VTT TECHNOLOGY 405 FinnFusion Yearbook 2021

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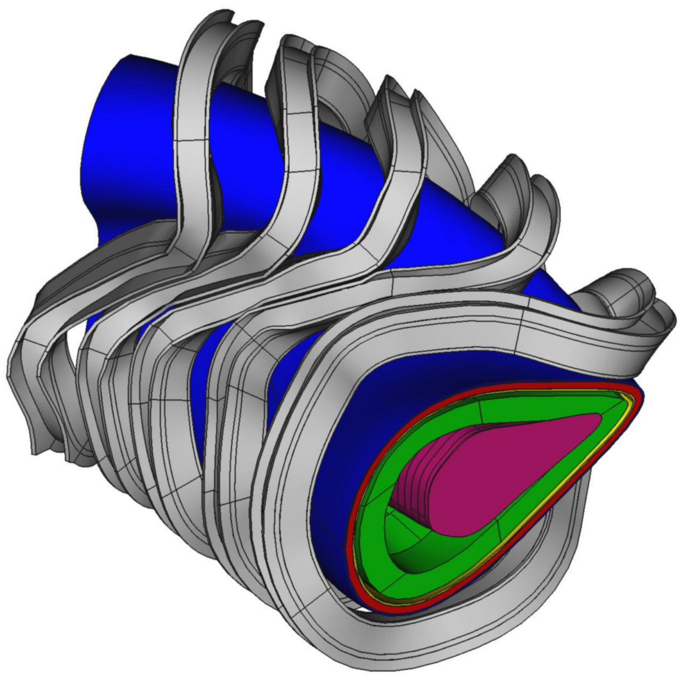

FinnFusion Yearbook 2021

Anu Kirjasuo | Jari Likonen (Eds.) |

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VTT Technical Research Centre of Finland Ltd

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Preface

A year ago I started this Preface of the FinnFusion Annual Yearbook by looking ahead of many new great opportunities for 2021 to come, like the start of the European Framework Program FP9 in 2021-2027, the ITER assembly with vacuum vessel sectors, magnets and cryostat on site, the JET DT campaign, the EUROfusion Advanced Computing Hub at UH Kumpula Campus and life without any major impact of the COVID-19 pandemic. Now a year later, I can happily state that at least all the fusion related opportunities have worked out really well, and indeed, we are just not looking ahead, but things are really on-going.

The most remarkable achievement in the world-wide fusion energy research in 2021 was by far the new fusion energy record in JET ─ record-breaking 59 megajoules of sustained fusion energy. These landmark results from EUROfusion scientists and engineers working for JET were in line with predictions, strengthening the case for ITER ─ the JET record results are the clearest demonstration in a quarter of a century of the potential for fusion energy to deliver safe and sustainable low-carbon energy. I myself had the pleasure to contribute to the JET DT campaign onsite, which on its other side of the coin, also gives another indication very much looked forward to, i.e. COVID-19 pandemic is gradually easing up. The scientific results will be analysed and published in 2022 and the FinnFusion researchers are actively participating in these fascinating tasks.

Year 2021 was also the most successful year ever from the FinnFusion funding point of view. EUROfusion awarded approximately 20M€ of fusion research funding to FinnFusion for years 2021-2025. And it was not just the funding but even more the amount and magnitude of brand new openings in Finnish fusion research. The largest one is the Advanced Computing Hub granted to FinnFusion hosted by UH, but there are also several other new research FinnFusion initiatives receiving EUROfusion funding as follows: breeding blanket studies (WPBB), magnet conductor/insulator research (WPMAG), DONES viewing system development for RM (WPENS), silicon optics steady-state magnetic field sensor design (WPENR), nuclear waste and decommissioning tasks (WPSAE), HHFM Materials Modelling (WPMAT+WPPRD), hot-cell work on irradiated materials analysis (WPMAT), ion implantation and irradiation, positron annihilation spectroscopy (WPPWIE), materials modelling at Aalto (WPPRD), remote maintenance tasks at LUT (WPRM), and fusion power plant fire hazard studies (WPSAE). Furthermore, the EUROfusion education funding to FinnFusion students increased by 30% to 429k€/y and subcontractor funding was granted to FinnFusion in WPMAG, WPRM, WPSAE and WPBOB.

While year 2021 was very remarkable for world-wide fusion thanks to the successful JET DT campaign, it certainly was also for FinnFusion itself ─ Business Finland granted around 4M€ for FinnFusion research units and around 2M€ for the four Finnish companies. The funded fusion co-innovation entity called *ECO-Fusion* has the following high-level goals: (i) through well-targeted fusion research, facilitate the entry to international fusion tenders and research projects for Finnish companies and academia, (ii) build a fusion ecosystem for Finnish companies to reach the development targets from the ordinary company to the international high-tech service provider, and (iii) advance industry's and academia's scientific, technological and business expertise in fusion related high-tech area. The ECO-Fusion funding has made it possible to start several new fusion research openings listed above. One of the ECO-Fusion projects is the largest ever single FinnFusion project, the E-TASC Helsinki Advanced Computing Hub, which started operation in August 2021. The partners of the Hub are UH, CSC, VTT, Aalto and Åbo Akademi. With its EUROfusion funding, the Hub employs around 10 full-time advanced computing experts. They are developing novel numerical methods to solve key issues in fusion research by applying high-performance computer science, artificial intelligence, uncertainty quantification and data management to support other EUROfusion projects, tasks and experiments.

Another change in FinnFusion in 2021 was that now in FP9 the FinnFusion program owner is the Ministry of Employment and Economy (MEAE). This clarified the roles of MEAE and Business Finland appropriately, and now the present roles correspond well to the organization of the fusion stakeholders in most other European countries.

With a good confidence and with a certain curiosity, we can all be looking ahead to year 2022 with the eagerness to hear about the first results of all the new FinnFusion research openings and, also by the ECO-Fusion companies in 2022. Furthermore, we can (indications look promising at the time when writing this in mid-March) also finally meet up in the FinnFusion annual seminar May 2022 to share the new research results and network ourselves face-to-face.

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
BBNBI	Beamlet-based neutral beam injection (simulation code)
BCA	Binary collision approximation
BOP	Balance-of-plant
CCFE	Culham Centre for Fusion Energy
CFC	Carbon fibre composite
CMM	Cassette Multifunctional Mover
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
DTE2	Deuterium-tritium campaign nr 2 at JET (DTE1 was in 1997-98)
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
ESS	Energy storage system
EUROfusion	European consortium implementing the Fusion Roadmap
F4E	Fusion for Energy (the European Domestic Agency of ITER)
FNG	Frascati Neutron Generator
FP9	EUROfusion European Framework Program 9
GPU Programming	General-purpose computing on a 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
ICME	Integrated computational materials engineering
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)
ITG	Ion Temperature Gradient
ITPA	International Tokamak Physics Activity
JET	Joint European Torus (tokamak facility)
JINTRAC	Set of plasma simulation codes
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
MPH	Material property handbook
NBI	Neutral beam injection
NJOC	New JET Operating Contract
OTSG	Once-through steam generator
PCS	Power conversion system
PD	Paschen´s discharge
PFC	Plasma-facing component
PHTS	Primary heat transfer system
PIE	Post irradiation experiment
PRA	Probabilistic risk assessment
RACE	Remote applications in challenging environments (research facility)
RH	Remote handling
RHC	Remote handling connector
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)
TCV	Tokamak à Configuration Variable (tokamak facility)
TDS	Thermal desorption spectrometry
TOF-ERDA	Time-of-flight elastic recoil detection analysis
TUNI	Tampere University
TUWien	Technische Universität Wien, Austria
UH	University of Helsinki
VDE	Vertical displacement event
VTT	VTT Technical Research Centre of Finland Ltd
VVUQ	Verification, validation and uncertainty quantification
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 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 Grants by F4E 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 plays the role of the program owner. Now within the EUROfusion Consortium, VTT is the beneficiary and therefore plays the role of 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.

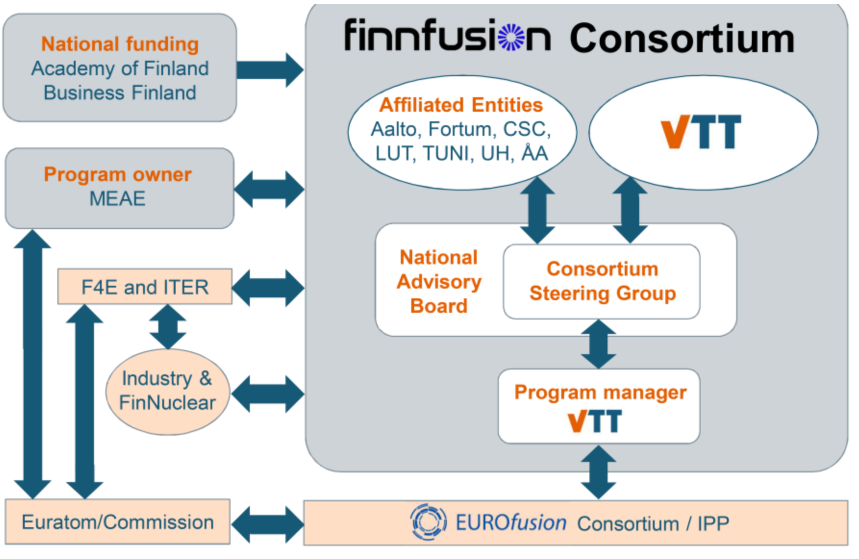


Figure 1.1. Organigram of Finnish Fusion Research Community in 2021–2025.

1.3 ECO-Fusion

An important part of the FinnFusion activitites is a Business Finland co-innovation project ECO-Fusion. It consists of parallel research project by research organizations and companies. The ECO-Fusion consortium's company partners are Comatec, EOS Finland, Luvata, and Platom, while the research partners are VTT and University of Helsinki. The projects continue until 2024 and are funded by Business Finland, participating companies, and in addition, the EU contributes significantly to the funding via the EUROfusion Consortium.

Cross-technological research is the key element supporting the business goals of the ECO-Fusion project. Research encompasses topics in robotics, artificial intelligence, materials technology, power plant technology, fusion reactor physics as well as licensing and safety. ITER is by no means the ultimate goal, but fusion power plants following it are also already in the scope.

1.4 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 2021:

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, MSc. Anu Kirjasuo, MSc. Aki Lahtinen, Prof. Jaakko Leppänen, Dr. Jari Likonen, MSc. Sixten Norrman, Dr. Antti Salmi, Mrs. Kirsi Selin (administration), Dr. Marton Szogradi

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

Activities: Materials modelling
Members: MSc. Jukka Aho, MSc. Timo Avikainen, Dr. Andris Freimanis, Dr. Minna Kotilainen, Dr. Anssi Laukkanen, Ms. Johanna Lukin, MSc. Rami Pohja, MSc. Tomi Suhonen

Activities: Hot cell analyses and experimental materials research
Members: MSc. Pentti Arffman, MSc. Petteri Lappalainen, Mr. Jussi Leporanta, Dr. Pekka Moilanen, Mr. Seppo Peltonen, Mr. Kimmo Rämö, Mr. Jarmo Saarinen, MSc. Tommi Seppänen

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, Dr. Antti Räty

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

Activities: Ecosystem research
Members: MSc. Antti Ahola, Dr. Tiina Apilo, MSc. Juuli Huuhanmäki, Dr. Sofi Kurki, Dr. Jorge Martins, MSc.Tapani Ryynänen, 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, MSc. Jani Hietala, MSc. Petri Honkamaa, MSc. Tero Jokinen, MSc. Petri Kaarmila, MSc. Kalle Kanervo, MSc, Kai Katajamäki, MSc. Pekka Kilpeläinen, MSc. Otto Korkalo, Lic. Tech. Jukka Koskinen, MSc. Janne Lyytinen, MSc. Timo Malm, MSc. Hannu Martikainen, MSc.Kari Rainio, MSc. Olli Rantanen, Dr. Olli Saarela, MSc. Hannu Saarinen, MSc. Qais Saifi, MSc. Janne Sarsama, MSc. Janne Saukkoriipi, MSc. Mika Siren, Lic.Tech. Mikko Siuko, MSc. Mikko Tahkola, MSc. Seppo Valli, MSc. Juha Virtanen, MSc.Tero Välisalo

Aalto University (AU), School for Science, Department of Applied Physics

Activities: Physics
Members: Prof. Mathias Groth (Head of Laboratory), MSc. Francis Albert, Dr. Laurent Chôné, MSc. Riccardo Iorio, Dr. Eero Hirvijoki, MSc. Andreas Holm, Dr. Niels Horsten, Dr. Timo Kiviniemi, MSc. Joona Kontula, MSc. Henri Kumpulainen, Dr. Taina Kurki-Suonio, Dr. Susan Leerink, MSc. Roni Mäenpää, MSc. Patrik Ollus, Dr. Lucia Sanchis, Dr. Seppo Sipilä, Dr. Antti Snicker, MSc. Vladimir Solokha, MSc. Jari Varje, MSc. Filippo Zonta, Suvi Niemelä (admin. support)

Students: Henri Brax, Laura Heikkilä, Algot Silvennoinen, Aake Kesälä, Tuomas Mäkelä, Tommi Lyytinen (summer student from University of Jyväskylä), Luukas Myllynen

Activities: Materials physics
Members: Sara Bouarich (admin support), MSc. Ludovico Caveglia Curtil, MSc Rashmi Dahal, MSc. Rafael Nuñez, Prof. Andrea Sand (Group Leader)

Comatec Oy

Activities: Remote maintenance
Members: MSc. Veikko Puumala, MSc. Stefan Muhlig-Hofmann

CSC IT Center for Science Ltd

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

Electro Optical Systems Finland Oy (EOS Finland Oy)

Activities: Novel AM materials for Energy Generation (NAMMEG)
Members: MSc. Juha Ottelin, MSc. Antti Mutanen, Ms. Jenni. Setola, MSc. Juha Kotila, Dr. Pilvi Ylander

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

Activities: Robotics
Members: Prof. Heikki Handroos, Dr. Amin Hekmatmanesh, MSc. Changyang Li, Dr. Ming Li, BSc. Jesse Myller, MSc. Nikola Petikov, MSc. Guodong Qing, MSc. Qi Wang, Prof. Huapeng Wu (Project manager), MSc. Zhixing Yao, MSc. Ruochen Yin

Tampere University (TUNI)

Activities: Remote handling, DTP2
Members: Prof. Atanas Gotchev, MSc. Lionel Hulttinen, MSc. Ali Ihtisham, Prof. Jouni Mattila (Project Manager), BSc. Morteza Mohammadkhanbeigi, MSc. Pauli Mustalahti, MSc. Jani Mäkinen, Dr. Longchuan Niu, 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 Kaporha, Dr. Antti Kuronen, MSc. Aki Lahtinen, MSc. Emil Levo, M.Sc. Viktor 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, Dr. Leonid Zakharov, MSc. Iuliia Zhelezova

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

1.5 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.

Chairman	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	*Mathias Groth, Aalto*
Steering Group	*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 2021, April 13 (online) and November 24 at UH Campus Kumpula, Helsinki.

Figure 1.2. FinnFusion Advisory Board at the accelerator laboratory of the University of Helsinki on the meeting organised in November.

1.6 Finnish members in the European Fusion Committees

1.6.1 Euratom Programme Committee, Fusion configuration

- Timo Haapalehto, MEAE

1.6.2 EUROfusion General Assembly

- Tuomas Tala, VTT

1.6.3 EUROfusion HPC Allocation Committee

- Susan Leerink, AU

1.6.4 EUROfusion Project Boards

- DEMO: Leena Aho-Mantila, VTT
- ENR - Materials: Kai Nordlund, UH
- E-TASC: Kai Nordlund, UH
- Stellarator: Taina Kurki-Suonio, Aalto
- Theory: Eero Hirvijoki, Aalto
- Tokamak Exploitation: Markus Airila, VTT

1.6.5 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

1.6.6 Other international duties and Finnish representatives in the following fusion committees and expert groups in 2021

- 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 chairperson of the Mechanisms of Vacuum Arcs (MeVArc) workshop series, and 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).
- Mathias Groth is a member of the programme committee of the Plasma Surface Interaction Conference (PSI) 2013-2022.
- 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.

2. Fusion Science Workprogramme 2021

2.1 WP JET1: Analysis and modelling tasks 2021

Research scientists: F. Albert, M. Groth, N. Horsten, T. Kiviniemi, H. Kumpulainen, S. Leerink, V. Solokha, J. Varje, AU
J. Karhunen, P. Sirén, L. Zakharov, UH
M. Airila, A. Kirjasuo, A. Salmi, T. Tala, VTT

2.1.1 Overview

The year 2021 was extra-ordinarily interesting for JET operation and scientific campaigns, although almost all the scientific work had to performed remotely due to the COVID-19 pandemic. This year was special as the two main experimental campaigns C40 and C41 were devoted either to 100% Tritium operation (C40) or 50-50% DT operation (C41). The main focus was on studying the isotope physics in 100% Tritium campaign (C40) and achieve 10MW fusion power during 5s stationary plasma discharge in DT operation (C41). As the two campaigns were dominantly performed in the autumn period, the scientific analysis and reporting will take place in 2022.

FinnFusion contributed to investigations of particle transport and density peaking in the core, divertor physics and tungsten transport modelling, implementation of a new code for JET for the interpretation of vertical displacement events (VDE's), fast ion modelling and related synthetic diagnostics development as well as ammonia formation studies on plasma-facing components. In this Yearbook we highlight the experiment on particle transport and the role of NBI fueling on density peaking where the scientific leadership was provided by FinnFusion. In addition, similar particle transport experiment on DIII-D is described in international collaboration in section 7.1.

2.1.2 Particle transport and sources

JET experiments comparing particle transport and density peaking between 8MW NBI and 8MW ICRH heated H-mode plasmas have been analysed and results submitted to Nuclear Fusion for publication. In the case of pure NBI, heating is naturally accompanied by NBI particle source reaching the plasma centre while with pure ICRH no core particle fuelling was present. In both cases nearly identical (<5%) q-profiles, ion and electron temperature profiles and volume averaged densities were achieved which ensures nearly identical turbulence regimes (ITG dominant, typical for JET). The experimental steady state density profiles (from High res. Thomson Scattering) of the pair are shown in the Figure 2.1. Peaked density profiles are desirable for fusion power generation as fusion power increases with the squared density and occurs mostly in the hot centre of the plasma.

The importance of the remaining differences in toroidal rotation, impurity densities and radiation losses were studied with ASTRA-TGLF integrated transport simulations and found to be small. One could conclude that the more peaked density profile with NBI heating is dominantly due to the NBI particle source.

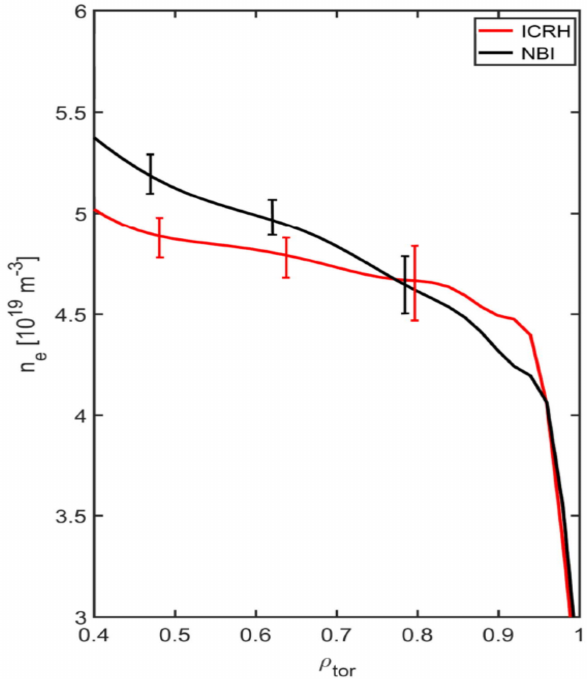


Figure 2.1. Steady state electron density profiles illustrating the difference in density peaking between the pure NBI and pure ICRH heated

It is noteworthy, however, that while ASTRA-TGLF and GENE are often able to reproduce the experimental kinetic profiles, they are struggling in this parameter regime. In fact, both codes predict slightly hollow density profiles without the particle sphysics is missing, or codes incorrectly capture this plasma regime. Further work is needed to understand this.

