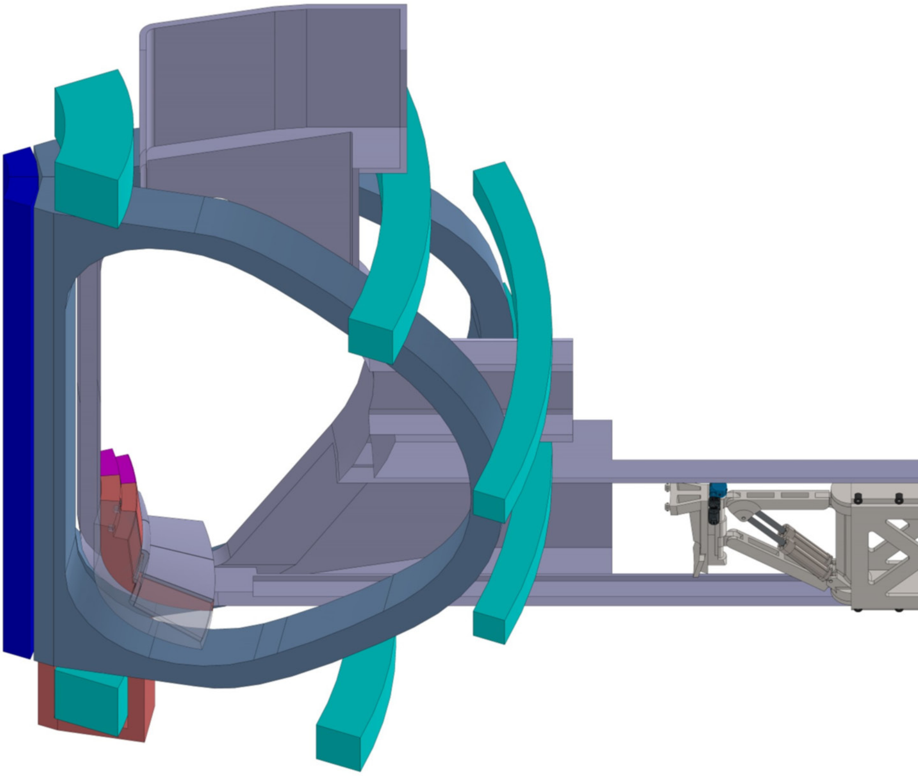

VTT

beyond the obvious

FinnFusion Yearbook 2020

Jari Likonen (Ed.)

VTT TECHNOLOGY 393

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VTT Technical Research Centre of Finland Ltd

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Preface

Looking ahead toward the new research opportunities in the European Framework Program FP9 in 2021-2027, looking ahead toward the ITER assembly with vacuum vessel sectors, magnets and cryostat on site, looking ahead toward the JET DT campaign in summer 2021, looking ahead toward starting the EUROfusion Advanced Computing Hub at UH Kumpula Campus and certainly, looking ahead to life without any major impact of the COVID-19 pandemic – I do hope that next time around when writing this preface we are just not looking ahead but things are really on-going.

Year 2020 will certainly be a year to remember as a major change to everything. The impact of the COVID-19 pandemic on fusion research was visible on all levels. The international character of the European fusion research really experienced many changes even if remote working mode and virtual meetings and workshops had been a routine already for more than a decade. While virtual meetings like Task Force meetings or even EUROfusion General Assembly meetings can be organized and run on a smooth and efficient way, it is clear that for example running JET experiments and operation remotely with multi-national team is a great challenge and suffers significantly from the remote operation mode. Suddenly the fusion researchers in Finland have felt a bit isolated and the distance away from the major European fusion experiments and activities is a real one.

