for Licensing of Fusion during 2022.

9.3 Visitors

Juuso Karhunen from UKAEA, Culham, the United Kingdom, visited VTT in 12 – 13 May 2022.

Jasper Ristkok from University of Tartu, Tartu, Estonia, visited VTT in 12 – 16 May 2022.

Alicia Marin Roldan from Comenius University, Bratislava, Slovakia, visited VTT in 12 – 20 May 2022.

Peeter Paris from University of Tartu, Tartu, Estonia, visited VTT in 12 – 20 May 2022.

Wojciech Gromelski from IPPLM, Warsaw, Poland, visited VTT in 16 – 20 May 2022.

Salvatore Almaviva from ENEA, Frascati, Italy, visited VTT 17 – 20 May 2022.

Paul Coad from UKAEA, Culham, the United Kingdom, visited VTT in 22 – 26 May 2022.

Steve Lisgo of Pylon Energy, Canada, visited Aalto University 8 - 31 August 2022.

Francesco Sciortino of Institute for Plasma Physics, Garching, Germany, visited Aalto University 15 - 26 August 2022.

The Advanced Computing Hub hosted an onsite progress meeting for the ENR-MOD.01.FZJ at the University of Helsinki, 29 August – 2 September 2022. Participating scientists were Sven Wiesen (FZJ), Stefan Dasbach (FZJ), Andreas Gillgren (Chalmers), Aaron Ho (DIFFER), Alex Panera (DIFFER), Yoeri Poels (TuE), Adam Kit (UH), Aaro Järvinen (VTT). (WPAC / WPENR)

10. Publications 2021

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

10.1 Refereed journal articles

1. C.A. Hirst, F. Granberg, B. Kombaiah, P. Cao, S. Middlemas, R.S. Kemp, J., Li, K. Nordlund and M.P. Short, Revealing hidden defects through stored energy measurements of radiation damage, Science Advances **8** (2022), eabn2733.
2. Y. Ruochen, Y. Cheng, H. Wu, Y. Song, B. Yu and R. Niu, Fusion Lane: Multi-Sensor Fusion for Lane Marking Semantic Segmentation Using Deep Neural Networks, IEEE Transactions on Intelligent Transportation Systems **23** (2022) 1543.
3. G. Qin, H. Wu, Y. Cheng, H. Pan, W. Zhao, S. Shi, Y. Song and A. Ji, Adaptive trajectory control of an under-actuated snake robot, Applied Mathematical Modelling **106** (2022) 756.
4. A. Lopez-Cazalilla, C. Cupak, M. Fellinger, F. Granberg, P.S. Szabo, A. Mutzke, K. Nordlund, F. Aumayr and R. Gonzalez-Arrabal, Comparative study regarding the sputtering yield of nano-columnar tungsten surfaces under Ar^+ irradiation, Physical Review Materials **6 (**2022) 075402.
5. A. Liski, T. Vuoriheimo, P. Jalkanen, K. Mizohata, E. Lu, J. Likonen, J. Heino, K. Heinola, Y. Zayachuk, A. Widdowson, K.-K. Tseng, C.-W. Tsai, J.-W. Yeh, F. Tuomisto and T. Ahlgren, Irradiation Damage Independent Deuterium Retention in WMoTaNbV, Materials **15** (2022) 7296.
6. A. Fellman and A.E. Sand, Recoil energy dependence of primary radiation damage in tungsten from cascade overlap with voids, Journal of Nuclear Materials **572** (2022) 154020.
7. A. Hekmatmanesh, H. Wu, M. Li and H. Handroos, A Combined Projection for Remote Control of a Vehicle Based on Movement Imagination: A Single Trial Brain Computer Interface Study, IEEE Access **10** (2022) 6165.
8. S. Ustinov, H. Wu and H. Handroos, A Hybrid Model for Fast and Efficient Simulation of Fluid Power Circuits With Small Volumes Utilizing a Recurrent Neural Network, IEEE Access **10** (2022) 48824.
9. Q. Wang, H. Wu, Y. Cheng, P. Hongtalo, Y. Yang and Q. Guodong, Friction-identification of harmonic drive joints based on the MCMC method, IEEE Access **10** (2022) 125893.
10. A. Esfandiarpour, J. Byggmästar, J.P. Balbuena, M.J. Caturla, K. Nordlund and F. Granberg, Effect of cascade overlap and C15 clusters on the damage evolution in Fe: An OKMC study, Materialia **21** (2022) 101344.
11. K. Airola, S. Mertin, J. Likonen, E. Hartikainen, K. Mizohata, J. R. Dekker, A. T. Sebastian and T. Pensala, High-fidelity patterning of AlN and ScAlN thin films with wet chemical etching, Materialia **22** (2022) 101403.
12. P. Cano-Megias, E. Viezzer, J. Galdon-Quiroga, L. Sanchis, M. Garcia-Munoz, D.J. Cruz-Zabala, R.M. McDermott, J.F. Rivero-Rodriguez, A. Snicker, W.A. Suttrop and M. Willensdorfer, Fast-ion transport and toroidal rotation response to externally applied magnetic perturbations at the ASDEX Upgrade tokamak, Nuclear Fusion **62** (2022) 07605.

13. F. Zonta, L. Sanchis and E. Hirvijoki, A backward Monte Carlo method for fast-ion-loss simulations, Nuclear Fusion **62** (2022) 26010.

14. M. Reinhart, S. Brezinsek, A. Kirschner, J. W. Coenen, T. Schwarz-Selinger, K. Schmid, A. Hakola, H. van der Meiden, R. Dejarnac, E. Tsitrone, R. Doerner, M. Baldwin and D. Nishijima, Latest results of Eurofusion plasma-facing components research in the areas of power loading, material erosion and fuel retention, Nuclear Fusion **62** (2022) 42013.