2.2 WP TE: Tokamak exploitation campaigns

Research scientists: M. Groth, T. Kurki-Suonio, P. Ollus, L. Sanchis, S. Sipilä, A. Snicker, AU
A. Lahtinen, T. Vuoriheimo, UH
A. Hakola, J. Likonen, A. Salmi, T. Tala, VTT

2.2.1 Overview

The year 2021 marked the advent of the new WPTE Work Package, which combines the experimental as well as analysis and modelling activities on all the EUROfusion-funded tokamaks, including JET. During the course of the year, WPTE contributed to the scientific programmes on ASDEX Upgrade (AUG), TCV, and the first physics campaign of MAST-U, almost exclusively relying on remote participation. The originally planned WEST campaign C6 was postponed into 2022 due to issues with the machine. In addition, the last two months of the JET DTE2 campaign were formally conducted under the WPTE governance; however, reporting of the scientific outcomes of this unique effort are to be made within the former JET1. The main activity areas where the Finnish contribution was the most noticeable were studying erosion of plasma-facing components on AUG, modelling of fast ions using the ASCOT code on AUG and MAST-U, as well as investigating particle and momentum transport and carrying out numerical modelling for characterizing detachment on AUG, TCV, and MAST-U.

2.2.2 Erosion of plasma-facing components in H-mode plasmas

In 2021, analysing erosion of Au and Mo marker samples after their exposure to H-mode discharges with small ELMs on AUG was pursued. The underlying goals were identifying the balance between gross and net erosion, assessing the impact of surface roughness on erosion rates, and make detailed comparisons between L- and H-mode cases. We noticed that in H-mode, the markers had eroded at a high rate (up to 4 nm/s) and that the net-erosion profile was relatively flat poloidally throughout the analyzed samples (see Figure 2.2) – unlike in L-mode where only a relatively sharp erosion peak in the vicinity of the strike point is observed. In addition, no clear differences in net erosion were measured between samples of different surface roughness, again contradicting the results reported in L-mode: the rougher the surface, the smaller the net erosion. Our results confirm the strong influence of local plasma parameters in the different plasma operation modes on PFC erosion rates.

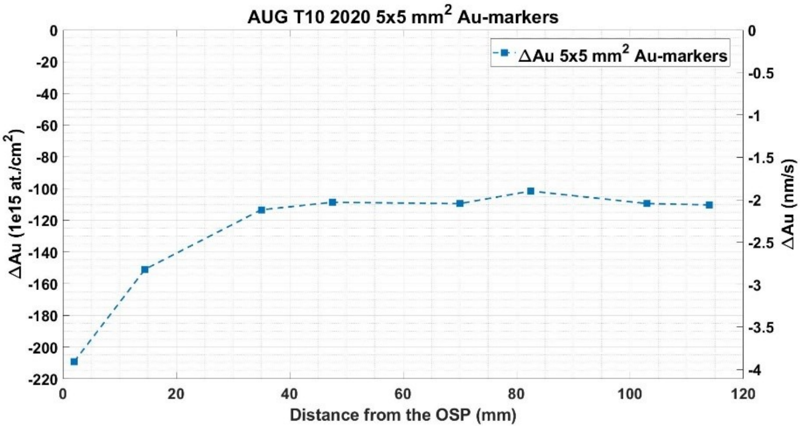


Figure 2.2. Poloidal net-erosion profile as a function of distance from the strike point, measured for Au marker samples following their exposure to H-mode plasma discharges with small ELMs on AUG.

2.2.3 Deputy Task Force Leadership activities

Antti Hakola acted as one of the Deputy Task Force Leaders (TFL) for WPTE throughout the year 2021, as part of the team of 6 TFLs (9 after the inclusion of JET in WPTE from October onwards). His main responsibility areas were (i) material erosion, migration, and fuel retention; (ii) detachment control; (iii) ELM suppression using resonant magnetic perturbations and (iv) characterization of runaway electrons. Related experiments or analyses/modelling activities were carried out on all the operating devices (AUG, TCV, and MAST-U). Besides coordinating research activities, the deputy TFL duties included reporting of the scientific outcomes, preparing new campaigns, and most importantly getting familiar with JET and its new role in the EUROfusion structure.

2.3 WP JET2: Plasma-facing components

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

Main aim in 2021 was to continue erosion/deposition and fuel retention studies on divertor, wall tiles and in-vessel erosion-deposition probes (EDP) removed during the 2016-2017 shutdown. 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.

A set of Be samples cut from inner wall limiter tile 2XR11 and from outer wall limiter tile 4D15 both exposed in 2011-2016 were analysed using SIMS for fuel amount. Comparison was made with ion beam and TDS data. Both SIMS and IBA (at IST) indicate that at the central part of tile 2XR11 deuterium amount is on the level of 10^{16} cm^{-2} and the D amount increases to ~10^{18} cm^{-2} at both ends of the tile (see Fig. 2.3). Overall agreement between SIMS and IBA data is very good but TDS results are clearly higher than SIMS and IBA data. Reason for the discrepancy is still under investigation.

In the case of samples from tile 4D15 deuterium amounts are on the level of low 10^{17} cm^{-2} on the central part of the tile and the deuterium amounts increase to ~$10^{18}$$cm^{-2}$ near both ends of the tile. The D amounts on the central part of tile 4D15 are about one order of magnitude higher than on tile 2XR11. Overall agreement between SIMS and IBA data is very good except in few cases where SIMS results are clearly lower.

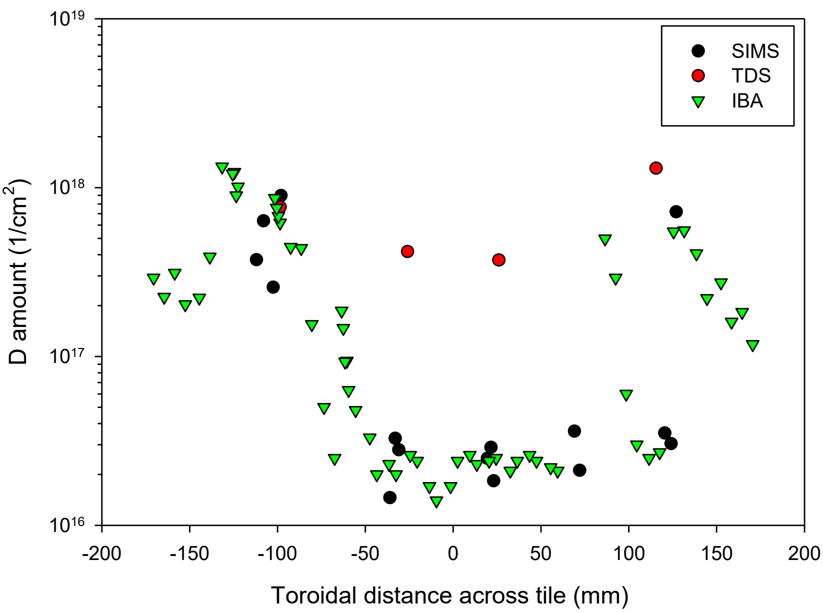


Figure 2.3. Deuterium amounts on tile 2XR11 measured with SIMS, IBA and TDS.

During 2021 for WPJET2, three deposition monitor boxes were analysed by ToF-ERDA at the 5MV tandem accelerator of University of Helsinki. Each box had three plates, two top plates and one bottom plate. The top plates were analysed from both sides (outer and inner), the bottom plate from the deposition side (inner). All the samples were measured transversely at the centre of the samples, over the deposition monitor slit. The top plates were measured during same scan, and the samples were separated with a thin copper wire, which was used as marker of the slit position in the analysis.

H, D, Be, C, N and O were detected on the deposition monitor plates. Small amounts of Al or Si and a very small amount of Ti or similar mass elements were also detected. Detection of heavier elements was limited by substrate events (tungsten substrate). The samples had relatively rough surface, which limits the depth resolution and the accuracy of the analysis results, but the detected deposition layers were relatively thin.

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

Research scientists: M. Groth, A. Holm, N. Horsten, H. Kumpulainen, R. Mäenpää, V. Solokha, AU
T. Ahlgren, F. Granberg, F. Kporha, A. Lahtinen, A. Lopez-Cazalilla, K. Nordlund, K. Mizohata, J. Räisänen, T. Vuoriheimo, UH
L. Aho-Mantila, M. Airila, A. Hakola, A. Järvinen, J. Likonen, VTT

2.4.1 Overview

WPPWIE is the successor of WPPFC from the previous framework program and has, to a large extent, the same focus points: understanding erosion, fuel retention and surface damage characteristics of different plasma-facing components (PFCs), both experimentally and with the help of numerical simulations. A new ingredient is incorporating modelling and design work for alternative divertor configurations in the work programme. The second major change from 2022 onwards is the inclusion of surface analyses of JET tiles and components among the main PWIE deliverables. The Finnish focus areas of PWIE in 2021 were surface analyses of tokamak (AUG, WEST), stellarator (W7-X), and laboratory samples, numerical modelling of different plasma-wall-interaction and scrape-off-layer (SOL) phenomena based on experiments carried out on AUG and JET, assessing retention and erosion characteristics of different Be and W plasma-facing components, and fluid simulations for alternative divertor configurations.

2.4.2 Plasma-wall interaction studies on W7-X and WEST

Surface analyses in 2021 concentrated on a series of samples obtained from various wall components in W7-X and WEST. The W7-X samples were extracted from three upper-divertor tiles after the OP1.2B campaign and the analyses using secondary ion mass spectrometry (SIMS) concentrated on determining the deposition profiles of the tracer element ^{13}C on the tiles as well as the depth profiles of other key impurities. The highest ^{13}C inventories were found as stripe-like patterns on both sides of the different strike lines on the analysed tiles and of similar quantities as measured earlier close to the ^{13}C injection valve on the other side of the W7-X vessel. In addition, layered deposition of elements like Cr, Ni, Mo and B was found to reflect various events such as high release of metallic impurities during the OP1.2A campaign and three boronizations carried out during OP1.2B.

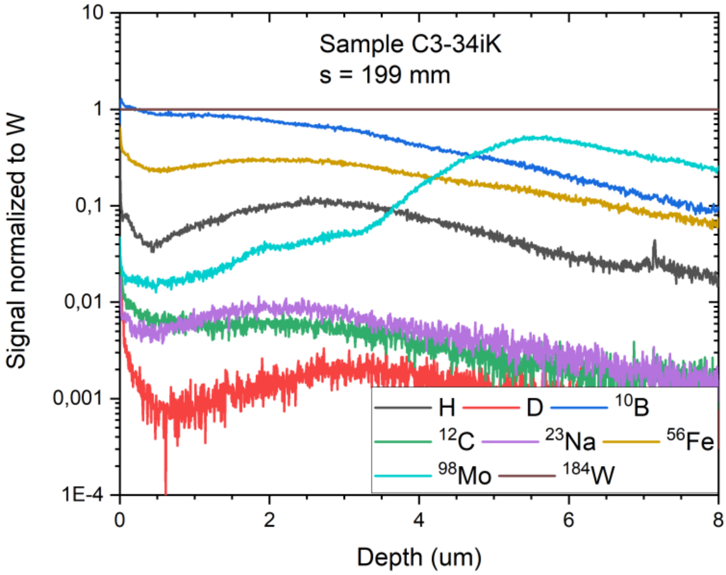


Figure 2.4. Example of SIMS depth profiles for different elements, measured for an inner-divertor tile of WEST after the C3 campaign. This particular measurement point is taken from a region with a thick co-deposited layer (thickness ~4 µm) on top of the original marker coatings W (1-2 µm) and Mo (~0.1 µm).

On the WEST front, two tiles with W and Mo marker coatings, removed from the vessel after its C3 campaign, were shipped to VTT for SIMS measurements and for extracting core samples for analyses in other EUROfusion labs. The SIMS results indicated complex structure of the co-deposited layers on the tiles, consisting not only of the plasma fuel D and the main impurities B and C but also measurable amounts of metallic elements (like Cr, Fe, and Ni). On erosion-dominated regions, the marker coatings had completely eroded, and the surface exhibited a mixture of impurities and remnants of the original coating material (Mo and W). An example of the SIMS depth profiles can be found in Figure 2.4.

2.4.3 Plasma-background modelling for erosion investigations on AUG

In 2021, new plasma backgrounds were created using the OSM-EIRENE code such that they could be used in follow-up ERO simulations from 2022 onwards. The newly created backgrounds solved a number of issues connected with earlier modelling efforts, namely the strong deviations of the simulated electron density and temperature profiles from experimental values as well as the the validity of the traditionally used assumption of electron and ion temperatures being equal. Based on available SOLPS-ITER simulation runs, the ion temperature was now set to T_i=0.8 T_e, leading to a good correspondence with the experimental date as Figure 2.5 shows. In addition, the predicted upstream values were aligned with the lower envelope of the experimental measurements in the SOL. These data will be used to create a new set of ERO test runs for improved understanding of the erosion and deposition of marker elements on AUG.

2.4.4 ADC: Fluid simulations of alternative divertor configurations

Studies on alternative divertor configurations (ADCs) aim to optimize the exhaust strategy and expand the operational regime of DEMO. The work has focused on geometric variations of the conventional, ITER-like single-null (SN) divertor. VTT has participated in these activities in 2021 by coordinating the work of the fluid modelling team, simulating the detailed exhaust processes in the double-null (DN) DEMO divertor configuration, and analyzing the edge plasma properties in the X-divertor (XD) and super-X (SX) configurations.

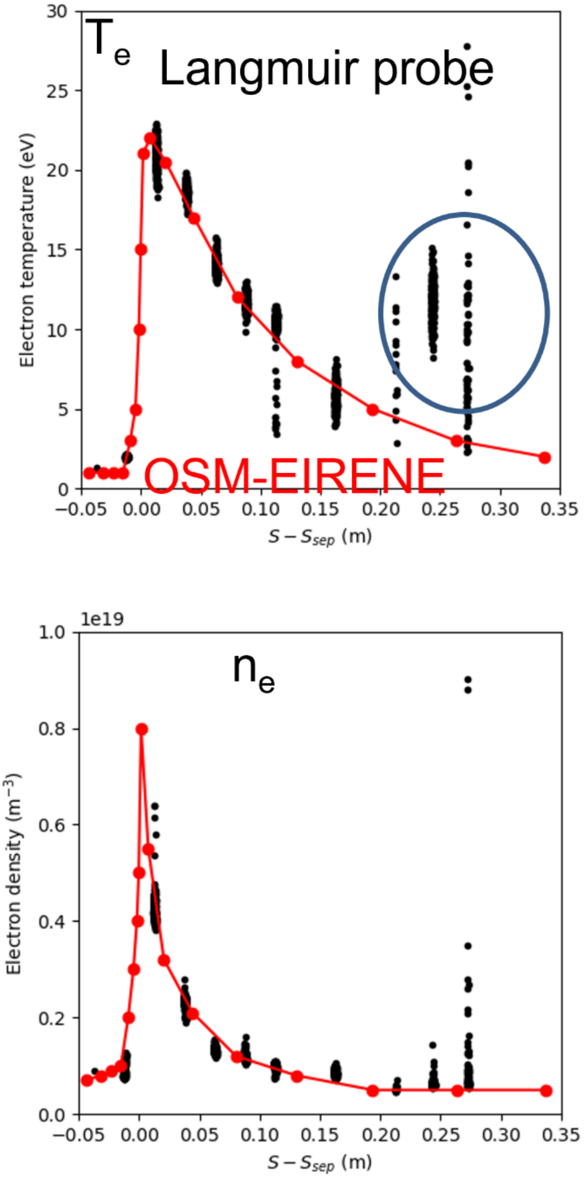


Figure 2.5. Experimental (black dots) and results of optimized OSM-EIRENE simulations (red circles) for the electron temperature (top) and density (bottom) of an AUG discharge #35617. This particular discharge is used as a reference in modelling gross and net erosion of different plasma-facing materials in high-temperature L-mode discharges in D.

In 2021, several new modelling tasks and new modellers were introduced to the team, followed by a careful exchange of information regarding the previously used modelling setups and assumptions. Further understanding of the predicted characteristics of DEMO power exhaust was obtained, based on first SOLPS-ITER simulation results with activated cross-field drifts, Snowflake magnetic configuration, and variations in the divertor closure in the DEMO configuration. Major efforts were made to improve the physics description and analyses by e.g. setting up kinetic neutral simulations in various ADCs, activating cross-field drifts in the DN simulations, and building tools to analyse the parametric dependencies in the edge plasma, see Figure 2.6. The work is expected to conclude in 2022 with these new features and tools fully in use for the analyses.

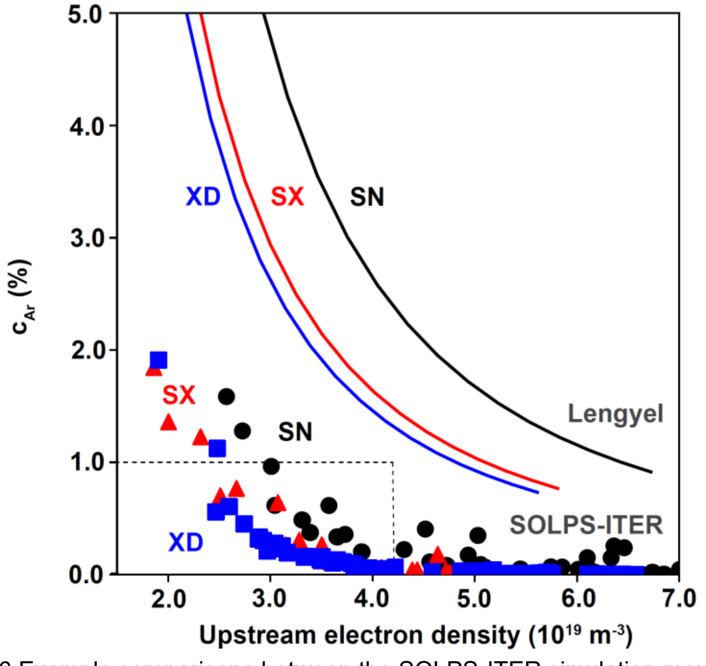


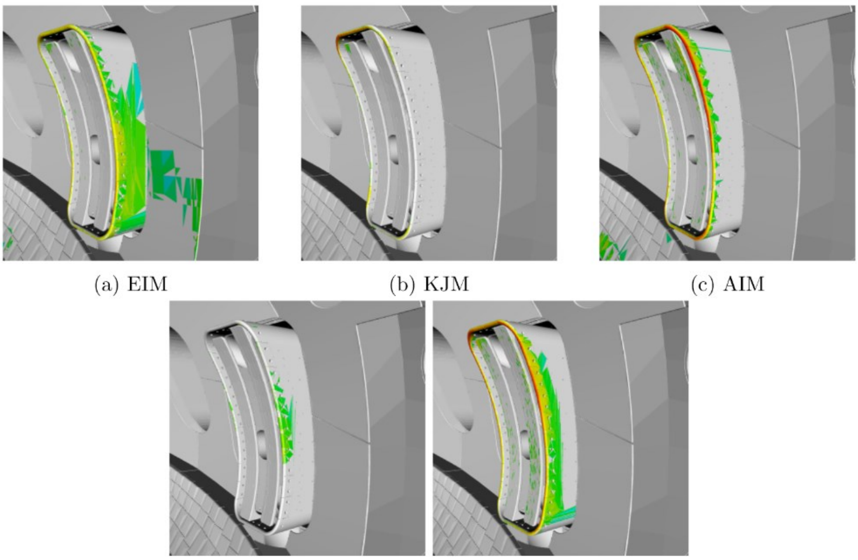
Figure 2.6 Example comparisons between the SOLPS-ITER simulation results and the analytic Lengyel model.

2.5 WP W7X: Fast ion behaviour in the Wendelstein 7-X stellarator

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

The ASCOT work on the W7-X stellarator has mainly been focused on predictive modeling of fast ion power loads, particularly from NBI ions. This work has already led to the armoring of several device components, demonstrating the predictive capability of ASCOT. Continuing this work, this year was focused on modelling of NBI fast ion power loads to the upcoming ICRH antenna. These simulations provide necessary groundwork with regards to proposed heating scenarios which utilize concurrent NBI and ICRH heating.

Five reference magnetic configurations and five antenna positions were scanned to provide an overview of the power load behaviour in various operating conditions. The wall power load was found to increase exponentially with decreasing distance to the last closed flux surface. The five studied magnetic configurations also had qualitative and quantitavite differences in their loads, with the low iota and low mirror configurations in particular exhibiting increased wall loads. The bulk of the power was deposited to the antenna limiter, which is designed for high heat loads. The more sensitive antenna straps and box were not subjected to excessive loads. These results, when combined with the thermal plasma, radiative and NBI ion power loads, will allow safe operation of the ICRH antenna in future campaigns.