Regardless of all the challenges due to pandemic, the past year has been very successful to FinnFusion. Well before the deadline of the major EUROfusion 2021-2025 calls for proposals due in December, we took the approach to encourage and to initiate new interdisciplinary projects and challenges and further to expand the FinnFusion collaboration into new areas of expertise by mixing both researchers inside and outside fusion research. The great work in preparing the EUROfusion Calls was awarded with resources worth more than 18.5M€ for FinnFusion partners and for their collaborating companies – a dream result exceeding all the most optimistic expectations! In addition to more traditional FinnFusion research topics and the granted Advanced Computing Hub, the following new topics were awarded with EUROfusion resources: Breeding Blanket studies (WPBB), magnet conductor/insulator research (WPMAG), IFMIF-DONES viewing system development for RM (WPENS), nuclear waste and decommissioning tasks (WPSAE), high-heat flux materials modelling (WPMAT+WPPRD), VTT hot-cell work on irradiated materials analysis (WPMAT), investigation of the effects of various materials processing routes on the detailed defect distributions in complex materials (WPPWIE) and Fusion Power Plant fire hazard studies (WPSAE). Furthermore, the amount of education funding for FinnFusion students increased by 30%.

The largest ever single FinnFusion project, the E-TASC Helsinki Advanced Computing Hub, will start its operation in August 2021. The partners of the Hub are UH, CSC, VTT, Aalto and Åbo Akademi. With its 3M€ budget from EUROfusion, the goal is to hire some 10 full-time advanced computing experts. The target of the Hub is to develop 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. The vision is the following: "The E-TASC Helsinki Advanced Computing Hub for the highest level Artificial Intelligence, Big Data handling, Fusion Physics, and Computational Physics backed up by 500 specialists in the same location."

Another new project or at least a new way of working in FinnFusion is the national fusion industry co-ordination including the F4E/ITER ILO activities. FinNuclear was awarded with Business Finland orchestration funding and thereby nominated to act as the Finnish ILO in F4E. The aim is that both the Finnish fusion R&D and industry activities will have the best possible opportunities to maximize the benefits from the European fusion research. One of the main annual events to facilitate this, the FinnFusion annual seminar, could not be organised in 2020 due to the pandemic and it seems that year 2021 will not be any better in this respect. In addition, the main European events on industrial fusion research business, such as ITER Business Forum and Big Science Business Forum, were postponed or organised virtually with a reduced scope.

Looking ahead to all the great events and opportunities in fusion research, and without the major impact of the pandemic is now the bright future to look forward. Finally yet importantly, stay healthy and energetic notwithstanding the current unusual circumstances!

Tuomas Tala
Head of Research Unit
FinnFusion Consortium

Contents

List of acronyms and names

AFSI	AFSI Fusion Source Integrator (simulation code)
ASCOT	Accelerated Simulation of Charged Particle Orbits in Tori (particle tracing code)
AU	Aalto University, Espoo/Helsinki, Finland
AUG	ASDEX Upgrade (tokamak facility)
BBNBI	Beamlet-based neutral beam injection (simulation code)
CCFE	Culham Centre for Fusion Energy
CFC	Carbon fibre composite
DIII-D	Tokamak facility at General Atomics, San Diego
DEMO	Future demonstration fusion power plant
DONES	DEMO oriented neutron source
DT	Deuterium-tritium
DTP2	Divertor test platform phase 2 (test facility in Tampere)
ECCD	Electron Cyclotron Current Drive
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
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)
FIDA	Fast ion hydrogen line-radiation
FILD	Fast Ion Loss Detector
FNG	Fusion Neutron Generator
HCPB	Helium Cooled Pebble Bed

HPC	High-performance computing
IAEA	International Atomic Energy Agency
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
KSTAR	Korea Superconducting Tokamak Advanced Research (tokamak facility)
LOC	Linear Ohmic confinement
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)
NBI	Neutral beam injection
NJOC	New JET Operating Contract
OTSG	Once-through steam generator
PCS	Power conversion system
PFC	Plasma-facing component
PHTS	Primary heat transfer system
RACE	Remote applications in challenging environments (research facility)
RH	Remote handling
RHC	Remote handling connector
RU	Research Unit (member of EUROfusion)
Serpent	Monte Carlo reactor physics simulation code developed at VTT
SIMS	Secondary ion mass spectrometry
SOC	Saturated Ohmic confinement
SOL	Scrape-off layer
SOLPS	Scrape-off Layer Plasma Simulation (fluid plasma simulation code)