15. M.E. Fenstermacher, M. Groth, A. Holm, A. Järvinen, A. Salmi and T. Tala, DIII-D research advancing the physics basis for optimizing the tokamak apparoch to fusion energy, Nuclear Fusion **62** (2022) 42024.

16. T. Tala, F. Eriksson, P. Mantica, A. Mariani, Antti Salmi, E.R. Solano, I.S. Carvalho, A. Chomiczewska, E. Delabie, J. Ferreira, E. Fransson, L. Horvath, P. Jacquet, D. King, Anu Kirjasuo, S. Leerink, E. Lerche, C. Maggi, M. Marin, M. MaslovS. Menmuir, R.B. Morales, V. Naulin, M.F.F. Nave, Henrik Nordman, C. Perez Von Thun, P.a. Schneider, M. Sertoli, K. Tanaka, Role of NBI fuelling in contributing to density peaking between the ICRH and NBI identity plasmas on JET, Nuclear Fusion **62** (2022) 066008.

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10.2 Conference presentations

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30. F. Granberg, J. Wu, D.R. Mason and J. Byggmastar, High-Dose Accumulation of Defects in Fusion Relevant Materials under irradiation, 10th International Conference on Multiscale Materials Modeling, 2 October 2022.
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32. X. Zhang, F. Zhao, X. Zhang, C. Wan, Z. Zhou, Y. Hu, J. Liu and H. Wu, A General Fault Prediction Framework based on Relationship Mining and Graph Neural Network, Global Reliability and Prognostics and Health Management (PHM-Yantai), 13 October 2022.
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38. F. Granberg, J. Wu, E. Levo, J. Byggmästar, C. Hirst, D. Mason, M. Short and K. Nordlund, Högdosstrålningssimuleringar av fusionsmaterial, Finlandssvenska Fysik och Kemidagarna, 18 November.

10.3 Research reports

1. A. Kirjasuo and J. Likonen (eds.), FinnFusion Yearbook 2021, VTT Technology **405** (2022).
2. M. Airila, T. Lavonen and A. Leskinen, Waste inventories assessment for liquid waste streams and techniques for waste reduction, Deliverable SAE.S-05.02-T001-D002 (EFDA_D_2MDTVS)

10.4 Academic theses

1. Andreas Holm, Role of hydrogenic molecules in fusion-relevant divertor plasmas, PhD thesis, Aalto University, Espoo, 2022.
2. Changyang Li, Design and analysis of robot for the maintenance of divertor in DEMO fusion reactor, PhD Thesis, LUT university, 2022.
3. Quodong Qin, Research on key technologies of snake arm maintainers in extreme environments, PhD Thesis, LUT university, 2022
4. M. Szogradi, Multidisciplinary fusion engineering, PhD Thesis, Aalto University, Espoo, 2022.
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11. Otso Hyvärinen, Development of a field line tracingtool for thermal power load analysis, BSc thesis, Aalto University, Espoo, 2022.

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Title	**FinnFusion Yearbook 2022**
Author(s)	Anu Kirjasuo and Jari Likonen (Eds.)
Abstract	This Yearbook summarises the 2022 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 University. FinnFusion participates in several EUROfusion work packages, the largest being experimental campaigns at JET and ASDEX Upgrade and related analyses, advanced computing, materials research, plasma-facing components and remote maintenance. F4E projects in 2022 focused on the development of the High Level Control System subsystems for ITER Remote Handling System. EUROfusion supports post-graduate training through the Education work package that allowed FinnFusion to partly fund 37 PhD students in FinnFusion member organizations. In addition, two EUROfusion Researcher and Engineering Grants were running in 2022. The FinnFusion annual seminar 2022 was coupled with two other Nuclear Ecosystems (SMRs and Decommissioning) in an event called Nuclear Energy Ecosystems' Open Business Day 2022. The event was organized by VTT in co-operation with FinNuclear and jointly funded by Business Finland co-innovation projects EcoSMR, dECOmm, ECO-Fusion and project FINUELS.
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Nimeke	**FinnFusion vuosikirja 2022**
Tekijä(t)	Anu Kirjasuo ja Jari Likonen (toim.)
Tiivistelmä	Tähän vuosikirjaan on koottu FinnFusion-konsortion vuoden 2022 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 JET- ja ASDEX Upgrade -koelaitteissa tehtäviin kokeisiin ja analyyseihin, kehittyneen tietojenkäsittelyn keskukseen, materiaalitutkimukseen, ensiseinämäkomponentteihin ja etäkäsittelyyn. FinnFusionin F4E-työt liittyivät ITERin etäkäsittelyn järjestelmätason suunnitteluun ja etäkäsittelyn ohjelmistokehitykseen. EUROfusion tukee jatko-opiskelua omalla rahoitusinstrumentillaan, jonka turvin FinnFusion rahoitti osittain 37 jatko-opiskelijan työtä jäsenorganisaatioissaan. Lisäksi vuoden 2022 aikana oli käynnissä kaksi EUROfusionin rahoittamaa Researcher and Engineering Grants projektia. FinnFusion vuosiseminaarí järjestettiin Nuclear Energy Ecosystems – Open Business Day 2022 -tilaisuudessa yhdessä kahden muun ydinenergia-alan ekosysteemin (SMRs and Decommissioning) kanssa. Tapahtuman järjesti VTT yhteistyössä FinNuclearin kanssa. Rahoittajina toimivat Business Finland:n co-innovation yhteishankkeet EcoSMR, dECOmm, ECO-Fusion sekä FINUELS projekti
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