(a) EIM (b) KJM (c) AIM (d) FTM (e) DBM

Figure 2.7. Wall loads to the ICRH antenna for the different magnetic configurations. The antenna is set to the working position. The color axis is the same in all the configurations.

2.6 WP AC: Code development for integrated modelling

Research scientists: M.Sc. Bruno Cattelan, Dr. Laurent Chôné, Dr. Fredric Granberg, Prof. Keijo Heljanko, 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

The Advanced Computing Hub (ACH) project was started officially in July 2021, with the main premise at the University of Helsinki. This project is a collaboration between UH, VTT, CSC, ÅA and Aalto. The main aim of the ACH projects is to support TSVVs and other EUROfusion projects with programming support, code optimization, code parallelization and AI implementations to mention a few. In total five of these ACH projects were started. 14 TSVV projects were also started in April 2021. The ACH in Finland focuses on AI, GPU programming, data management and VVUQ.

During the first half-a-year of the project, the personnel were hired and collaborations with the TSVVs started. Most of the collaborations are continuing to 2022, as most of them are long-term support to the codes. To mention a few examples; Development and optimization of EIRENE has been started in collaboration with TSVV-5; Uncertainty quantification in collaboration with TSVV-11; CI/CD development for different codes in collaboration with TSVV-3 Use of Bayesian methods for parameter search for DREAM in collaboration with TSVV-9 and AI methods to be used for defect energies in collaboration with WP-PRD-IREMEV. During the first half-a-year most of the problems were identified and methods to remedy them were tested or are already being implemented into the codes.

2.7 WP TSVV: Theory-Simulation-Verification-Validation

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

Research scientists: L. Chôné, UH

Within TSVV Task 4, an effort is focused on evaluating the accuracy of gyrokinetic models near the edge. To this end, prototype codes are being developed that solve the ion kinetic and electron drift-kinetic (or fully kinetic) equations, along with the full-wave Maxwell's equations. The codes are developed with collaborators at IPP Garching and built on high-performance finite-differences and finite-elements frameworks AMReX and MFEM. These prototypes aim to leverage recent advances in geometric integration methods to produces faithful and scalable simulations of plasma turbulence that can serve as a reference for (or supplement) gyrokinetic simulations near the edge. Development is on track to meet its first milestones scheduled in 2022.

2.7.2 TSVV Task 5 Neutral Gas Dynamics in the Edge

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

To evaluate the impact of transport of metastable, vibrationally excited states of the hydrogen molecule in dense and cold plasmas each vibrational state must be simulated as an individual species. Eirene neutral gas simulations of a one-dimensional flux-tube using a metastable-resolved model indicate a 30% to 100% decrease in the effective dissociation rate compared to simulations using a metastable-unresolved setup, which consider a single molecular species. Zero dimensional Eirene simulations omitting transport effects predict a 25% to 65% decrease in the effective dissociation rate due to differences between the metastable-unresolved AMJUEL and the metastable-resolved H2VIBR rates available in Eirene.

2.7.3 TSVV Task 6 Impurity Sources, Transport, and Screening

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

Simulations of JET-ILW type-I ELMy high-confinement mode (H-mode) plasmas, including ad-hoc edge-localised modes (ELMs), with the JINTRAC and ERO2.0 codes predict that 60-80% of the ELM-averaged tungsten erosion is produced during the ELM by fuel (D, T) ions and W self-sputtering (~20 %). The codes predict that 80-100% of the W erosion occurs at the divertor targets. In the inter-ELM phase, the largest W sources are due to Be ions at divertor electron temperature (T_e) below 40-60 eV, fuel ions at T_e > 60 eV, and energetic fuel atoms in areas of low ion flux.

2.7.4 TSVV Task 7 Plasma-Wall Interaction in DEMO

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

Hydrogen isotopes present in the fusion devices will contaminate the wall material, both the surface and the bulk material. In order to understand how deuterium on the surface and in the close vicinity of the surface will affect the sputtering, we have started to investigate how to reliability create such structures for impact simulations. We investigated how different methods and different interatomic potentials affected the structure and retained deuterium concentration. We identified a suitable interatomic potential and have a method for generating the decorated and supersaturated surfaces needed for further investigations.

2.7.5 TSVV Task 12 Stellarator optimization

Research scientists: S. Äkäslompolo, AU

Stellarator Optimization has the aim to produce modern computer codes for stellarator optimization as well as concrete candidate magnetic configurations for possible future stellarator devices. Only early losses of fast alpha particles are traditionally included in the stellarator optimization loop, while late losses were estimated by proxies. Fast particle confinement over the full slowing-down time is ready to be included in optimizers and paves the way for more detailed studies on divertor and wall heat loads.

In a collaboration b/w Aalto University and ACH-EPFL, ASCOT5 has been improved on two main fronts: Improved GPU performance and better interfacing with other codes. Implementing support for stellarator specific modalities is progressing, particularly related to 3D wall support. The interfacing to other TSVV-12 codes is to be done using the IMAS framework. Container images and python interfaces have been prepared for ASCOT5. The work is ongoing, but it is already possible to do full ASCOT5-simulations from python. The GPU port is based on the OpenMP Offload directives for performance portability. The GPU performance improvements include new random number generators, performance assessments with various compilers and GPU hardware. However, the first benchmark results show a wide difference in performance using different hardware/compilers. In order to resolve this issue, the parallelization scheme has been tentatively changed from task parallelism to parallel-for to allow better compiler support.

2.8 WP ENR: Enabling Research

FinnFusion participated in six Enabling Research projects in 2021:

- ENR-MFE19-MPG-04 MAGYK: Mathematics and Algorithms for GYrokinetic and Kinetic models
- 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

2.8.1 MAGYK: Mathematics and Algorithms for GYrokinetic and Kinetic models

Research scientists: L. Chôné, T. Kiviniemi, AU

Linear growth rates of gyrokinetic full-f code ELMFIRE were compared to results of fully-kinetic 6D code in a box-geometry. In ELMFIRE, box-type geometry was obtained by neglecting the toroidal drifts in the equation of motion. Relatively good agreement was found but work continues to understand the differences.

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

Research scientists: L. Caveglia Curtil, A. Sand, AU

Two key processes affecting the integrity of plasma-facing components are sputtering and defect formation from incident plasma particles. Understanding these processes is crucial for operating a future fusion reactor with minimum maintenance. While sputtering has been studied extensively, little attention has been given to the partitioning of energy deposition of plasma species in wall materials, or the interaction potentials of plasma particles with wall species. At the same time, these quantities are the key input variables for computer codes used to model erosion and implantation in plasma facing components. This enabling research project aims to experimentally measure these fundamental quantities, to calculate them using first principles methods, and to assess the obtained data as input for models to predict sputtering and defect formation. We focus on the most relevant plasma-facing components and their constituents, i.e., ITER-grade W, Fe and EUROFER steel.

Work at AU for the ENR-MAT.01.VR project was begun in September of 2021. Preliminary investigations of the sputtering yield of Fe from deuterium ions was carried out using detailed molecular dynamics (MD) simulations, with standard interaction potentials and electronic stopping from SRIM. This work will form a benchmark for further studies, and also serve as a rough estimate to validate initial sputtering experiments carried out at TUWien under the framework of this collaboration. The initial experiments showed a discrepancy with binary collision approximation (BCA) simulations. In contrast, our MD results show very close agreement with the experiments, indicating that BCA estimates in this energy range can be off by more than a factor of two. We see a different angular distribution of sputtered particles than found in experiment, which is interpreted as being due to crystallographic effects, since simulations have yet been carried out for only one surface orientation.

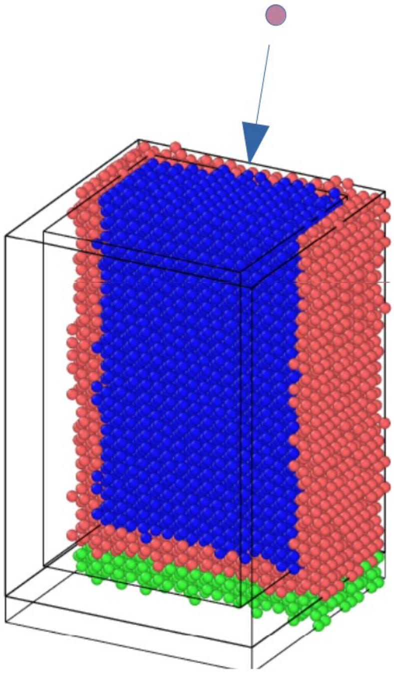


Figure 2.8: View of the simulation cell for atomistic simulations of sputtering. Atoms in the blue region evolve according to the dynamics of an NVE ensemble, while the red regions have an applied thermostat, and atoms in the green region are fixed. The cell has periodic boundary conditions in the lateral directions, and represents a region of the surface of a reactor component.

2.8.3 ENR-08 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-08 is focused on investigating the applicability of machine learning (ML) and artificial intelligence (AI) methods in fusion to facilitate predictions for plasma-exhaust and plasma-wall interaction. The team encomppasses more than 10 scientists from Germany, Netherlands, Sweden, and Finland. The PI is Sven Wiesen (FZJ/Germany). The ENR-08 is divided into 4 sub-projects (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 [Saarelma *Phys. Plasmas* 2019, Snyder *Phys. Plasmas* 2012] databases for training the models. In 2021, the focus has been on investigating the ML methods using the EUROfusion JET pedestal database [Frassinetti Nuc. Fus, 2021]. Adam Kit (UH) completed his BSc thesis in 2021 investigating the utility of supervised ML algorithms in developing regressions for pedestal density, $n_{e,PED}$, predictions. $n_{e,PED}$ is very challenging to predict accurately, which is why models such as [Saarelma *Phys. Plasmas* 2019, Snyder *Phys. Plasmas* 2012] take $n_{e,PED}$ either as an input or use simplified models or log-linear scaling laws for $n_{e,PED}$ [Saarelma *Phys. Plasmas* 2019, Frassinetti Nuc. Fus. 2021]. Supervised ML algorithms offer a great potential for regression beyond the standard log-linear approach, and indeed many of the supervised ML algorithms show improved regression performance, with the gradient boosted decision trees (XGBoost [Chen, *Proc. 22nd ACM SIGKDD 2016*]) showing the best performance among the tested methods (Fig. 2.9).

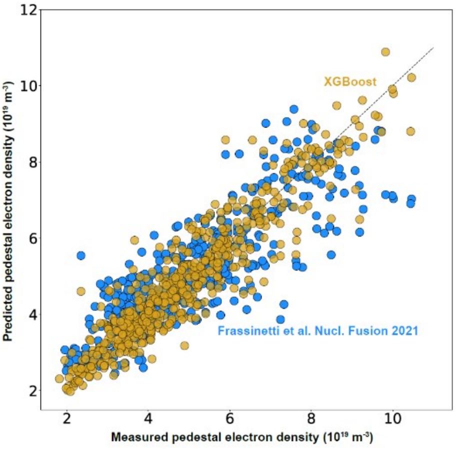


Figure 2.9. Predicted pedestal electron density as a function of measured pedestal electron density within the JET EUROfusion pedestal database using the log-linear scaling from Frassinetti et al. [Frassinetti Nuc. Fus. 2021] (blue circles) and using the XGBoost gradient boosted tree algorithm.

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

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

Aalto University participates in the enabling research project to develop a novel tomographic reconstruction of the fast-ion distribution functions. Naturally, we may use a forward model to go from numerical distribution functions to synthetic diagnostic and compare those to experimental measurements. However, this process cannot accommodate all diagnostics that were measured during the experiment. Moreover, it is very useful to obtain a distribution function based solely on measurements. Therefore, we may invert the problem to construct the distribution function from measurements. The method to obtain this is tomography.

Within this particular project, we are taking the existing tomographic methods and developing them further with an ambitious goal to be able to construct a 5D (3 spatial coordinates + 2 velocity space coordinates) distribution function in both tokamaks and stellarators. Novel methods to obtain that include using simulated distribution functions to span the basis functions for the tomography. This involves running the Monte Carlo orbit-following code ASCOT5 for an ensemble of particle input ensembles. To obtain this, ASCOT5 has been further developed to enable launching simulations directly from a python interface that interacts with the C-calculation part. In 2021, the python part was constructed and the testing was initiated to see how many distribution functions we can realistically use for the basis.

2.8.5 Silicon optics steady state magnetic field sensor

Research scientists: T. Aalto, A. Hokkanen, M. Kapulainen, D. Shahwar, A. Salmi, F. Sun, B. Wälchli, VTT

The Enabling Research project no:16 "Silicon optics steady state magnetic field sensor" lead by the VTT aims to develop a new type of sensor for measuring the steady state magnetic field in a fusion experiment. The traditional coil / solenoid based diagnostics are great for transient magnetic field measurement as they rely on the time varying magnetic flux. However, in steady state no current / voltage is induced and over time, noise accumulates and distorts the steady state measurement. The new sensor concept is based on the Faraday rotation of light travelling along the magnetic field. Here we use novel 3μm coiled silicon square waveguides to fit the sensor on 2x2cm SOI chip. The simplified schematic of the sensor is shown in Figure 2.10.

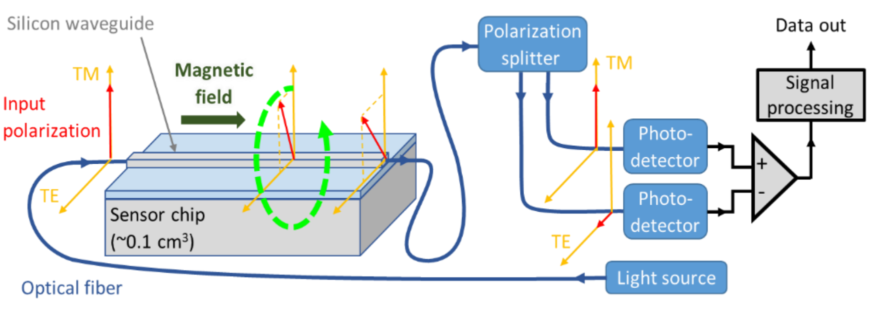


Figure 2.10. Simplified schematic of the sensor concept.

The sensor itself and the accompanied polarization splitters, interferometers etc are composed of silicon and silicon oxide and require no electronics at the measurement location (robust radiation tolerance) and is expected to be compatible with proximity to a burning plasma. During the 9 months of activities in 2021 we have designed multiple versions of the individual sensor components (U-turns, splitters, waveguides, interferometers) to select the best performers (delicate manufacturing process). Manufacturing is presently ongoing at the VTT Micronova facility and components are expected to be ready in early 2022. Component characterization, optimization and system integration will be on the agenda 2022.

3. Fusion Technology Work Programme 2021

3.1 WP BB: Neutronics for FNG WCLL mock-up

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

In the frame of the EUROfusion Work Package "Breeding Blanket (BB)", Aalto University collaborates in the design of the BB for the future European Demonstration Fusion Power Reactor (DEMO). Among the different BB concepts, one of the most promising is the Water Cooled Lithium Lead (WCLL). To assess this candidate, a mock-up of the WCLL BB was irradiated at the 14 MeV Frascati Neutron Generator (FNG) facility. Our task within this project is to provide a numerical tool that can predict tritium production in different BB configurations and analyze its shielding capabilities. This tool is based on Serpent, a Monte Carlo transport code developed at VTT.

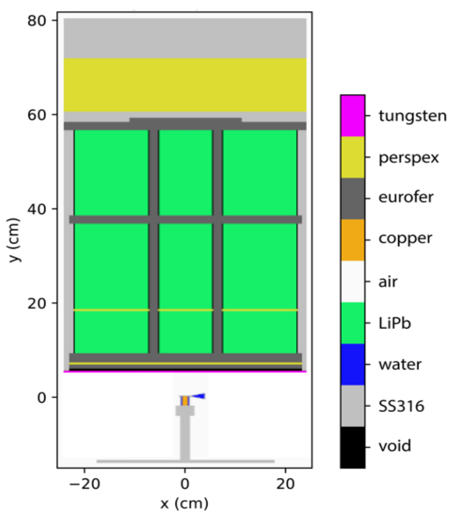


Figure 3.1. The Serpent2 geometry of the WCLL mock-up.

We implemented a Serpent model (see figure 3.1) according to the latest WCLL mock-up geometry and material composition, together with the specifications of the FNG neutron source. Using this model, the results of the neutron fluxes in the mock-up were benchmarked against the MCNP code, which is a Monte Carlo code similar to Serpent but with a strong limitation in the complexity of the geometries, it can handle. Codes were found to agree within 10% error. Additionally, we used the measured data of the mock-up experiment to validate our model, showing that most of the Serpent estimations were within 20% error of the measured values. At this stage, Serpent is ready to provide modeling support to optimize the set-up of the next experiments.

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

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

During the transition period between the DEMO plant design pre-conceptual and the conceptual phases, relevant data for more profound model updates have been delayed. Hence, the activities in WB BOP during 2021 have been more modest compared to previous years. However, during the year, some improvements of the Apros models have been adopted and further analyses have been performed. The plant concept in focus has been the Water-Cooled Lithium-Lead breeding blanket (WCLL BB) configurations equipped with a small energy storage system (ESS).

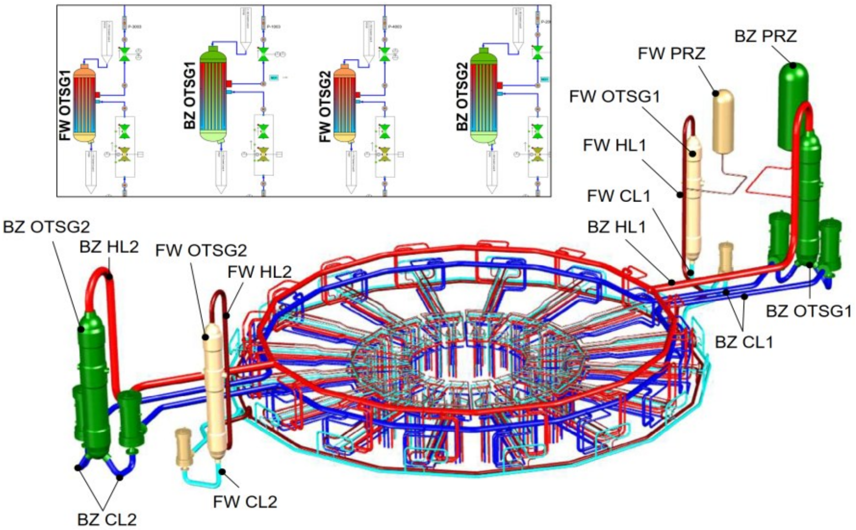


Figure 3.2. Upper section CAD model of the WCLL PHTS and the SGs in Apros.

The primary side of the WCLL model incorporates two separate, high-pressure water coolant loops, namely the first wall (FW) and the breeding zone (BZ) loops. Two pairs of Once-Through Steam Generators (OTSGs) couple the primary to the secondary system, each pair composed of a FW and a BZ OTSG. The blanket model is discretized into 7 distinct poloidal regions, which are modelled separately in two IB and three OB segments. Each region is represented by a Breeding Unit (BU) that contains the three submodules (FW, BZ and Vacuum Vessel, VV). The power deposition profiles (radiative, volumetric) vary based on the poloidal, radial and toroidal location of a given heat structure.

A new OTSG control scheme has been introduced in order to overcome challenges posed by Primary Heat Transfer System (PHTS) and Power Conversion System (PCS) limitations. Applying user-defined flow rate boundary conditions, primary coolant temperatures, SG riser levels and steam qualities were maintained within acceptable ranges nonetheless such simple logic represents only a base for further development.

3.3 WP DES: DEMO plasma exhaust modelling

Research scientists: Leena Aho-Mantila, VTT

The work in WPDES started in 2021 with the aim of producing analyses, which are central to the development of the baseline DEMO design. The work is done in close collaboration with the DEMO central team. VTT participates in this work by performing SOLPS-ITER modelling of the DEMO plasma edge in a group of simulation experts focusing on power and particle exhaust and the related design questions.

VTT's work in 2021 started with comparisons between the simulation assumptions used in the earlier EUROfusion DEMO modelling efforts. Significant differences were identified in the levels of transport coefficients and plasma fuelling assumed in the different work packages, emphasizing the need of coordination work in the future. Furthermore, we compared simulation results obtained using either the fluid neutral or the kinetic neutral model. Understanding the role of the neutral model for DEMO predictions is important because of the significant computational expense associated with simulations using the more detailed kinetic neutral model. In our comparisons, differences were observed in particular in the far scrape-off layer profiles of plasma temperature, see Figure 3.3, but it is not yet clear whether this is due to the neutral model or due to differences in the numerical treatment in the simulations. The work is planned to continue in 2022 including also intermediate, so-called advanced/hybrid neutral models in the comparisons.