TAE	Toroidal Alfvén Eigenmodes
TBM	Test Blanket Module
TCV	Tokamak à Configuration Variable (tokamak facility)
TDS	Thermal desorption spectrometry
Tekes	The Finnish Funding Agency for Innovation
TEM	Trapped Electron Mode
TGFL	Trapped gyro-Landau-fluid
TOF-ERDA	Time-of-flight elastic recoil detection analysis
TUNI	Tampere University
UH	University of Helsinki
VDE	Vertical displacement event
VTT	VTT Technical Research Centre of Finland Ltd
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 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.

1.2 EUROFUSION and FinnFusion Consortia

During the Horizon 2020 framework, 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 2020 through a Joint programme of the members of the EUROfusion consortium. A 942 M€ grant (including NJOC) for the period 2014–2020 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. The role of Tekes changed from being the signing body of the Association to act as the national funding body of the Finnish fusion research projects. Towards the European Commission and the EUROfusion Consortium, Tekes 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 are acting as linked third parties to the Consortium. The FinnFusion organigram is presented in Figure 1.1.

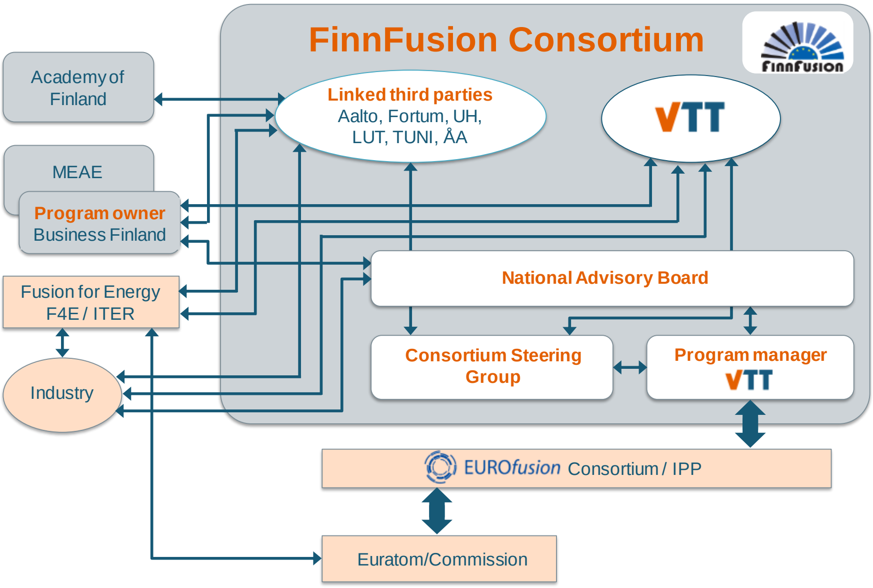

Figure 1.1. Organigram of Finnish Fusion Research Community in 2014–2020.

1.3 Research Unit

The Finnish Research Unit, FinnFusion, consists of several research groups from VTT, universities and industry. The Head of the Research Unit is Dr. Tuomas Tala from VTT. The following institutes and universities participated in 2020:

VTT Tech. Research Centre of Finland – Smart industry and energy systems

Activities: Co-ordination, tokamak physics and engineering
Members: Dr. Tuomas Tala (Head of Research Unit), Dr. Leena Aho-Mantila, Dr. Markus Airila, Dr. Eric Dorval, Dr. Antti Hakola (Project Manager), Mrs. Anne Kemppainen (administration), BSc. Anu Kirjasuo, Prof. Jaakko Leppänen, Dr. Jari Likonen, MSc. Sixten Norrman, Dr. Antti Salmi, Mrs. Kirsi Selin (administration), Dr. Marton Szogradi