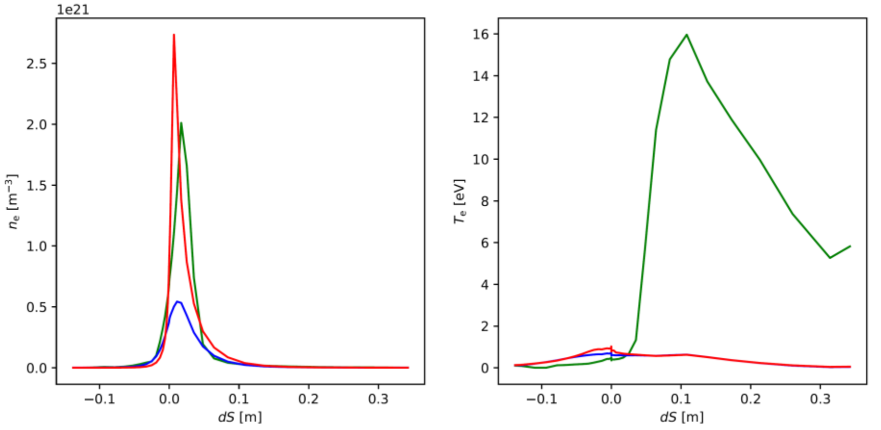


Figure 3.3. Comparisons between outer target plasma profiles in DEMO using either fluid (red, blue) or kinetic (green) neutral model.

3.4 WP ENS: Early Neutron Source definition and design

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

International Fusion Material Irradiation Facility - DEMO Oriented Neutron Source (IFMIF-DONES) is being designed for the validation of structural materials of DEMO. In IFMIF-DONES, the materials are irradiated and tested with fusion characteristic neutron spectrum. The specification and design of IFMIF-DONES is carried out in Work Package Early Neutron Source (WPENS). VTT has participated in WPENS providing probabilistic risk assessments (PRA) for IFMIF-DONES. The PRA aims to give insights to the strengths and weaknesses of the design and operation of IFMIF-DONES.

In 2021, VTT work has concentrated on the update of IFMIF-DONES internal events PRA based on the latest design information and the review of available IFMIF-DONES material on operator and maintenance actions. Both tasks will continue in 2022.

Event trees have been developed for the relevant, identified internal initiating events leading to diverse accident scenarios with different responses of IFMIF-DONES. For the safety functions defining the different layers of defence in the event trees, fault trees have been created. The current internal events PRA model includes six event trees.

In Fig. 3.4, an example of the lithium perturbation event tree is shown. When lithium flow perturbation occurs, the most important safety function is to shut down the deuterium beam, which creates the neutron flux from the deuterium-lithium interaction. If the shutdown fails, the beam breaks the system boundary confining the liquid lithium and induces a risk of radiological release.

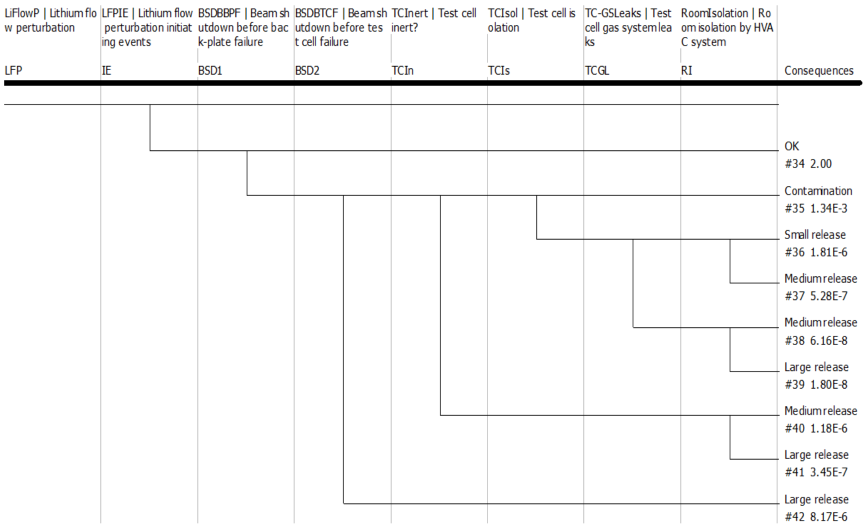


Fig. 3.4. Lithium perturbation event tree.

At the moment, the estimate on the frequency of large release of IFMIF-DONES is relatively high (1.8E-5/year). Most of the frequency comes from events requiring fast beam shutdown, such as the lithium flow perturbation event described above. It should be emphasised that the frequency estimate is only preliminary and reflects the current state of the plant design and knowledge of accident phenomena.

3.5 WP MAG: Magnet conductor/ insulator research

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

The deliverable and task focus is on working with insulation criticalities in terms of identifying the role of various defects, discontinuities and penetrations critical to insulation performance by employing multiscale materials modeling of the respective material, insulation and performance features. The task develops and employs computational means to that effect. This provides means and results to deliver ever more robust insulation concepts and pushes forwards the respective designs, supporting the understanding and systematic elimination of potential failures in the respective solutions. Further, it is expected that the findings will provide a basis for evolving the design(s) to be focused on, assessing also behavior with respect to manufacturability and the effects arising from heat treatments.

During 2021 the task completed the following activities. A baseline on insulation issues for specification of the VTT activities (in line with D001-VTT on insulation criticalities) was completed, both with respect to the required additional characterization, experimental and model definition work (on defects, material properties, designs etc.). A demonstration modeling solution was implemented to assess the properties and performance of some common identified cases used in demonstrations. Trial analyses and early validation against published results and earlier experimental findings was carried out. The developed solution can be further utilized in various multiphysical and multiscale case analyses and rather easily added with additional features with respect to materials, structures etc. Initial parametric investigation on specific criticalities identified for (material parameters, defects vs pristine etc.) to perform initial assessment of the proposed approach modeling solution. Benchmark analyses on differing physical phenomena, such as Paschen's discharge (PD), were initiated and are being further worked on during the completion of this deliverable.

3.6 WP MAT: Materials

Research scientists: P. Lappalainen, P. Arffman, J. Leporanta, P. Moilanen, J. Lukin, J. Lydman, J. Saarinen, VTT

The main scope of the materials' work package (WPMAT) is to develop and qualify three baseline materials, i.e. EUROFER steel for blankets, tungsten as plasma-facing armour material, and copper chromium-zirconium (CuCrZr) for divertor heat-sinks. Further objectives include risk mitigation, the development, characterisation, and industrialisation of advanced materials with improved operational performance (i.e. radiation resistance, improved design). The one specific objective is to carry out a vigorous neutron irradiation program on reference materials for conditions relevant to the design in Material Test Reactors. This includes Post Irradiation Experiments (PIEs) to measure resulting material property changes and implement data in the Material Property Handbook (MPH) and as appendices to Codes & Standards.

The task specification of the EUROfusion WPMAT entitled PIE of LOT-II presents progress in promoting the activities required to perform required mechanical testing for irradiated specimens reliably in a hot cell where the mechanical properties (tensile, fatigue and static fracture toughness) of CuCrZr alloy (ITER specification) irradiated to 5 DPA is determined. The promoting activities of the preparation phase include e.g. the validation of mechanical test methods, preparation of specimens per irradiation temperature for validation tests, the design of necessary loading tools and jigs for the specimens required in the mechanical tests, and the validation of tensile test and the evaluation of results.

The tensile test strain-stress curves at elevated temperatures are shown in 3.5. Validation tests were performed with a commercially available material Elmedur X, which has similar properties as the ITER (IER grade) CuCrZn alloy. The test results were compared to the mechanical properties of the Elmedur X validation material and were in good agreement. Therefore, the validation of tensile testing is considered successful.

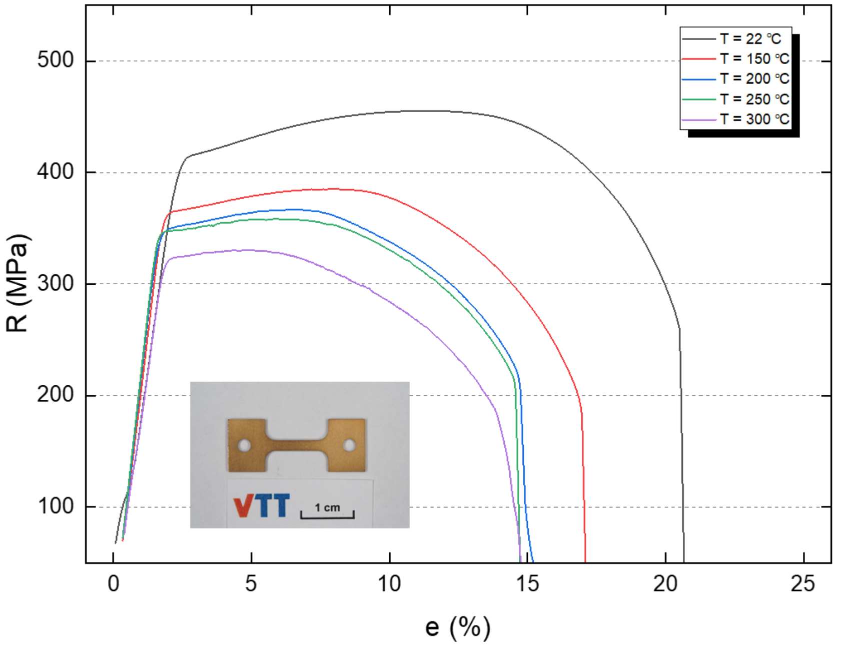


Figure 3.5. Tensile stress-strain curves for CuCrZr alloy at the crosshead rate (v_c) of 0.12 mm/min at RT, 150 °C, 200 °C, 250 °C and 300 °C.

3.7 WP PRD: Prospective R&D

3.7.1 HHFM High heat flux materials

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

The work focuses on the development of W, W-alloys (doped, binary, tertiary etc.) and W-based refractory alloys. The targets are to find i) alternative chemistries (from minor doping or multi-elemental alloys to complex concentrated alloys) which might improve either properties (such as strength/ductility characteristics) or manufacturability (decrease the occurrence of specific defects), ii) investigate manufacturing processes themselves (for metal additive manufacturing (AM), establish processes and parameter sets yielding the most favoured properties), iii) fundamentals of microstructure to material property correlations, iv) use optimization and machine learning (ML) to address (i–iii) and v) develop in-situ and small scale testing methods for ambient and elevated temperatures to validate models and provide first hand in-sights on the respective material behaviors.

The results of the work during 2021 are briefly summarized in the following. Equiatomic (MoNbTaVW) RHEA has been manufactured, material synthesis carried out by powder bed fusion (PBF) metal additive manufacturing, further work is ongoing with W and alloys. HHFM material development is being carried out utilizing ICME principles: High throughput computing and machine learning methodologies used and integrated to the design workflow, including CALPHAD and PBF simulations, use of ML GAP potentials etc. Select modeling and development activities performed within 2021 are (with an idea to form a whole to support material design and manufacturing route identification):

CALPHAD and DFT modeling to support alloy design activities and identify effects of alloying elements to W.

MD, PFC and PF modeling of manufacturability and better quantifying causalities between the process-property stages.

Crystal plasticity modeling modeling of deformation and failure processes, linking to engineering material properties related to strength and ductility, including model development using W as the starting chemistry.

Multiscale modeling workflow targeting manufacturability is outlined below in Figure 3.6.

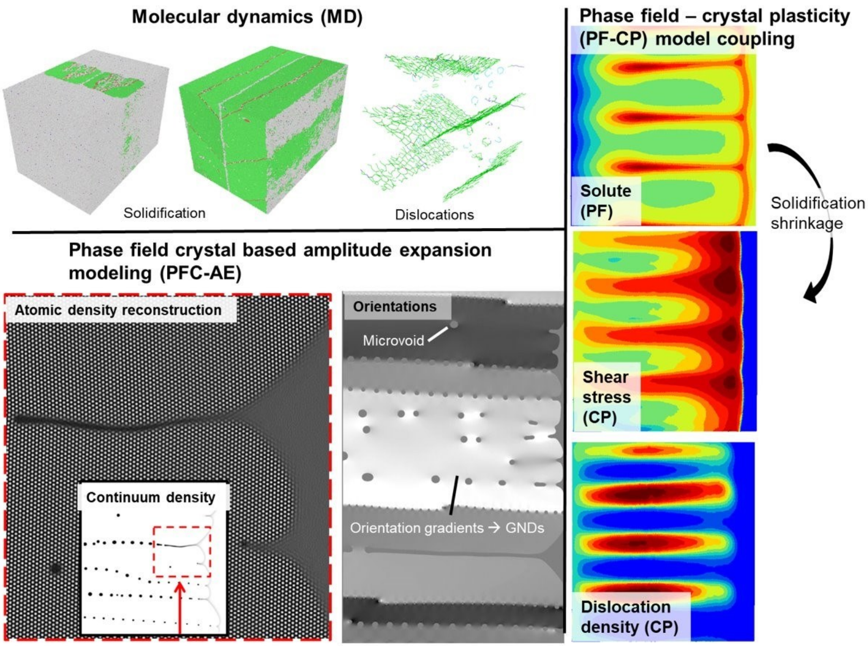


Figure 3.6. Multiscale modeling framework utilized to investigate manufacturability of high heat flux materials.

3.7.2 IREMEV activities

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

Tungsten is the material of choice for some of the most demanding parts in the fusion devices. It is known that the mechanical properties of metals are determined by the movement of dislocations. At Univ. Helsinki we have investigated the energy for double-kink formation in tungsten utilizing ML interatomic potentials, to accurately determine this energy, which will affect how easily the dislocation moves. We have also investigated how hydrogen-isotopes affect the defect build-up in tungsten, which will affect both the tritium retention as well as how the dislocations get pinned in the material. We found the double-kink formation energy for tungsten and other fusion relevant materials and compared the results to classical interatomic potentials. Experimentally it has been observed that the presence of deuterium will affect the defect build-up in tungsten, and we found a similar trend in our preliminary high-dose irradiation simulations.

At Aalto University, we have investigated the cumulative formation of radiation damage in tungsten under loading conditions. Tensile strain was found to enhance the formation of vacancies, with compressive strain decreasing the vacancy count compared to the unstrained case. These results indicate that cascades can have a healing effect in highly damaged microstructure under loading conditions, evening out heterogeneous strain fields under prolonged irradiation. We also found that small dislocation loops are much more likely to form under compressive than under tensile strain. The morphology of the damage structures that are formed is thus affected by the stresses and strains in the material.

3.7.3 Serpent2 neutron model for HELIAS stellarator

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

Aalto University has contributed to the design of the HELIAS stellarator within the WP PRD project, under the stellarator reactor design. The neutron transport code Serpent2 has been used to simulate the neutron flux and the resulting tritium breeding ratio (TBR) in the HELIAS geometry. In 2021, the project concentrated on the creation of the geometry necessary for the Serpent2 calculations and benchmark between Serpent2 vs. MCNP5 calculations. Several important things were found out. Firstly, Serpent2 allows the smooth generation of geometry inputs via the STL interface. In practice, one can utilize existing CAD designs, convert them to STL files and then directly use these geometries are part of the Serpent2 input (see Figure 3.7). This saves a lot of time since geometry generation has traditionally been by far the most time-consuming part of the neutron transport calculation chain.

Secondly, a discrepancy between the two codes was observed. Since the discrepancy is larger than expected, of around 7%, a reason for this was sought out. The current working hypothesis is that the discrepancy is due to different ways to deal with the geometry. In Serpent2, a full 360-degree geometry is used, while the geometry in MCNP5 is built on a five-fold symmetry of the design with reflective boundary conditions. The current hypothesis is that reflective boundary conditions do not work in this geometry (since each part is not just periodically symmetric but the symmetry involves also rotation). To confirm this, further investigations are needed.

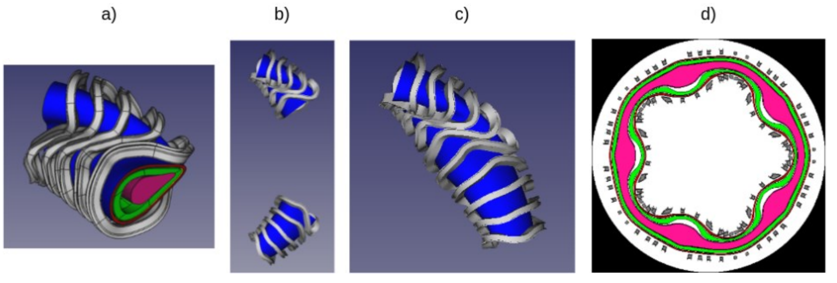


Figure 3.7: a) The original half module including the non planar field coils in STP format. b) The original half module (top) and its counterpart (bottom). The counterpart is a mirror of the original part which is also rolled by 180°. c) The connected full module by 72° rotation around the z-axis. d) The full geometry plotted in Serpent2.

3.7.4 EOS: Novel AM materials for Energy Generation

Research scientists: J. Ottelin, A. Mutanen, J-J. Setola, J. Kotila, EOS

Electro Optical Systems Finland Oy (EOS Finland Oy) is a competence center for metal materials for additive manufacturing (AM), developing metal powder material and process products for EOS direct metal laser solidification (DMLS) systems. In this project, our focus is in “Novel AM materials for Energy Generation (NAMMEG)”. We are developing materials of high interest for the energy generation industry, especially for future fusion energy as well as today’s nuclear and gas turbine applications, using AM technology. New materials are needed to elevate AM as an innovative production method providing new solutions and help take technological leaps in energy generation.

In the early phase of our work EOS Finland Oy has concentrated on AM process development of tungsten and zirconium materials. For tungsten, the first target of developing a high productivity process for select applications was reached. The tungsten development work now continues to optimize the process and material towards optimal microstructure. This work is expected to continue throughout the remaining project duration. For Zirconium, it has been compulsory to put effort on the printing machine HW before conducting further process or material development. This work started with the research of required modifications to our EOS laser printing machine; not only for a quality building process but also for how to handle and process the metal powder in a safe manner and to fulfill all the safety requirements. Together with material and process development actions we have investigated and carried out the required modifications and are ready to process the new material.

3.8 WP RM: DEMO Remote maintenance

Research scientists: J. Alanen, W. Brace, A. Järvinen, K. Katajamäki, J. Lyytinen, T. Malm, H. Martikainen, S. Qais, O. Rantanen, H. Saarinen, M. Siren, M. Siuko, T. Välisalo, VTT
L. Changyang, W. Huapeng, L. Ming, Y. Ruochen, LUT
S. Muhlig-Hofmann, V. Puumala, Comatec

DEMO is set to be the first example of a commercial fusion power plant using the heat produced in the reactor to generate electricity. The Work Package Remote Maintenance (WPRM) framework has high-level objectives of delivering the DEMO Remote Maintenance (RM) System whilst providing design input to developing plant designs to ensure availability and maintainability. The primary focus in the pre-conceptual design phase, 2014-2020 (Framework Programme 8 (FP8)) was on developing integrated maintenance solutions, implementing novel solutions with the most significant challenge. The FP9 WPRM represents the concept phase organised to achieve a conceptual design for the primary DEMO maintenance systems by 2027. In addition to the high-level objectives, emphasis is on the technical risk assessments and impact on plant design. Therefore, risk mitigation is sought initially through design assessments and technology R&D activities. The FP9 work is collaborative between VTT, LUT, Comatec and the broader European counterparts within the Eurofusion Consortium.

3.8.1 Overview

The WPRM FP9 conceptual design requires the critical risks to be mitigated by developing suitable processes to meet the maintenance requirements. These processes require an integrated strategy of synergistically combining supportive technology R&D in critical areas and system design to demonstrate the feasibility of the process. Therefore, the 2022 WPRM work focus on participation in the Remote Maintenance System design (RM-S) and the Remote Maintenance Technology (RM-T) activities. RM-T is focusing on developing the underpinning technologies needed to validate the designs of the RM-S. Integration and formalised approach to the system and technology design and development are critical in FP9; therefore, a Systems Engineering (SE) approach identified as the Tokamak Assess Integration (TAI) was pursued in the work package. TAI task covers the MANAGEMENT and INTEGRATION of the Tokamak Access within WPRM. Consequently, a model-based SE approach is used, implicating SysML to model the maintenance processes, strategies and systems within the Upper Port, Lower Port and Equatorial Port maintenance areas, where development spans multiple work packages within DEMO.

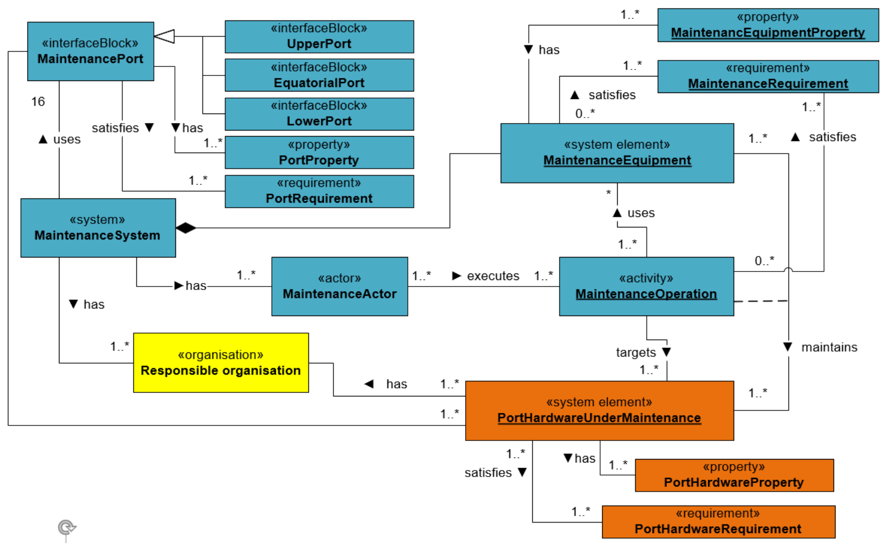


Figure 3.8. Ontology of information items for the Tokamak access integration management.

3.8.2 RM System Design

In WPRM FP9, there are a wide range of maintenance processes to be considered under the RM-S activities. The task includes designing and developing in-vessel maintenance systems and In-bio-shield, including in-cryostat maintenance systems. The in-bio-shield work includes designing and developing inspection and maintenance systems for vacuum heat shields, magnet systems, cryostat, and central solenoid. Contribution in the in-vessel maintenance RM-S comprises plant architecture assessment. The activities include undertaking high-level maintenance assessments of newly proposed and existing alternative plant architectures to assess potential viability. In addition, the work included evaluating existing concepts to reduce stress, risks, payload limits, incorporating seismic mitigation strategies and enhancing safety, rescue, and recovery.

Further work includes developing RM systems for maintaining and servicing hardware (breeder blankets, divertors, and limiters) through the various access ports. Due to the restricted space within the access ports and the extreme environmental conditions (radiation, contamination, residual heat, and magnetic fields), integrated processes and the use of a universal or single system for maintenance are vital to the viability of the plant. Therefore, the work includes assessing the suitability of a single Mover device to provide all the gross movements and structural support required for handling the Multifunction effectors needed for all In-Vessel maintainable hardware (Blankets, Limiters, and Divertors) through the lower port.

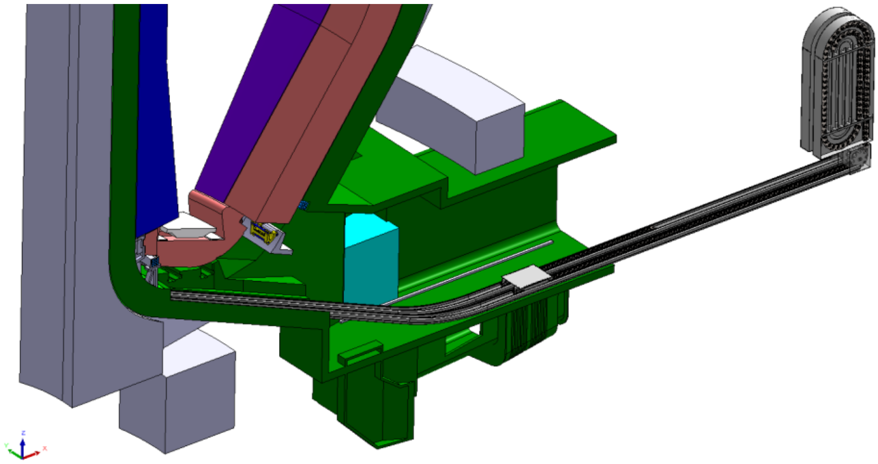


Figure 3.9. The concept for a single mover for gross movements in the lower access port.

3.8.3 RM Technology R&D

In WPRM FP9, the Technology R&D (RM-T) activities focus on developing the underpinning technologies needed to validate the designs of novel maintenance systems. The task includes work that assesses or enhances state of the art in applicable technology areas, including prototyping and testing the RM Systems. Therefore, applicable technologies that offer the most flexibility in plant design and architecture are developed. The applicable technologies are diverse, including advanced robotics, specialised materials, radiation hardened control and sensing hardware, transport guidance systems, condition monitoring, and logistic simulation modelling. VTT and LUT participated in three major RM-T tasks: logistic simulation modelling, condition monitoring, and stochastic modelling engine development. Logistic modelling comprises testing and validating existing modelling tools. The condition monitoring and stochastic modelling engine development comprise studying and making implementation plans for the rest of FP9. The stochastic engine is developed to be within the existing software, ARTEMIS as developed by

UKAEA-RACE. The stochastic engine was designed to be built as a collection of algorithms to work together for handling uncertainty, predicting the most probable system states, updating input parameters distribution, and detecting the failure to perform a task due to ageing in the long term. Therefore, a stochastic modelling engine is designed as a collection of algorithms that interact and work toward a common goal and perform four main tasks chronologically in a loop to achieve the best estimate state with the highest probability.

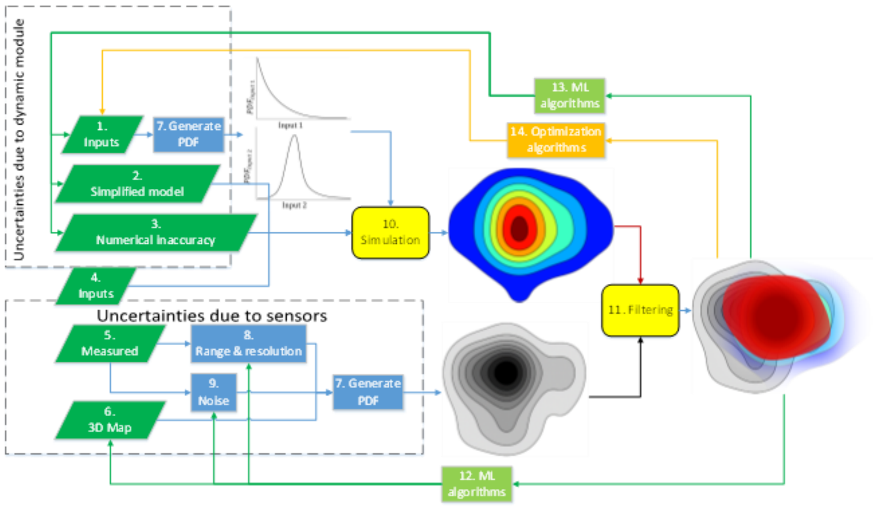


Figure 3.10. The process of a stochastic engine.

3.8.4 Remote Maintenance at LUT

In 2021 LUT started to participate in the DEMO work package in WP RM for the first time, and the tasks include:

1) development of new and existing maintenance concepts for the power plant architectures. In the task, different section compositions of the blanket are considered, which include concepts consisting of five sections, one full section (inboard and outboard together) and a cylinder shape blanket. Regarding the maintenance research, the workspace, and the deformation analysis of the heavy-duty manipulator as multipurpose deployer (MPD) has been carried out. The first wall in-situ repairing using the 3D laser additive technology has been suggested.

2) accuracy analysis of parallel manipulator HKM for the blaket remote maintenance. The HKM is a parallel manipulator designed for transfering the blanket through the upper port. However, repeatability of the manipulator is poor because of the free motion in the linear drive system. The research work includes the error modelling and kinematics simulation, and the result shows that the repeatability of the manipulator is 6 mm. To improve the accuracy of the manipulator extra position sensors have to be added to the linear drives.

3) development of stochastic engine. The task is to develop a collective of algorithms that can conduct the parameter sensitive analysis, dynamic parameters identification and dynamical model tracking, given the functioncal mockup unit, and the algorithms could be finally integrated into the ARTMIS environment.
4) condition monitoring of remote handling system for DEMO. The task is to develop condition monitoring system for human-in loop remote handling system. A hybrid method that comprising the data driven (using deep learning algorithms) model and physical model based on bayesian inference has been developing to predict and identify the system faults and the operator’s emotional conditions.

4. Communications

4.1 Articles and public relations

The FinnFusion Annual Seminar which has been organised annually was cancelled due to restrictions imposed by the COVID-19 pandemic in Finland. The Annual Report, *FinnFusion Yearbook 2020,* VTT Technology **393** (2021) 83 p., was published in April.

During 2021, Finnish media published several articles and interviews on the fusion research activities in Finland:

- Taina Kurki-Suonio; Kilpajuoksu kohti fuusiotuottoa käynnistynyt – kilpailijoilla eri matkat ja tavoiteajat (Race towards fusion energy production kicked off – competitors have different routes and target times), interview in Nuclear Technology magazine ATS Ydintekniikka 1/2021, Vol. 50, pp. 31-35. https://www.ats-fns.fi/images/files/ydintekniikka/atsyt_2021_1.pdf

- Tuomas Tala; Ihmiskunnan suuri unelma: Vuosikymmeniä suunnitellun fuusioenergian kehitystyö kiihtyy. Tutkijan mukaan seuraavat 15 vuotta ratkaisevat (Big dream of the humankind: research on fusion energy has been ongoing for decades, now picks up speed. Researcher states that the next 15 years will be crucial), interview in a tabloid newspaper Iltalehti on 14 March 2021. https://www.iltalehti.fi/talous/a/589d9f9b-e5a0-48aa-8fd2-9fe2a983b906

- Fredric Granberg, Tuomas Tala; Fuusion ongelmia ratkotaan pian tekoälyn avulla Suomessa (Challenges of fusion will be soon solved with artificial intelligence in Finland), interview with Tekniikka & Talous on April 1 2021 regarding the new Advanced Computing Hub to be opened as collaboration of University of Helsinki, Åbo Akademi, VTT and CSC. https://www.tekniikkatalous.fi/uutiset/lumi-toi-miljoonapotin-suomeen-perustetaan-uusi-tutkimuskeskus-ratkaisemaan-fuusioenergian-ongelmia-tekoalyn-avulla/8600f9f8-ab1d-466e-885d-916879664e22

- Tuomas Tala; Fuusioenergian tuotannossa tehdään pian historiallinen koe – vastaava tehty viimeksi 1997, nyt tavoitteena 50-kertainen kesto ja uusi maailmanennätys (A historical experiment expected in fusion energy production - a similar experiment was last done in 1997, now the aim is 50 times longer duration and new world record). Interview with Tekniikka & Talous on 7 April 2021. https://www.tekniikkatalous.fi/uutiset/fuusioenergian-tuotannossa-tehdaan-pian-historiallinen-koe-vastaava-tehty-viimeksi-1997-nyt-tavoitteena-50-kertainen-kesto-ja-uusi-maailmanennatys/5d643e3b-1c69-487b-9a93-d5483fcdb23f

- Tuomas Tala; Näkijä Tuomas Tala, Fuusio tuottaa perusvoimaa (Visionary Tuomas Tala, Fusion produces baseload elecricity). Interview with Tekniikan Maailma magazine in April 2021. https://tekniikanmaailma.fi/lehti/8a-2021/fuusio-tuottaa-perusvoimaa/

- Taina Kurki-Suonio; 20 000 000 000 euroa: Historian kallein ja pitkä tieteellinen koe – tiedemiehet ja -naisetkin ehtivät hautaan (20 000 000 000 euros: The most expensive and longest scientific experiment in history – scientists in several generations). An interview with Tekniikka & Talous on 23rd April 2021 about the history of ITER. https://www.tekniikkatalous.fi/uutiset/20-000-000-000-euroa-historian-kallein-ja-pitka-tieteellinen-koe-tiedemiehet-ja-naisetkin-ehtivat-hautaan/fc11d3dd-cab5-44eb-9f73-419cd1048b5f

- Tomas Lindén: Kaupallinen fuusioenergia saadaan jo vuoteen 2030 mennessä, uskoo amerikkalainen yritys – otimme selvää, missä fuusion kanssa mennään nyt (Commercial fusion energy available by 2030, says American company – current status of fusion energy revisited). Interview with Tekniikka & Talous on 12th May 2021. https://www.tekniikkatalous.fi/uutiset/kaupallinen-fuusioenergia-saadaan-jo-vuoteen-2030-mennessa-uskoo-amerikkalainen-yritys-otimme-selvaa-missa-fuusion-kanssa-mennaan-nyt/bfa40447-dbf8-4c45-ad70-a0f327cc5a71
- Markus Airila: Supermagneetin asennus alkamassa (Installation of the supermagnet is about to start). Interview with Tekniikan Maailma on 7th July 2021 regarding the ITER magnet installation. https://tekniikanmaailma.fi/lehti/13a-2021/supermagneetin-asennus-alkamassa/

- Antti Hakola; Suomi jalostaa fuusioreaktorin monialaista tutkimusta bisnekseksi (Finland refining multidisciplinary research on fusion reactor into business). Interview with Alan-Uutiset magazine on 9th September 2021. https://promaintlehti.fi/Alan-Uutiset/Suomi-jalostaa-fuusioreaktorin-monialaista-tutkimusta-bisnekseksi

- Antti Hakola; Suomi jalostaa fuusioreaktoriosaamista uusille alueille (Finland extends fusion reactor expertise to novel areas). Interview with Uusi Teknologia magazine on 9th September 2021. https://www.uusiteknologia.fi/2021/09/29/suomi-jalostaa-fuusioreaktoriosaamista-uusille-alueille/

- Platom in collaboration with VTT’s new project in fusion energy possibilities. Press release by Platom on 4th October 2021. https://platom.fi/en/platom-in-collaboration-with-vtts-new-project-in-fusion-energy-possibilities/

- Antti Hakola; Rajattomasti energiaa (Limitless energy). Interview with MAL magazine, issue 3-2021.

https://bin.yhdistysavain.fi/1602541/JfOWKigZmQ36P7PyPH2e0WQNtZ/MAL-3-2021.pdf

- Kai Nordlund, Tuomas Tala; Fuusio on voimaa. Vanhan ja hankalan fissiovoiman tilalle tulee päästötön, turvallinen ja melkeinpä loputon fuusio – mutta koska se oikein tulee? (Fusion is power. Old and complicated fission power will be replaced by emission-free, safe, and almost limitless fission – but when will it really come?). Interview with Turun Sanomat newspaper on 2nd November 2021. https://www.ts.fi/teemat/5469628

- Tuomas Tala, Olli Naukkarinen, Kirsi Hassinen; Onko fuusioenergia ikuinen lupaus? (Is fusion energy a perpetual promise?). Interview in MustRead Energy newsletter #13, 17 November 2021. https://www.mustread.fi/uutiskirjeet/energy/

4.2 Courses on Fusion studies

Lecture courses at Aalto University, School of Science:

- *Fusion Energy Technology (M. Groth, spring 2021).*
- *Introduction to plasma physics for fusion and space applications (T. Kurki-Suonio, autumn 2021).*

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

In 2021, also FinnFusion adopted EUROfusion's new procedure of student reporting, which enables developing a better 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. As a result, the number of student project presentations in this FinnFusion Yearbook is significantly higher than in previous years, when only nominated FinnFusion students gave their reports.

During 2021, one Doctoral dissertation, two Master's theses and four Bachelor's theses were completed (see Section 11.3.4).

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:	Two gas-puffs are used near limiters in the FT-2 tokamak for the purpose of hydrogen refuelling during plasma discharges. This creates toroidal and poloidal asymmetry in particle sources near limiters which must be considered in the modelling. Thus, the aim of my project is to include toroidal asymmetry in particle source profiles in ELMFIRE and this is done by doing three small code changes. These code changes control the way particles get recycled back into the simulation domain in the radial and the toroidal direction. Simulations results are analysed to understand the impact of different particles sources on Scrape-off Layer (SOL) physics. Simulation results are also compared with Langmuir probe measurements in the SOL region. The results show that using radial particle source profile from ASTRA modelling and recycling particles near limiters gives better agreement with Langmuir probe measurements and radial profiles from ASTRA modelling.

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: Our research so far has been focused on performing MD simulations of hydrogen and deuterium irradiation on relevant PFC materials (Fe, Fe-alloys), in different surface configurations for both pristine and damaged materials, with ion energies in the sub-keV and keV ranges. The code of choice for this task is LAMMPS. The dependence of the sputtering yield on incident angle and surface morphology is being investigated and compared with experimental results. Results obtained with traditional EAM potentials will provide a benchmark for subsequent studies with a two-temperature modelling of the target materials.

Student: Rashmi Dahal (AU)
Supervisor: Andrea Sand (AU)
Instructor: Andrea Sand (AU)
Topic: *Primary Radiation Damage from collision cascades in Tungsten with pre-existing defects*

Report: Stresses and strains develop in reactor components under irradiation and can be expected to influence the long term accumulation of radiation damage. In this work, molecular dynamics (MD) simulations of consecutive collision cascades are carried out in systems with applied strain, to investigate the long term development of the microstructure in the limits of low defect mobility. Both compressive and tensile loading conditions are being investigated, with initial condition of both a pristine W bcc crystal, and a W system that has been pre-damaged using a combination of artificially introduced Frenkell pairs together with an additional 1500 consecutive cascades.

Student: Andreas Holm (AU)
Supervisor: Mathias Groth (AU)
Instructor: Mathias Groth (AU)
Topic: *Assessing the impact of molecular processes in the scrape-off layer of fusion devices*

Report: For vibrationally excited states of the hydrogen molecule in dense and cold plasmas, each vibrational state must be simulated as an individual species to evaluate the impact of transport of metastable states. A 30–50% decrease in the effective dissociation rate were observed in EIRENE simulations of a one-dimensional flux-tube using a metastable-resolved model compared to simulations using a metastable-unresolved setup, which consider a single molecular species. The decrease is due to an 25–65% decrease in the effective dissociation rates observed for zero-dimensional Eirene simulations omitting transport effects. The differences stem from the metastable-unresolved AMJUEL and the metastable-resolved H2VIBR rates available in Eirene.

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: Under the guidance of Dr. Hirvijoki, the paper where we proposed a metric bracket for representing Coulomb collisions in the guiding-center Vlasov-Maxwell-Landau model was published. While performing theoretical work, a numerical analysis of FT-2 tokamak data by means of the ELMFIRE code was conducted. Under the guidance of Dr. Kiviniemi and in collaboration with colleagues from the Ioffe Institute in Saint Petersburg, a first author paper in which we numerically revisited observations performed in FT-2 tokamak was submitted for publication after presenting the work in Plasma Edge Theory workshop.

Student: Joona Kontula (AU)
Supervisor: Mathias Groth (AU)
Instructor: Taina Kurki-Suonio (AU)
Topic: *Fast Ions in Stellarator Fusion Reactors*
Report: The first peer-reviewed publication for the PhD thesis was published in January 2021 on the topic of ASCOT simulations of 14 MeV neutron rates in future Wendelstein 7-X (W7-X) operational campaigns. Work on W7-X continued this year with simulations of NBI ion power load to the upcoming ICRH antenna. Improved simulation inputs and methods were used for this work, including the updated NBI simulation code BBNBI5. Close collaboration with the Max Planck Institute for Plasma Physics in Germany and CIEMAT in Spain continued in 2021, although planned research visits had to be postponed.

Student: Henri Kumpulainen (AU)
Supervisor: Mathias Groth (AU)
Instructor: Mathias Groth (AU)
Topic: *Impurity transport in tokamak edge plasmas*
Report: Dedicated W erosion experiments in JET-ILW standard ELMy H-mode plasma and diagnostics-optimised divertor plasma configurations with auxiliary heating (Paux) of 18 MW, and hybrid scenarios in plasma-performance optimised, strongly pumped divertor configurations with Paux > 30 MW were simulated with the time-dependent, core-edge coupled code package JINTRAC. The edge transport barrier and scrape-off layer radial transport models,

including ad-hoc, diffusion-driven ELM models, were adjusted to reproduce the upstream profiles of the electron densities and the electron and ion temperatures during both the inter-ELM and ELM phases, and to simultaneously reproduce the divertor particle fluxes, electron densities and temperatures, and the ELM energy and heat flux density to improve the accuracy of the simulated plasma conditions. ERO2.0 simulations of W erosion and transport were carried out on the JINTRAC inter-ELM and ELM phases. The validation of ERO2.0 W erosion sources is a critical step towards predicting ELM-resolved W influx to the confined plasma, which provides a physically established boundary condition for core W transport studies to predict the core W radiation.