Activities: Probabilistic risk assessment
Members: MSc. Atte Helminen (Project Manager), BSc. Essi Immonen, MSc. Tero Tyrväinen

Activities: Remote handling, DTP2
Members: MSc. Jarmo Alanen (Project Manager), MSc. Timo Avikainen, Dr. William Brace (Project Manager), Dr. Mikko Karppinen, MSc. Pekka Kilpeläinen, Lic. Tech. Jukka Koskinen (Project Manager), Dr. Simo-Pekka Leino, MSc. Janne Lyytinen, MSc. Timo Malm, MSc. Hannu Martikainen, MSc. Joni Minkkinen, MSc. Teemu Mätäsniemi, Dr. Timo Määttä, MSc. Jyrki Ollila, MSc. Jari Pennanen, MSc. Seppo Rantala, MSc. Olli Rantanen, MSc. Hannu Saarinen, MSc. Karoliina Salminen, Lic.Tech. Mikko Siuko, MSc. Petri Tikka

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

Activities: Physics
Members: Prof. Mathias Groth (Head of Laboratory), Dr. Laurent Chôné, MSc. Riccardo Iorio, Dr. Eero Hirvijoki, MSc. Andreas Holm, Dr. Niels Horsten, Dr. Juuso Karhunen, Dr. Timo Kiviniemi, MSc. Joona Kontula, MSc. Henri Kumpulainen, Dr. Taina Kurki-Suonio, Dr. Susan Leerink, MSc. Henrik Nortamo, MSc. Patrik Ollus, Dr. Lucia Sanchis, Dr. Seppo Sipilä, Dr. Paula Sirén, Dr. Antti Snicker, MSc. Ivan Paradela Perez, MSc. Vladimir Solokha, MSc. Jari Varje, MSc. Antti Virtanen, MSc. Filippo Zonta

Students: Mika Andersson, Henri Brax, Eerkko Ihalainen, Atso Ikäheimo, Roni Mäenpää, Heikki Systä, Lauri Toivonen

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

Activities: Robotics
Members: Prof. Heikki Handroos (Project Manager), MSc. Changyang Li, Dr. Ming Li, Prof. Huapeng Wu, MSc. Shayan Moradkhani, MSc. Ruochen Yin, Dr. Haibiao Ji, MSc.Tao Zhang, MSc. Nikola Petikov, MSc. Qi Wang

Tampere University (TUNI)

Activities: Remote handling, DTP2
Members: MSc. Liisa Aha, DSc. Mohammad Mohammadi Aref, 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. Laur Gonçalves Ribeiro, MSc. Olli Suominen

University of Helsinki (UH), Accelerator Laboratory

Activities: Physics, materials
Members: Dr. Tommy Ahlgren, MSc. Jesper Byggmästar, Dr. Flyura Djurabekova, Dr. Fredric Granberg, Dr. Kalle Heinola, Dr. Etienne Hodille, Dr. Pasi Jalkanen, Dr. Antti Kuronen, MSc. Aki Lahtinen, MSc. Emil Levo, MSc. Anna Liski, Dr. Kenichiro Mizohata, Prof. Kai Nordlund (Project Manager), Prof. Jyrki Räisänen (Project Manager), Dr. Andrea Sand, Prof. Filip Tuomisto, MSc. Tomi Vuoriheimo, Dr. Leonid Zakharov

Fortum Power and Heat Ltd.