Student: Roni Mäenpää (AU)
Supervisor: Mathias Groth (AU)
Instructor: Mathias Groth (AU)
Topic: *Nitrogen transport and chemistry in divertor plasmas*
Report: Comparison of spectroscopic N II emission with simulations by the 3D kinetic trace impurity Monte Carlo code ERO2.0 indicates that most nitrogen is being recycled as molecules instead of atoms, a process associated with an up to 50% higher volume-integrated, time-averaged number of doubly-charged nitrogen ions in the plasma. The increase in the number of doubly-charged nitrogen ions is attributed to higher plasma penetration by the molecular dissociation fragments due to the kinetic energy gained in the Franck-Condon process. Correspondingly, a decrease in the volume-integrated, time-averaged number of singly-charged nitrogen ions of approximately 25% is predicted by ERO2.0. The ERO2.0 simulations indicate that, assuming molecular recycling, the N II line emission across the low-field side divertor region increases, being qualitatively more consistent with spectroscopic measurements.

Student: Rafael Nuñez (AU)
Supervisor: Andrea Sand (AU)
Instructor: Andrea Sand (AU)
Topic: *Studies on energy dissipation mechanisms from energetic recoils*
Report: The formation of radiation damage is sensitive to the partitioning of the incident kinetic energy in the atomic versus the electronic subsystems. While energy losses to electrons through electronic stopping is theoretically well understood in the high energy limit, in the low energy limit orbital effects become important, and these processes are less known. Neutron-induced collision cascades give rise to a large population of atoms in this energy range, and the treatment of energy losses during cascades has been shown to

affect the damage predictions from atomistic simulations. In this project, the energy loss mechanisms of projectiles to the electronic system are studied with real-time time-dependent density functional theory, which explicitly accounts for local orbital effects.

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: The fast-ion charge-exchange (CX) model of the ASCOT particle-following code was used to simulate beam ions under the effect of CX reactions in a design scenario of the MAST-U spherical tokamak, which had its first experimental campaign in autumn 2021. ASCOT predicts that CX between beam ions and background atoms causes a beam power loss of 22%, and peak power loads of 70-80 kWm^{-2} from beam particles on the central poloidal field coils and the vacuum vessel wall between them. After reporting these and other demonstrative results in the journal Plasma Physics and Controlled Fusion, work has focused on the experimental validation of the CX model by comparing simulations to fast-ion deuterium-alpha spectroscopy and other diagnostic measurements.

Student: Vladimir Solokha (AU)
Supervisor: Mathias Groth (AU)
Instructors: Mathias Groth (AU)
Topic: *Isotope effect on detachment onset density and density limit in JET Ohmic plasmas*
Report: Measurements of the ion currents to the low-field side (LFS) target plate in JET ITER-like Wall made of tungsten (W) in ohmic and low-confinement mode discharges showed an approximately 10% decrease in the required detachment onset density with increasing main ion mass for as-pure-as-possible hydrogen, deuterium and tritium plasmas. At the detachment onset the molecular pressures in the sub-divertor were approximately 0.1 Pa for all hydrogenic species. Such pressures are indicative for species-mass dependent molecular flow through the pump ducts, anticipated to produce higher molecular pressures in front of the target plate for higher mass species. On the other hand, the detachment onset density was almost identical in deuterium plasmas with and without active pumping through the JET divertor cryogenic pump, implying that for L-mode plasmas and such a vertical-horizontal divertor plasma configuration the detachment onset is determined by

plasma recycling off the target plates, and largely independent from the sub-divertor pressure.

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: During 2021, two main topics were researched. First, a new Gauge free drift kinetic theory has been derived in Euler-Poincare coordinates and tested against the dipsersion relation derived by the standard gyrokinetic theory. Second, a new backward Monte Carlo integrator has been developed and tested as a module of Ascot suite. Aim of the scheme is to improve the statistics of current Monte Carlo schemes for fast ions, which traditionally suffer from Monte Carlo noise and bad statistics. The new Backward Monte Carlo sceme has been tested with AUG test cases.

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: A mobile parallel mechanism robotic system was designed, developed, manufactured and tested for the vacuum vessel assembly. The robotic system should carry out machining and welding processes. Then the multi-objective optimization of the parallel mechanism was carried out to optimize the parallel mechanism performance on load capacity and stiffness. The relations between the parallel mechanism performance to different geometry parameters are concluded from the study. The results can act as a guideline for other researchers in the future.

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: We are working on a lightweight and miniaturized snake arm maintainer to meet the practical application needs of visual navigation, cutting, welding, and handling in narrow environments. The snake arm maintainer uses a layered drive principle to achieve lightweight and miniaturized design requirements. The controller adopts a variety of control modes such as trajectory tracking and trajectory planning joint control to facilitate control. We also

developed an adaptive trajectory control algorithm based on the entire process of the snake robot entering and exiting narrow spaces and completing operational tasks to increase the convenience of use.

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: Since 1955, the harmonic drive has been widely applied in practice because of the following reasons: high torque output, lightweight design, and higher efficiency than traditional drives. A dynamic model of a manipulator contains many parameter uncertainties, so it is difficult to establish an accurate dynamic model. The purpose of the current study was to identify the key components of the robot joint with harmonic drive for example, the friction of a harmonic drive so that the force on the joint can be identified by the current on each joint to ensure the safety of the robot. The results present and explain the method used to identify the parameters by component decomposition related to motor position, current, temperature. We use the latest model for the friction of harmonic drive simulation and the hysteresis characteristics of friction.

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 work introduces the optimization of trajectory planning and precision control algorithm of the CFETR multipurpose overload robot (CMOR) using an AI algorithm. The CMOR is a kind of snake robot with multi-hinge structure, and it has a large degree of freedom of movement and load capacity. The total mass of the CMOR is up to dozens of tons, and the load capacity is also high. It is accompanied by large deformation during operation, the maximum deformation is up to 140mm.Therefore traditional motion planning algorithms are not suitable for CMOR. In this work we aim to find the optimal solution for a new control algorithm for the CMOR under the constraints of the complex environment.

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

Report:	The plasma-facing components require frequent maintenance and replacement. A large number of high-precision peg-in-hole assemblies are included in these tasks. As designed, maintenance work is carried out by a pair of robotic arms, one arm with a toolbox containing the peg for assembly and the other arm with an end-effector for finishing the tasks. So, the task can be divided into two sub-tasks. First, searching for peg and hole, driving the robotic arm to grab the peg and automatically approaching the hole; for this sub-task, we are using a CNN-based instance segmentation network and introducing some traditional algorithms to eliminate uncertainty in results. Second, inserting the peg and finishing the assembly task; for this one, we are using a deep reinforcement learning (DRL) network, which could find the most efficient path to complete the assembly task based on the RGB image and the Force/Torque sensor data.

Student:	Ihtisham Ali (TUNI)
Supervisor:	Atanas Gotchev (TUNI)
Instructor:	Atanas Gotchev (TUNI)
Topic:	*Visual SLAM for unregulated dynamic environment*
Report:	We investigated the applicability and extension of the core concepts of Visual SLAM towards perception, calibration, and visual servoing for a robot arm manipulation. In the study, Methods for Simultaneous Robot-World-Hand-Eye Calibration: A Comparative, we investigate hand-eye calibration methods and propose new methods and datasets to achieve better calibration results. Subsequently, we propose a geometrically constrained Multiview pose estimation method in the article Multi-View Global Pose Estimation for Robotic Arm Manipulation that yields accurate pose estimates for visual servoing. In addition, we also investigate the types of fiducial markers and their algorithms for detection and subsequent pose estimation for applications that require submillimeter accuracy.

Student:	Laura Maria Goncalves Ribeiro (TUNI)
Supervisor:	Atanas Gotchev (TUNI)
Instructor:	Atanas Gotchev (TUNI)
Topic:	*Vision enhancement in safety critical applications*
Report:	Proposed a retro reflective marker design to be used in ITER. Developed a marker-based vision system that estimates the pose of the knuckle of the divertor cassette locking system using markers attached to its surface. Evaluated the performance of pose estimation with monoscopic and stereoscopic setups. Built a demonstration of a pin tool insertion task. Developed a retro reflective marker design with a significant performance gain over

the previous version that circumvents the material restrictions of ITER environment. Improved the robustness of marker detection strategies. Considered the applicability of some of these methods to other usecases in ITER.

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 using 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 behavior of manipulators with nonlinearities of the gears make 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 rations and associated static nonlinearities. Additional key area of this study is force reflecting bilateral master-slave control for these manipulators.

Student: Zhehao Chen (UH)
Supervisor: Filip Tuomisto (UH)

Instructors: Filip Tuomisto (UH)
Topic: *Irradiation damage on high entropy alloys*
Report: Multiple-components alloys or High entropy alloys (HEA) are promising nuclear material candidates. In 2021, the two-phase structure Fe based multi-component alloys with low-activation elements, 60Fe-12Cr-10Mn-15Cu-3Mo (at.%) and 60Fe-12Cr-8Mn-15Cu-3Mo-2V (at.%), was irradiated by low-temperature (50K) 10 MeV proton. To study the vanadium effect on defect's movement, the in-suit positron annihilation lifetime measurements were performed at the different annealing temperatures. We also studied the helium behaviours in the Cantor HEA (CrMnFeCoNi). Samples were irradiated by Ni and He at room temperature. The cross-sectional images of helium distribution were obtained by Focus Ion Beam and Transmission Electron Microscopy. Samples were also characterized by Extended X-ray Absorption Fine Structure measurements.

Student: Faith Kporha (UH)
Supervisor: Kai Nordlund (UH)
Instructors: Fredric Granberg (UH)
Topic: *Effect of surface morphology on tungsten sputtering and reflection yields*
Report: In many computer simulations of sputtering an atomistically flat surface is used to obtain the sputtering yield for a certain energy, incoming angle and ion. However, the experimentally flat surface is never completely flat, and surface features of at least nanometer heights are almost always present. In order to better understand the sputtering phenomena, we investigate how different surface features affect the sputtering and the reflection of the ion. We have started to investigate how nanopillars are affecting the sputtering under different ion irradiation and conditions.

Student: Emil Levo (UH)
Supervisor: Kai Nordlund (UH)
Instructor: Fluyra Djuberokova (UH), Fredric Granberg (UH)
Topic: *Radiation Damage in High Entropy Alloys*
Report: Experimentally it has been observed that the irradiation temperature will affect the surviving number of defects in High-entropy alloys (HEAs). We have studied the high-dose defect build-up in several HEAs with computer simulations. We found a decrease in the surviving number of defects as the temperature increased. We also carried out RBS/c simulations on our simulated cells and compared them to experiments, carried out under similar conditions. We found a good agreement between both methods, thus indicating that our defective structure with atomistic resolution

is comparable with the experimental structures. These results and previously obtained ones have been collected into a thesis, which was defended in January 2022.

Student: Victor Lindblad (UH)
Supervisor: Kai Nordlund (UH)
Instructors: Fredric Granberg (UH)
Topic: *Studying kink formations on screw dislocation lines, using MD*
Report: Screw dislocations in metals are known to determine the macroscopic mechanical properties of the material. The screw dislocation mobility is on the other hand dependent on the double-kink formation energy, which dictates how easy the screw dislocation can move forward. We have with several classical and new ML AI interatomic potentials determined the formation energies of the double-kinks, for the fusion relevant materials tungsten and iron. We have also investigated how vacancies are binding to the screw dislocation, which also affect the mobility and therefore the mechanical properties of the material.

Student: Otto Lindblom (UH)
Supervisor: Tommy Ahlgren (UH)
Instructors: Tommy Ahlgren (UH)
Topic: *A computational study of hydrogen interactions with tungsten*
Report: In 2021 we studied tritium removal from tungsten defects using isotope exchange. Molecular dynamics simulations were conducted to provide an atomic-scale explanation to the processes related to hydrogen isotope exchange in bulk materials. Our results show that lattice mono-vacancies and small vacancy clusters, usually produced in irradiation experiments, exhibit isotope exchange even at low temperatures. The results also indicate significantly improved tritium removal rates for all considered temperatures when isotope exchange is employed, compared to removal by pure annealing.

Student: Anna Liski (UH)
Supervisor: Filip Tuomisto (UH)
Instructors: Filip Tuomisto (UH)
Topic: *High entropy alloys as first wall materials*
Report: High Entropy Alloys (HEAs) are a novel class of materials characterized by a random mixture on five or more elements with nearly equal concentrations. The high mixing entropy leads to superior mechanical properties under elevated temperatures. Our project is evaluating the suitability of WMoNbTaV alloy as plasma facing material by experimentally studying hydrogen trapping and the retention dynamics in the material.

The previous research suggests that the WMoNbTaV alloy tends to store considerable proportion of implanted hydrogen. Currently we investigate whether the binding is related to the implanted dose. Alloy and samples of W are being implanted with 20keV deuterium with four doses 5e15, 5e16, 5e17 and 5e18 D/cm^2. The most crucial point of success is to avoid any sputtering of the holder material onto the samples in the prolonged implantation processes with the largest dose. The amount of retained deuterium will be measured by Elastic Recoil Detection Analysis (ERDA).

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: We have obtained and analysed positron data on silicon doped nitrides (GaN and AlGaN) for radiation-hard optical sensors. Highly doped GaN samples demonstrated low concentrations of free charge carriers and cation defects. These findings leave an open question on the mechanisms of Si compensation, which cannot be linked to formation of the acceptor-like defects or presence of acceptor-impurities, as their concentrations are relatively low. We also performed X-ray absorption (XAS) measurements at Si K-edge in this set of samples to have a better understanding of the chemical specification. It appears as if the local environment of Si is different depending on whether the Si is compensated or not, as well as if the compensation is spatially correlated.

Student: Anton Saressalo (UH)
Supervisor: Fluyra Djuberokova (UH)
Instructors: Walter Wuench (CERN)
Topic: *Experimental study of the role of extrinsic and intrinsic vacuum arc breakdown mechanisms*
Report: Electrical discharges take place near metal surfaces exposed to high electric fields, for instance, in plasma sheath. The phenomenon, also known as electrical breakdown, may take place even in high and very high vacuum. The experimental study of the breakdown phenomenon is done with Cu electrodes separated by a vacuum gap. The statistical analysis of breakdowns generated by applying high-voltage pulses allowed to assess contribution of different effects of extrinsic (i.e. surface contamination) and intrinsic (i.e. plastic deformations under the electrode surface) nature on probability of breakdown event on flat surface within submicrometer roughness.

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: In 2021 we studied sequential deuterium implantations to tungsten samples with low and high energies to mimic ELM energies observed in JET and estimated to occur in ITER. The results show increased deuterium retention in tungsten with the sequential implantations due to defect production by high energy ions as well as increased retention due to low energy implanted deuterium stabilizing defects created by the high energy ions. Other work included hydrogen isotope exchange experiments in high entropy alloy WMoTaNbV and writing a publication about earlier results from Wendelstein 7-X 13C tracer depositions measured by SIMS.

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: This project is dedicated to investigation of the point defects and radiation hardness of beta-gallium oxide (beta-Ga_2O_3) crystals and beta-Ga_2O_3-based devices capable of operating under extreme conditions (high temperature, radiation) in spacecraft, particle accelerators, fusion reactors etc.

Point defects strongly affect the performance and reliability of the beta-Ga_2O_3-based devices, hence the identification and control of dominating defects is the most important step for further improvement of the properties of beta-Ga_2O_3 devices. This will be implemented by ion beam based materials modification and characterization, complemented with Positron Annihilation Spectroscopy, in particular orientation-dependent experiments of the Doppler broadening of the positron-electron annihilation.

Student: Nikola Petkov (UKAEA)
Supervisor: Huapeng Wu (LUT)
Instructor: Roger Powell (UKAEA)
Topic: *Condition monitoring of Remote handling system for DEMO*
Report: The remote maintenance system of a fusion power plant must be designed to be robust and resistant to the inherent risks involved of operating equipment in high temperature, radioactive environment. Some of these risks can be mitigated by design to some degree. Even though the risk is considered mitigated by design, this risk

mitigation strategy is still governed by a feed-forward process where there is no real feedback from the degradation progression in real-time. Condition monitoring has already been proven as a valuable tool for mitigating risks of critical equipment failures. The latest developments in Machine learning and Data science allow for high quality condition monitoring and prognostics methodologies to be developed, which indicates a rising trend of innovation in condition monitoring methodologies needed to tackle the challenges of risk mitigation in fusion industry.

Student: James Simpson (UKAEA)
Supervisor: Mathias Groth (AU)
Instructor: David Moulton (UKAEA), Carine Giroud (UKAEA)
Topic: *Modelling of edge pedestal and scrape off layer integration*
Report: The core transport code, JETTO, coupled to the neutral Monte Carlo code, EIRENE, has been used to examine the sensitivity of the JET H-mode pedestal to the neutral flux crossing the separatrix. The Neutral Penetration Model (NPM) predicts the width of the density pedestal along the neutral path to scale with the inverse of its height. By keeping the same physics assumptions in the NPM and setting the deuterium atoms to cross the separatrix at the same location as the synthetic diagnostic line of sight (i.e., at the outer mid-plane), we were able to reproduce this scaling in JETTO-EIRENE. However, when the atoms were set to cross the separatrix at the X-point (more consistent with EDGE2D-EIRENE simulations of JET H-modes), the density width at the outer midplane was found to be much more sensitive to the pedestal height. This is attributed to a radial variation in the poloidal flux expansion from MP to X-point, over the range of ionisation mean free path lengths explored in the can. Accounting for this variation allowed the expected scaling at the OMP to be recovered.

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 work focuses on studying the microstructure level length-scale dependent deformation behavior of the Copper material, of particular significance with respect to accumulation of plasticity. Material’s grain structure variations, segregation and any possible manufacturing defects in microstructure are relevant in terms of susceptibility to creep and damage from the loading evolution imposed by its operating environment. The reduced micromorphic crystal plasticity model, which is similar to strain gradient models, is used in this investigation. Firstly, the model’s size dependent

plasticity effects are evaluated. Secondly, different microstructural aggregates presenting different material sections are analyzed. Grain size dependent hardening responses, i.e., Hall-Petch like behavior, can be achieved with the enhanced hardening associated with the micromorphic model at polycrystalline level

Student: Matias Haapalehto (VTT)
Supervisor: Fluyra Djuberokova (UH)
Instructors: Anssi Laukkanen (VTT), Tatu Pinomaa (VTT)
Topic: *Atomistic modeling of rapid solidification and properties of metallic refractory materials and alloys*
Report: Refractory materials are characterized by a relatively high melting point, which is relevant to fusion applications. Novel atomistic modeling methods, such as GAPs, are developed with improved predictive power compared to other existing methods. These methods are applied to rapid solidification and defect generation phenomena, which are instrumental to materials design. New refractory high-entropy alloys (RHEAs) are sought that display superior high-temperature mechanical properties, such as a combination of high strength and high ductility.

Student: Atte Helminen (VTT)
Supervisor: (AU)
Instructors: (VTT)
Topic: *Safety and risk assessments*
Report: The research goal is to apply probabilistic risk assessments (PRA) in the field of fusion energy. In PRA, a quantitative risk model is created for a system, such as a fusion power plant or fusion material irradiation facility. The added value provided by PRA is that it considers all possible combinations of equipment failures and human errors and quantifies the probability of hazardous events or sequences. This achievement makes possible to identify important features of the fusion power plant risk portfolio, e.g. the relative risk impact of unavailability of various components, systems or events and provides inputs into a safety ranking based on quantitative risk indicators. Such information, which cannot be obtained without PRA, may be used for the decision making purposes to efficiently improve the plant safety and to demonstrate compliance with quantitative safety targets.

Student: Anu Kirjasuo (VTT)
Supervisor: Filip Tuomisto (UH)
Instructors: Antti Salmi (VTT), Tuoma Tala (VTT)
Topic: *Particle source impact on density peaking in JET experiments*

Report: Fusion energy production in a tokamak scales to the density squared. On the other hand, a plasma with too high density cannot be contained. Therefore, a peaked density profile, where central density is higher than the pedestal density, is desirable. In JET the heating is dominated by neutral beams (NBI), which are not foreseen for ITER or fusion reactors. In 2021 simulations were ran to try and quantify the portion of density peaking caused by the particle source (NBI). In H-mode the results show that about half of the density peaking comes from NBI, in fairly flat profiles even more, while in L-mode plasmas the source contribution is at most about 20%. The results will be compared to ASDEX Upgrade and applied to a database of JET pulses in 2022. A Master's Thesis was completed on the topic on 2021.