Activities: Power plant and safety engineering
Members: MSc. Antti Rantakaulio, MSc. Olli Suurnäkki, MSc. Antti Teräsvirta, Dr. Harri Tuomisto, MSc. Merja Väänänen, Dr. Jaakko Ylätalo

1.4 FinnFusion Advisory Board

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

Chairman	Janne Ignatius, CSC
Members	Henrik Immonen, Abilitas
	Anna Kalliomäki, Academy of Finland
	Herkko Plit, Baltic Connector
	Kari Koskela, Business Finland
	Arto Timperi, Comatec
	Marjut Vähänen, Finnuclear
	Harri Sairiala, Fluiconnecto
	Jaakko Ylätalo, Fortum
	Olli Naukkarinen, Luvata
	Olli Kalha, Procurement and Contracting Consultant
	Mika Korhonen, Suisto Engineering
	Lauri Siivonen, Tamlink
	Liisa Heikinheimo, TEM
	Jarmo Lehtonen, Tevolokomo
	Arto Kotipelto, TVO
	Tommi Nyman, VTT
	Karoliina Salminen, VTT
	Timo Määttä, VTT
	Mathias Groth, Aalto
	Kai Nordlund, UH
	Jouni Mattila, TUNI
	Heikki Handroos, LUT
	Jan Westerholm, ÅA
Co-ordinator	Tuomas Tala, VTT
Secretary	Markus Airila, VTT

The FinnFusion advisory board had one meeting in 2020 and a set of written procedure documents.

1.5 Finnish members in the European Fusion Committees

1.5.1 Euratom Programme Committee, Fusion configuration

- Tuomas Tala, VTT
- Kari Koskela, Business Finland

1.5.2 EUROfusion General Assembly

- Tuomas Tala, VTT

1.5.3 EUROfusion HPC Allocation Committee

- Susan Leerink, AU

1.5.4 EUROfusion Science Department Project Boards

- WP JET2: Antti Hakola, VTT
- WP PFC: Jari Likonen, VTT

1.5.5 Wendelstein 7-X S1 Programme Board

- Taina Kurki-Suonio, AU

1.5.6 Governing Board for the Joint European Undertaking for ITER and the Development of Fusion Energy, “Fusion for Energy” (F4E GB)

- Kari Koskela, Business Finland
- Tuomas Tala, VTT

1.5.7 Procurements and Contracts Committee for the Joint European Undertaking for ITER and the Development of Fusion Energy, “Fusion for Energy” (F4E PCC)

- Herkko Plit, Baltic Connector

1.5.8 Other international duties and Finnish representatives in the following fusion committees and expert groups in 2020

- Markus Airila is the VTT representative in EUROfusion Communications Network (FuseCOM).
- Mathias Groth is a member of the programme committee of the Plasma Surface Interaction Conference (PSI) 2013-2020.
- Hannu Juuso is an Industrial Liaison Officer (ILO) for F4E, Timo Määttä is the European Fusion Laboratory Liaison Officer (EFLO).
- 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
- Taina Kurki-Suonio is a member of the *Nuclear Fusion* Editorial Board.
- 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.
- 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) and SHIM (Swift Heavy Ions in Matter) 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.
- Harri Tuomisto is a member of the Fusion Industry Innovation Forum Management Board (FIIF MB).
- Harri Tuomisto is a member of the DEMO stakeholders group.

2. ITER Physics Workprogramme 2020

2.1 WP JET1: Analysis and modelling tasks 2020

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

2.1.1 Overview

The whole year was full of JET operation and scientific campaigns, although all experiments after the onset of the COVID-19 pandemic, the scientific work was carried out remotely. The main focus was on establishing the necessary physics references, plasma operation scenarios and operational capability in view of the upcoming 100% tritium followed by the 50-50% DT campaigns in 2021. The C39 campaign included Hydrogen operation and 100% Tritium operation with NBI power.

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 particle transport and source studies 2020 JET experiments with the scientific leadership provided by FinnFusion and using several computer codes in the detailed analysis. In addition, particle transport experiment and modelling studies between JET and DIII-D are described.