Student: Marton Szogradi (VTT)
Supervisor: Andrea Sand (AU)
Instructor: Antti Snicker (AU)
Topic: *The multiphysics calculation chain of DEMO*
Report: The work entails the assembly and development of a calculation chain, composed of Finnish codes such as 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.

5.2 WP TRA: EUROfusion Researcher Grant

Validation of fluid and hybrid fluid-kinetic models for the neutral hydrogenic particles in JET

Research scientist: N. Horsten, AU

Neutral particles (atoms and molecules) in the plasma edge are typically simulated by means of a Monte Carlo (MC) simulation of the kinetic equation, which leads to a tremendous computational cost for high-collisional reactor-relevant regimes. In 2020, a spatially hybrid fluid-kinetic approach has been proven successful in reducing the computational cost. However, the purely fluid treatment of atoms resulting from molecular dissociation leads to significant remaining discrepancies due to deviations from a Maxwellian distribution for the atoms. These deviations are to a large extent resolved by combining the spatially hybrid approach with the micro-macro approach. Figure 5.1 shows that the newly developed hybrid approach reduces the maximum discrepancies with a simulation with fully kinetic neutrals to 20% for the outer divertor plasma profiles of a JET L-mode plasma. With the hybrid approach, the average computational time for a single MC particle is reduced with an order of magnitude, making it a promising method for future ITER and DEMO simulations.

In addition, we have experimentally validated the models for several important synthetic diagnostics, such as Langmuir probe data at the targets, bolometric measurements, and line-integrated deuterium Balmer-α (Dα) emission. Although an agreement between the simulations and the experiments is observed for low-recycling conditions, the simulations give an error of approximately 50% for high-recycling conditions. The simulation-experiment discrepancy does not increase when using the hybrid neutral model, which makes it extremely valuable for further model validation and reactor design for computationally challenging regimes.

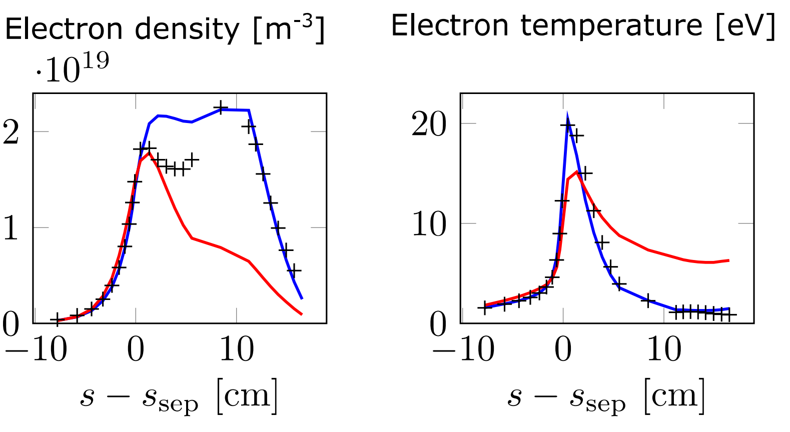


Fig. 5.1. Outer divertor target profiles: fully kinetic neutrals (blue lines), spatially hybrid neutrals (red lines), and newly developed hybrid approach (pluses).

6. NJOC and PMU

6.1 Overview

Two FinnFusion scientists were seconded to work in the JET operating contract team (NJOC) in 2021. This section highlights the NJOC projects:

- NJOC Viewing and thermal measurements diagnostician, Juuso Karhunen, UH
- NJOC NPA and alpha diagnostician, Paula Siren, UH

6.2 NJOC Viewing and thermal measurements diagnostician

Inference of molecular density in the JET divertor from tomographic reconstructions of deuterium Balmer line emission

Research scientist: J. Karhunen, UH

A previously introduced Monte Carlo methodology for estimating 2D distributions of the divertor plasma conditions (n_e, T_e, n_{at}) from intensity ratios of reflection-corrected tomographic reconstructions of filtered camera images of deuterium Balmer line emission in the JET divertor was amended to distinguish the Balmer D_α and D_γ emission contributions arising from plasma-molecule interactions. With the help of the AMJUEL and H2VIBR atomic and molecular databases, the molecularly induced emission fractions were used to infer the local molecular divertor density during detachment in L-mode. The independent nmol estimates derived from $D_{\alpha,mol}$ and $D_{\gamma,mol}$ both suggest emerging presence of D_2 molecules near the outer strike point at $T_{e,osp}$ < 2.0 eV with increase to nmol,osp = 1—2×10^{20} m^{-3}, corresponding to up to 50% of local ne, in deep detachment at $T_{e,osp}$ < 0.7 eV. The observations are in agreement within experimental uncertainties with predictions of EDGE2D-EIRENE simulations.

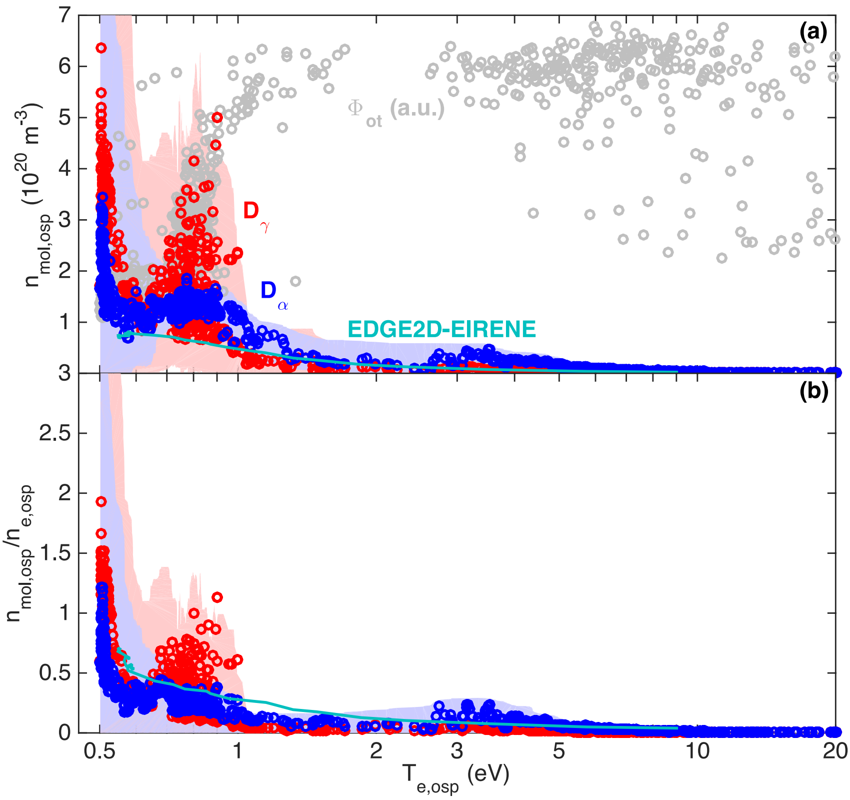


Figure 6.1: Molecular density (a) and its ratio to local electron density (b) inferred from experimentally distinguished molecularly induced D_α (blue) and D_γ (red) emission together with EDGE2D-EIRENE predictions (cyan) as functions of Te at the outer strike point. The process of detachment is presented by the outer target ion current (grey) in (a).

6.3 NJOC NPA and alpha diagnostician

Monitoring radiation damage in the lost alpha system fibres

Research scientist: P. Siren, UH

JET lost alpha particle diagnostics system is equipped with a test fibre for monitoring the effects due to radiation damage especially in TT and DT operations. Monitoring fibre (blind fibre loop with LED light source) was installed during the 2019 shut down and it has collected data from DD, TT and DT operations. Trend of the monitoring signal has been analysed after the DTE2 campaign, and it has been clearly seen that there is degradation in optical properties, such as darkening, observed especially during neutron intensive periods and recovering during operational breaks. The effects related to the temperature of the fibre etc. will be studied in the future and the data samples will be studied in more detail, if clear correlations with plasma properties (RF/NBI power level, neutron energy spectra) can be found.

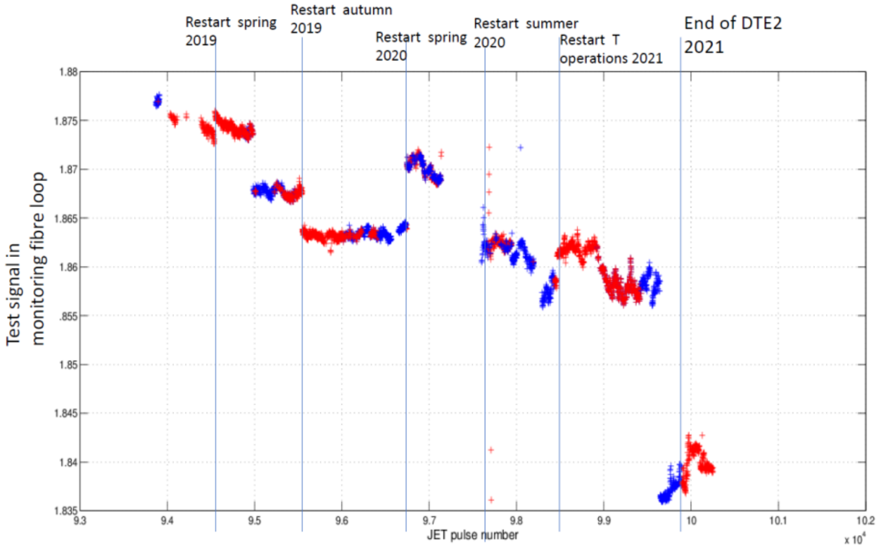


Figure 6.2: Time evolution of JET lost alpha system test signal of the monitoring fibre from 2019 to 2022.

7. International collaborations

7.1 DIII-D tokamak

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

Synthetic spectroscopy analysis of UEDGE-CRUMPET simulations implies the radiative power exhausted by molecular radiation corresponds to approximately 10% of the atomic hydrogen radiation for low-confinement mode plasmas under high recycling divertor conditions in DIII–D. The predicted band-integrated intensity of the molecular Fulcher (600-640 nm) band is 10% of the $H_{\text{-}\alpha}$ intensity, compared to approximately 1% inferred from Wide Spectral Emission (WiSE) and Multi-chord Divertor Spectrometer (MDS) measurements of dedicated DIII-D plasmas. These findings imply that hydrogen molecular radiation is not expected to significantly affect the DIII–D divertor power balance under high-recycling conditions. However, future machines push towards higher divertor density operation under detached conditions, increasing the density of molecules and, subsequently, the role of molecular processes in the divertor.

The role of collisional-radiative (CR) molecular processes that cannot be measured by the DIII–D spectroscopic system are assessed using the self-consistent fluid-molecular model in UEDGE coupled to the CR code CRUMPET. The peak intensites of the wide, low-intensity molecular Lyman-Werner (120-170 nm) emission spectra are predicted to be more than two orders of magnitude lower than the $L_{y\text{-}\alpha}$ peak intensities: consequently, the Lyman-Werner band could not be resolved by the DIII–D spectroscopic diagnostics employed in the experimental measurements. Instead, UEDGE-CRUMPET simulations were used to calculate the band-integrated intensity of the Lyman-Werner band, predicted to correspond to 15% of the $L_{y\text{-}\alpha}$ intensity.

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

First part of the DIII-D experiment to study density peaking and particle transport between Hydrogen and Deuterium isotopes has been performed in early 2021 remotely in collaboration with the local DIII-D team. The best H-mode discharge obtained during the session is in pure Hydrogen at 2T/0.9MA and features 3.33Hz gas puff modulations to probe perturbative particle transport. The follow up dimensional match for comparison in Deuterim is scheduled for 2022. Once complete, both discharges will be simulated with codes like JINTRAC-TGLF and GENE to pinpoint the reasons for differences in density peaking. It is of interest to quantify also the role of the NBI fueling in density peaking and compare it against existing JET results.

7.2 CFETR tokamak

Research scientists: H. Handroos, J. Koivisto, C. Li, M. Li, H. Wu, LUT

LUT in collaboration with ASIPP, China, has developed a robotic machine for the assembly and maintenance of CFETR tokamak. The robotic system, which has a very the compact size and is designed for high stiffness in performance, can carry out machining, welding, and NDT testing inside of the CFETR VV. The robot was delivered to ASIPP on 1st of March 2022.

Meanwhile, the double doctoral degree programme between the ASIPP and the LUT has been running successfully so far. One doctoral degree was awarded in 2021 and three others are ongoing. The research activities include development of a robot CMOR for replacements needed on the blanket /first wall, and a robot MOVER for the replacements needed on blankets and divertors, as well as AI alogrithms for the robotic maintenance.

Figure 7.1. Mobile robotic machine for the assembly and maintance of CFETR.

8. Fusion for Energy activities

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

F4E grant: F4E-GRT-0901

Research scientists: J. Alanen, O. Rantanen, H. Saarinen, VTT
U. Budak, H. Bui, A. Zia, D. Hästbacka, I. Ali, L. Gonçalves Ribeiro, O. Suominen, A. Gotchev, 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) to be incorporated into the ITER Remote Handling (RH) control room. During 2021, the main activity was to integrate the C&C application and GENROBOT robot control middleware (both implemented by GTD, a Spanish system and software engineering company) with the HLCS at the Divertor Test Platform (DTP2) hosted by VTT to demonstrate the Cassette Multifunctional Mover (CMM) divertor cassette remote maintenance operations.

Development of yet another HLCS subsystem, Computer Assisted Teleoperation, was coordinated by Tampere University (TUNI). The 3D Node system created by TUNI was further developed during 2021 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, development of a software stack to interface the 3DNode with HLCS was started. The 3D Node 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.

8.2 Digivalve tests on DTP2

F4E grant: F4E-GRT-0974

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

ITER divertor replacement requires several robot-like devices, handling of ~10 tons load, tight jacking and high torque bolting. All the operations need to be highly accurate. Also, the cassette maneuvering along its path to/from its place is to be made within few mm accuracy. The ITER divertor replacement operations have been developed and trained at VTT laboratory in Tampere since 2008.

Digi hydraulics is a novel control method of hydraulic devices. The inbuild redundancy of Digi hydraulics makes it very reliable and therefore ideal for ITER robotics, and control of fast settling time and accuracy provides safe divertor replacement operations, and technique suitable for any handling of heavy loads in complicated environments in high accuracy.

This novel control technique has been developed at Tampere University and it is developed specially to control hydraulic systems using water as a pressure media in hydraulic system.

As usual, hydraulic systems use oil as a pressure media (industrial presses, excavators, hydraulic robots etc.). In fusion environment, however, oil leaks would be hard to clean and would contaminate the plasma. Oil would also be activated and problematic waste after use. Water, instead, can be treated in the same way as ITER is treating all the other activated cooling water. The water used in ITER water hydraulic systems should be similar type of water that is used in conventional nuclear power plants, i.e. demineralized water.

Typically, accurate control of hydraulics has been done using commercial servo valves to control flow to actuators. This will also be done in ITER. Due to low viscosity of water, servo valves for water are manufactured with extremely tight tolerances. Therefore, servo valves (specially water-compatible) are sensitive to temperature, impurities (size > 3 μm) and many others. In addition, corrosion also behaves differently. After all, the current servo valves have caused problems, so they are not recommended to be used in ITER RH-devices. Tests are now made to replace them with Digi valves.

In Digi hydraulics, one servo valve is replaced with a group of redundant, fault tolerant On-Off -valves, which can be set to produce needed servo-like output flow. The set of on-off valves needed to produce one servo-output is called “Digi valve”.

However, water hydraulic applications or components do not exist commercially yet. F4E is interested in Digi hydraulics to be used in some high precision devices, like ITER divertor cassette maintenance system and hydraulic manipulators.

Therefore, the control valves of ITER CMM in DTP2 are replaced with Digi valves and the replacement operations are driven with Digi valve-controlled CMM. The control software used to control the Digi valves Genrobot is developed by Spanish GTD.

The results (accuracy, speed) of the operations are compared to those obtained with servo control. Currently, the software controlling the valves is under installation. After the software is operating, the test drives can be started.

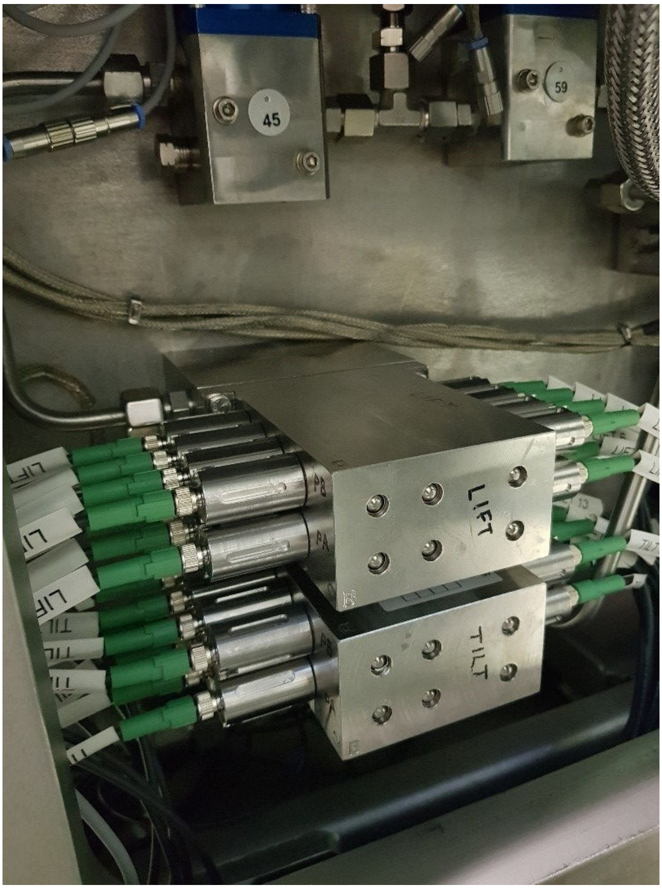


Figure 8.1. Two servo valves have been replaced by two digi valves (steel blocks). Each valve block consists of 16 separately controlled on-off -valves.

9. Code development in FinnFusion

9.1 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 9.1). 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 Descign Phase.

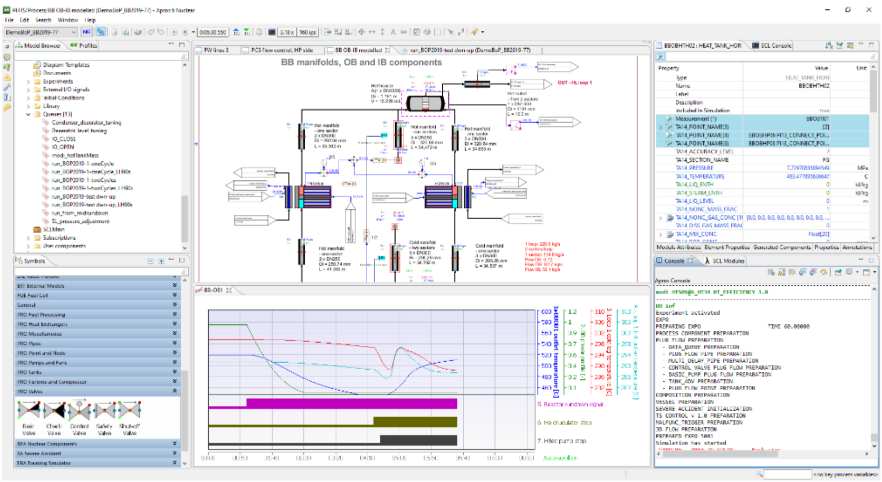


Figure 9.1. Apros user interface.

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

Research Scientists: J. Kontula, T. Kurki-Suonio, P. Ollus, S. Sipilä, S. Äkäslompolo, AU

Despite serious efforts to adhere only to the most recent version of the ASCOT suite-of-codes, ASCOT5, it was still necessary to continue also with ASCOT4. This is because the IMAS and ITM environments are currently using the older version, and the ICRH-operator RFOF has not yet been implemented to ASCOT5.

Support for ASCOT4 in the IMAS and ITM environments was continued, and improvements were made related to bookkeeping and input/output of multiple marker species from different sources. Species-specific velocity and energy distribution limits were also implemented.

For ASCOT5, the development work in 2021 was focused on improving its performance in challenging applications, like for stellarator geometries. Majority of the work has been carried out as TSVV-work (see Sec. 2.7.5). The main improvements are related to GPU performance and interfacing ASCOT5 with other codes. Also implementing support for stellarator specific modalities is progressing. As a physics model enhancement, the CX model originally developed for ASCOT4 was implemented to ASCOT5.