2.1.2 Particle transport and sources

Experiments to study particle transport and sources in H-mode and in Ohmic plasmas have been performed. In both cases a gas scan was made to change SOL/pedestal density and thus ionisation source penetration while simultaneously measuring transient plasma response to modulated gas source. The high accuracy requirement for the subsequent analysis catalysed improvements in reflectometer data processing and have resulted in a new tool with broader use possibilities. Figure 2.1 shows high radial resolution measurement data of electron density in the H-mode gas/density scan. Comparison against first EDGE2D/EIRENE modelling is consistent with narrowly localised ionisation of deuterium atoms just inside the separatrix. It was found that additional experiments are required to expand the gas scan to access qualitatively different ionisation behaviour (e.g. due to detachment). Analysis of LOC/SOC effects on Ohmic plasma density peaking are ongoing and will clarify the role of ITG/TEM turbulence in density transport.

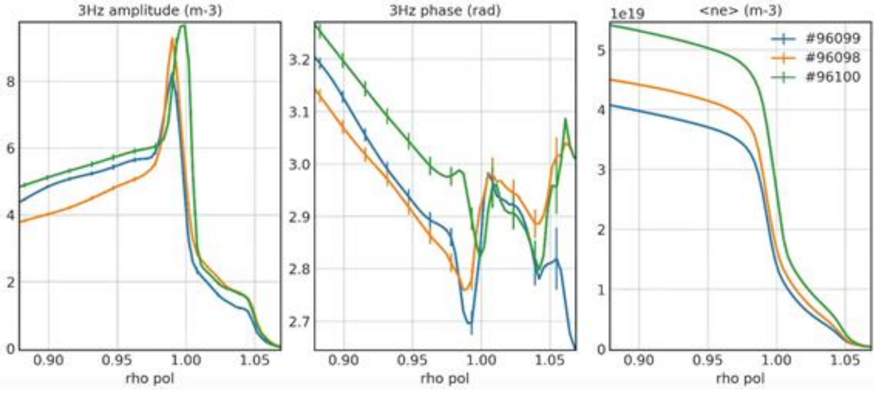

Figure 2.1 Electron density response to the gas modulation in gas scan, measured with reflectometer diagnostics. (Left frame) 3Hz density modulation amplitude, (middle frame) 3 Hz density modulation phase and (right frame) the time averaged density profile. Phase minimum/amplitude maximum are indicative of particle source location.

Furthermore, earlier experiments on JET and DIII-D to study the role of NBI fuelling in electron density peaking have further been investigated through detailed gyro-kinetic modelling in collaboration with Nordman and Fransson from Gothenburg University. The apparent contradiction between significant peaking due to the NBI in JET and its insignificant role on DIII-D (and AUG) could be explained by the different turbulence characteristics between the different tokamaks. In the modelling various contributing factors could be turned off selectively to show how large effect each difference in the kinetic and magnetic profiles between the experiments had on the peaking. The TGLF turbulence model used was able to smoothly move from JET H-mode to L-mode and from JET to DIII-D (by changing input profiles one by one) and to reproduce the measurements. It was seen that with more electron heating, like on DIII-D, turbulence regime shifts from ITG to mixed ITG/TEM that amplifies the turbulence influence on peaking and makes NBI less important. This is good news for ITER as it is expected that due to the large electron heating in ITER the density peaking can be significant thanks to ITG/TEM turbulence drive even though the negative ion (1 MeV) NBI particle source will be relatively weak.

2.2 WP JET2: Plasma-facing components

Research scientists: A. Lahtinen, K. Mizohata, J. Räisänen, T. Vuoriheimo, UH
A. Hakola, J. Likonen, VTT

In 2020 the JET2 programme focused on post-mortem analysis of divertor tiles and in-vessel erosion-deposition probes (EDP) and 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.

In 1996-1998 JET operated with a MkIIA divertor (see Figure 2.2 (a)) replacing graphite tiles with carbon fibre composite (CFC) tiles. A deuterium-tritium experiment (DTE1) was performed in 1997 introducing 35 g of tritium into the torus, mainly by gas puffing. After DTE1 experiment there was an extensive clean-up period for removing as much tritium from the vessel as possible running discharges in H or D and using glow discharge cleaning and baking. After this the machine was vented for tile exchange. All the divertor carriers were removed from the JET vessel, together with their CFC tiles still mounted. Two poloidal sets of carriers and tiles were retained for post-mortem analysis, whilst all the other carriers and tiles were put into storage in three ISO-containers at ambient temperature vented to an extract system because of continuing chronic tritium release. The MkIIA tiles are considered redundant and they are now being de-tritiated by baking to 1000℃ in a furnace. During the intervening period there have been some measurements of the off-gassing and the corresponding bulk tritium content from examples of these tiles.