9.3 Full-f gyrokinetic turbulence code ELMFIRE

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

Development of ELMFIRE code has focused on building a new 6-D electromagnetic particle-in-cell code which partly occurs within TSVV Task 4 as reported in Section 2.7.1. For the present electrostatic gyrokinetic version of ELMFIRE, different recycling models have been tested and using more realistic particle source profile gives a better agreement with Langmuir probe measurements, and profiles in simulations are close to initial values in most of radial locations when compared to the previous study with uniformly recycling in radius at last 2 cm in the radial direction and on one side of poloidal limiters in the toroidal direction as shown in Fig. 9.2.

A new algorithm for implementing Coulomb collisions in particle-in-cell codes was developed. The new formulation enables arbitrary marker-particle weights while preserving the density, momentum, and energy invariants to machine precision. The new algorithm is expected to be useful in simulations of the plasma edge and scrape-off layer where the plasma density changes radically and standard binary-collision algorithms, that require equal marker-particle weights, become inefficient.

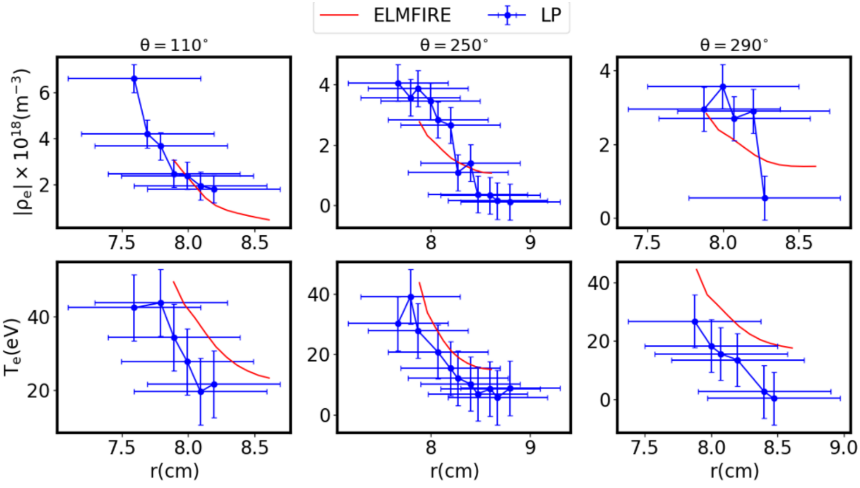


Figure 9.2. Density and temperature profiles from ELMFIRE simulations are within error bars of experimental Langmuir probe (LP) measurements.

A so-called backward Monte Carlo method was implemented into and tested with the ASCOT suite-of-codes to improve simulating fast-particle losses. The new algorithm estimates the escape probability of particles being lost to certain wall elements under investigation and uses the estimated probability as a priori information to perform importance sampling of the marker-particles to be simulated. In certain situations, the new method has potential to significantly improve the statistics of hits to wall elements of interest, consequently improving the computational efficiency of fast-ion studies.

9.4 Molecular Dynamics

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

The work on development of highly accurate machine-learning interatomic potentials for MD simulations have continued. In particular, we have developed a speed-up tabulation routine for Gaussian approximation potentials (GAP), called tabGAP. The tabulation of a GAP in to a tabGAP leads to a computational speed-up of two orders of magnitude with no loss in accuracy, as illustrated in Figure 9.3.

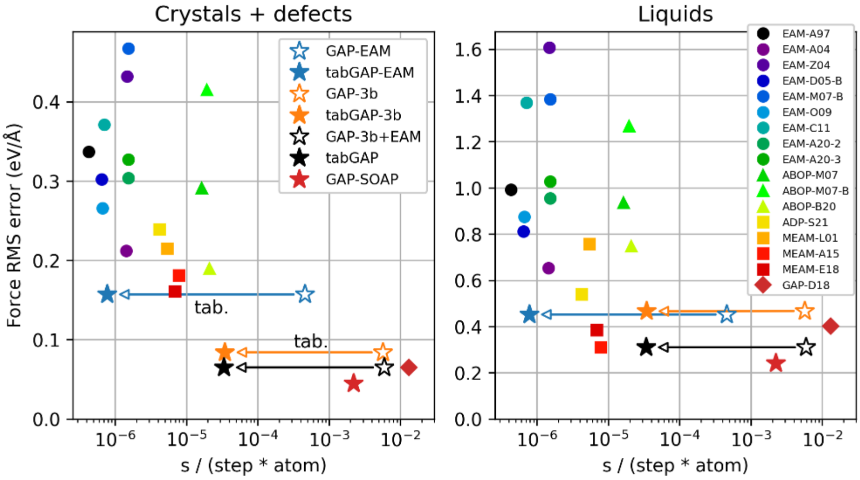


Fig. 9.3. Accuracy of various interatomic potentials for iron as functions of computational cost. The arrows show the speed-up of different machine-learning GAP potentials (unfilled stars) into the corresponding tabGAP potentials (filled stars).

9.5 Serpent

Research Scientists: J. Leppänen, VTT

Serpent is a Monte Carlo neutron and photon transport code, developed at VTT since 2004. The code was originally developed for the purpose of fission reactor physics, but in recent years the scope of applications has been broadened to new fields, including radiation shielding and fusion research. Serpent has a large international user community consisting of more than 200 universities and research organizations in 44 countries. The total number of users is around 1000.

In 2021 Serpent has been used under WP WPR Prospective R&D work in chapter 3.7.3 Serpent2 neutron model for HELIAS stellarator.

10. Other activities

10.1 Missions and secondments

Tuomas Tala to JET facilities, United Kingdom, 1–6 November 2021 (WPTE).

Aaro Järvinen to Chalmers University of Technology, Gothenburg, Sweden, 15–19 November 2021 (WPAC).

Jari Likonen to JET facilities, United Kingdom, 18–22 November 2021 (WPPWIE).

Patrik Ollus to MAST-U, Culham, UK, 29 November – 10 December 2021 (WPTE).

10.2 Conferences, seminars, workshops, and meetings

Taina Kurki-Suonio participated in ESFRI (European Strategic Forum for Research Infrastructures) ENE (Energy) SWG (Strategic Working Group) meeting (virtual), 22 January 2021.

Leena Aho-Mantila, Mathias Groth, Antti Hakola, Andreas Holm, Niels Horsten, Juuso Karhunen, Henri Kumpulainen, J. Simpson, and Vladimir Solokha participated in the 24th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Virtual Conference, 25 – 29 January 2021.

Taina Kurki-Suonio participated in ESFRI (European Strategic Forum for Research Infrastructures) ENE (Energy) SWG (Strategic Working Group) meeting (virtual), 16 February 2021.

Tuomas Tala participated in the EUROfusion Bureau meeting (virtual), 17 February 2021.

Riccardo Iorio gave a FusionEPtalk on 18 February 2021, online.

Taina Kurki-Suonio participated in ESFRI (European Strategic Forum for Research Infrastructures) ENE (Energy) SWG (Strategic Working Group) meeting (virtual), 5 March 2021.

Antti Hakola participated remotely in the 3rd WEST Experimental Planning Meeting (virtual), 22 – 24 March 2021.

Tuomas Tala participated in the ITPA Transport and Confinement meeting (virtual), 22 – 25 March 2021 (WPIC).

Tuomas Tala participated in the EUROfusion Bureau meeting (virtual), 23 March 2021.

Francis Albert and Riccardo Iorio participated Finnish Physics Days (virtual) 24 – 26 March 2021 organized by the University of Jyväskylä, online.

Mathias Groth participated in the International Atomic Energy Agency (IAEA) Technical Meeting on Atomic and Molecular Data on the Collisional-radiative Properties of Tungsten and Hydrogen in Edge Plasma of Fusion Devices (virtual), 29 March – 1 April 2021.

Taina Kurki-Suonio participated in ESFRI (European Strategic Forum for Research Infrastructures) ENE (Energy) SWG (Strategic Working Group) meeting (virtual), 29 April 2021.

Leena Aho-Mantila, Mathias Groth, Antti Hakola, and Tuomas Tala participated remotely in the 28th IAEA Fusion Energy Conference (virtual), 10 – 15 May 2021.

Vladimir Solokha attended the 18th International Conference on Plasma-Facing Materials and Components for Fusion Applications (virtual), 17 – 21 May 2021.

Antti Snicker participated in 25th ITPA Topical Group Meeting on Energetic Particle Physics (virtual),17 – 21 May 2021.

Juuso Karhunen and Paula Siren participated remotely in 4th European Conference on Plasma Diagnostics (virtual), 7 – 11 June 2021.

Fredric Granberg gave an invited talk at 5th International Workshop on Models and Data for Plasma-Material Interaction in Fusion Devices (MoD-PMI 2021) with the title “Molecular dynamics simulations of sputtering of rough tungsten surfaces”, 8 – 10 June 2021, Forschungszentrum Jülich, Jülich, Germany (virtual).

Tuomas Tala participated in the EUROfusion Bureau meeting (virtual), 15 June 2021.

Francis Albert, Eero Hirvijoki, Riccardo Iorio, Anu Kirjasuo, Timo Kiviniemi, Roni Mäenpää, Patrik Ollus, Antti Salmi, Tuomas Tala, and Filippo Zonta participated in the 47th EPS Plasma Physics Conference (virtual), 21 – 25 June 2021.

Antti Hakola participated in the 30th ITPA Divertor and Scrape-Off Layer meeting (virtual), 28 June – 8 July 2021.

Francis Albert participated in V International Summer School on the Physics of Plasma-Surface Interactions (V. Kurnaev Summer School, virtual), Moscow, MEPhI 5 – 9 July 2021.

Tuomas Tala participated in the EUROfusion General Assembly meeting (virtual), 6 – 7 July 2021.

Tuomas Tala participated in the F4E Governing Board meeting (virtual), 8 – 9 July 2021.

Francis Albert participated in Graduate Summer School organised by PPPL (virtual), 16 – 20 August 2021.

Francis Albert participated in the 2nd Computational Physics School for Fusion Research (virtual), 30 August – 3 September 2021.

Anu Kirjasuo, Susan Leerink, and Tuomas Tala participated in the 25th Joint EU-US TTF Meeting (virtual), 6 – 10 Septermber 2021.

Francis Albert, Andreas Holm, Niels Horsten, and Riccardo Iorio participated in the 18th International Workshop on Plasma Edge Theory in Fusion Devices (virtual), organized by the EPFL Swiss Plasma Center 13 – 15 September 2021.

Anu Kirjasuo, Antti Salmi and Tuomas Tala participated in the ITPA Transport and Confinement meeting (virtual), 13 – 15 September 2021 (WPIC).

Taina Kurki-Suonio participated in Stay tuned to the Future. Impact of research infrastructures 2.0 (virtual), 16 – 17 September 2021.

Taina Kurki-Suonio participated in the 2nd ESFRI Open Session, Leading theme: “European Green Deal”, 22 September 2021 and gave presentation: "Presentation of the activities within the Energy Strategy Working Group"

Antti Hakola participated in the ASDEX Upgrade Programme Seminar (virtual), Ringberg Castle, Germany, 25 – 29 October 2021.

Tuomas Tala participated in the EUROfusion Bureau meeting (virtual), 28 September 2021.

Francis Albert, Filippo Zonta and Riccardo Iorio participated in the 14th Carolus Magnus Summer School on Plasma and Fusion Energy Physics (virtual), 20 September – 1 October 2021.

Antti Hakola and Jari Likonen participated in the WP TE Programme Meeting (virtual), 30 September – 1 October 2021.

Tuomas Tala participated in the F4E Governing Board meeting (virtual), 7 October 2021.

Taina Kurki-Suonio participated in the 19th European Fusion Theory Conference (virtual), 11 – 15 October 2021.

Tuomas Tala participated in the EUROfusion General Assembly meeting (virtual), 13 – 14 October 2021.

Taina Kurki-Suonio, Antti Snicker, and Filippo Zonta participated in 26th ITPA Topical Group Meeting on Energetic Particle Physics (virtual), 2 – 5 November 2021.

Tuomas Tala participated in the F4E Governing Board meeting (virtual), 5 November 2021.

Taina Kurki-Suonio participated in ESFRI (European Strategic Forum for Research Infrastructures) ENE (Energy) Workshop on Horizon EU Preparatory Phase and Individual Support Funding, 15 November 2021.

Tuomas Tala participated in the EUROfusion Bureau meeting (virtual), 23 November 2021.

Taina Kurki-Suonio participated in ATS Nuclear Technology autumn seminar, 24 November 2021.

Taina Kurki-Suonio participated in Ydinturvallisuusseminaari – kokonaisuudistusta (Nuclear safety seminar – towards overall reform), University of Helsinki, 26 November 2021.

Mathias Groth participated in the 2nd Meeting of the Global Network for the Atomic and Molecular Physics of Plasmas (virtual), December 6 – 9, 2021.

Taina Kurki-Suonio participated in the 17th IAEA Technical Meeting on Energetic Particles and Theory of Plasma Instabilities in Magnetic Confinement Fusion (virtual), 6 – 9 December 2021

Tuomas Tala participated in the F4E Governing Board meeting (virtual), 9 – 10 December 2021.

Tuomas Tala participated in the EUROfusion General Assembly meeting (virtual), 14 – 15 December 2021.

Francis Albert, Riccardo Iorio, Timo Kiviniemi, Taina Kurki-Suonio, Susan Leerink, and Antti Snicker participated in the FINRUS seminar (virtual), organised in Aalto University 15 – 17 December 2021.

10.3 Visitors

Nikolai Tropin and Oksana Kaledina from Ioffe Institute visited Aalto University 3 – 18 December 2021.

11. Publications 2021

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

11.1 Refereed journal articles

1. X. D. Du, R. J. Hong, W. W. Heidbrink, X. Jian, H. Wang, N. W. Eidietis, M. A. Van Zeeland, M. E. Austin, Y. Liu, N. A. Crocker, T. L. Rhodes, K. Särkimäki, A. Snicker, W. Wu, and M. Knolker, Multiscale Chirping Modes Driven by Thermal Ions in a Plasma with Reactor-Relevant Ion Temperature, Physical Review Letters, **127** (2021) 025001.
2. X. D. Du, M. A. Van Zeeland, W. W. Heidbrink, J. Gonzalez-Martin, K. Särkimäki, A. Snicker, D. Lin, C. S. Collins, M. E. Austin, G. R. McKee, Z. Yan, Y. Todo, and W. Wu, Visualization of Fast Ion Phase-Space Flow Driven by Alfvén Instabilities, Physical Review Letters, **127** (2021) 235002.
3. E. Lu, J. Zhao, I. Makkonen, K. Mizohata, Z. Li, M. Hua, F. Djurabekova, and F. Tuomisto, Enhancement of vacancy diffusion by C and N interstitials in the equiatomic FeMnNiCoCr high entropy alloy, Acta Materialia, **210** (2021) 1174093.
4. R. Yin, Y. Cheng, H. Wu, Y. Song, B. Yu, and R. Niu, FusionLane: Multi-Sensor Fusion for Lane Marking Semantic Segmentation Using Deep Neural Networks, IEEE Transactions on Intelligent Transportation Systems, **23** (2021) 1543.
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11.2 Conference presentations

1. L. Aho-Mantila et al, Role of drifts, impurities, and neutrals for credible predictions of radiation and power flux asymmetries in the DEMO scrape-off layer, the 24th Plasma-Surface Interactions Conference, 25 January 2021.
2. M. Balden, M. Mayer, B. Bliewert, E. Bernard, M. Diez, M. Firdaouss, M. Missirlian, B. Pégourié, M. Richou, H. Roche, E. Tsitrone, C. Martin, and A. Hakola, Erosion and redeposition patterns on entire erosion marker tiles after exposure in the first operation phase of WEST, the 24th Plasma-Surface Interactions Conference, 25 January 2021.
3. R. Bisson, E. A. Hodille, J. Gaspar, D. Douai, T. Wauters, A. Gallo, J. Gunn, A. Hakola, T. Loarer, R. Nouailletas, J. Morales, B. Pégourié, C. Reux, R. Sabot, E. Tsitrone, S. Vartanian, E. Wang, N. Fedorczak, and S. Brezinsek, Deuterium and helium outgassing following plasma discharges in WEST: Delayed D outgassing during D-to-He changeover experiments studied with threshold ionization mass spectrometry, the 24th Plasma-Surface Interactions Conference, 25 January 2021.
4. S. Brezinsek, R. Ding, K. Krieger, A. Hakola, G. de Temmerman, E. Tsitrone, M. Balden, T. Dittmar, X. Gong, R. Neu, J. Peng, B. Pegourie, and M. Rasinski, The competition between metallic nanostructure formation, erosion and co-deposition in He plasmas of the tokamaks ASDEX Upgrade, EAST, and WEST, the 24th Plasma-Surface Interactions Conference, 25 January 2021.
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11.4 Academic theses

48. Ivan Paradela-Perez, Experimental and computational studies of power and momentum transport in tokamaks, Doctoral Thesis, Aalto University, Espoo, 2021.
49. Anu Kirjasuo, Particle source impact on fusion plasma density profile in JET experiments, MSc thesis, University of Helsinki, 2021.
50. Roni Mäenpää, Nitrogen transport in the JET divertor, MSc thesis, Aalto University, Espoo 2021.
51. Aake Kesälä, Interpretation of the scrape-off layer in DIII-D low-confinement mode plasmas with the two-point and onion-skin models, BSc thesis, Aalto University, Espoo 2021.
52. Adam Kit, Machine Learning Analysis on the JET Pedestal Database, BSc thesis, University of Leipzig, Germany, instructed by Aaro Järvinen at Aalto University 2021.
53. Luukas Myllynen, Assessment of the UEDGE fluid neutral molecular model using the kinetic neutral model EIRENE, BSc thesis, Aalto University, Espoo 2021.
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Title	**FinnFusion Yearbook 2021**
Author(s)	Anu Kirjasuo and Jari Likonen (Eds.)
Abstract	This Yearbook summarises the 2021 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 Oy, CSC - IT Center for Science Ltd., EOS Finland Oy, Fortum Power and Heat Ltd., Lappeenranta-Lahti University of Technology, Luvata 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 2021 focused on the development of the High Level Control System subsystems for ITER Remote Handling System and on testing of digivalve system for ITER remote handling. EUROfusion supports post-graduate training through the Education work package that allowed FinnFusion to partly fund 38 PhD students in FinnFusion member organizations. In addition, one EUROfusion post-doctoral research fellowship was running in 2021. The FinnFusion annual seminar in 2021 was cancelled due to the COVID-19 pandemic.
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Nimeke	**FinnFusion vuosikirja 2021**
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Tiivistelmä	Tähän vuosikirjaan on koottu FinnFusion-konsortion vuoden 2021 tulokset. Konsortion ohjelman painopistealueet ovat (i) ITER-reaktorin rakentamiseen ja järjestelmiin liittyvän teknologian kehitys yhdessä teollisuuden kanssa; (ii) osallistuminen Fuusion tiekartan toteuttamiseen EUROfusion-konsortion jäsenenä; (iii) seuraavan sukupolven eurooppalaisen DEMO-fuusiovoimalan konseptikehitys. FinnFusion-konsortion muodostavat Teknologian tutkimuskeskus VTT Oy, Aalto-yliopisto, Comatec Oy, CSC - Tieteen tietotekniikan keskus Oy, EOS Finland Oy, Fortum Power and Heat Oy, Helsingin yliopisto, Lappeenrannan-Lahden teknillinen yliopisto, Luvata Oy, Tampereen yliopisto ja Åbo Akademi. FinnFusion-konsortio osallistuu useisiin EUROfusion-projekteihin. Suurin työpanos kohdistuu JET- ja ASDEX Upgrade -koelaitteissa tehtäviin kokeisiin ja analyyseihin, kehittyneen tietojenkäsittelyn keskukseen, materiaalitutkimukseen, ensiseinämäkomponentteihin ja etäkäsittelyyn. FinnFusionin F4E-työt liittyivät ITERin etäkäsittelyn järjestelmätason suunnitteluun (3D Machine Vision, GENROBOT, Digivalve) ja etäkäsittelyn ohjelmistokehitykseen. EUROfusion tukee jatko-opiskelua omalla rahoitusinstrumentillaan, jonka turvin FinnFusion rahoitti osittain 38 jatko-opiskelijan työtä jäsenorganisaatioissaan. Lisäksi vuoden 2021 aikana oli käynnissä yksi EUROfusionin rahoittama tutkijatohtorin projekti. COVID-19 pandemian vuoksi vuosittainen fuusioalan vuosiseminaari jouduttiin peruuttamaan.
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