This work describes the last chance to make comparative measurements on these historic tiles. Two tiles (6IN 3 and 4BN 4) located at the inner corner of the MkIIA divertor were retrieved in 2019 for further analyses. The present work uses Thermal Desorption Spectroscopy (TDS) to determine tritium contents in these two divertor tiles, more than 20 years after the DTE1 campaign and compare the T profiles within the tiles with those measured shortly after DTE1 by full combustion on similar tiles. Total combustion of adjacent samples will be used to confirm/calibrate the TDS data once the restrictions due to COVID-19 pandemic have been lifted.

Figures 2.2 (b)-(c) show TDS spectra measured from bottom of tile 3 and from shadowed region of tile 4. In both cases tritium (measured as DT and T_2 molecules) was clearly detected and T amounts in these samples is in the range of 10 - 20 MBq/cm^2.

In 2020 additional positions on the louvre clips exposed during ILW3-campaign in 2015-2016 were analysed by ERDA to match positions analysed earlier from ILW2 and ILW1 samples. These new points include six measurements. Plates of three deposition monitors (sticking monitors) were measured using motorized sample manipulator. Analysis showed relatively thin co-deposited layer, and with the beam used, accurate composition analysis was not possible as the plates were made of tungsten, and the scattered beam yield from tungsten was too high to have enough statistics from the co-deposited layer. New measurements of the sticking monitors with different ion beam energy and geometry are planned to be made in February 2021.

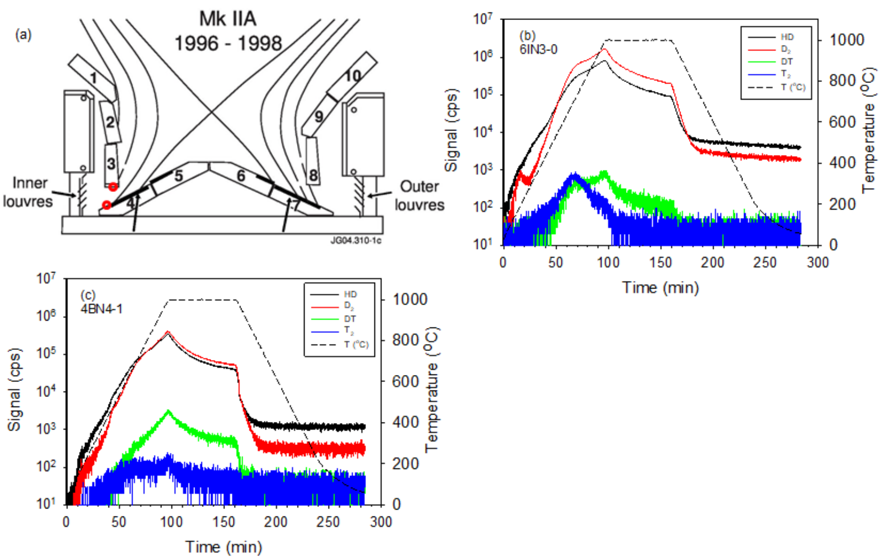

Figure 2.2. (a) JET MkIIA divertor, analysed samples marked with red circles, TDS spectrum for sample from bottom of tile 3 (b) and from shadowed area of tile 4 (c).

2.3 WP MST1: Medium-size tokamak campaigns

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

2.3.1 Overview

In 2020, MST1 experiments were executed on ASDEX Upgrade (AUG) and TCV. The first plasma on MAST-U was finally obtained in October 2020 but the commissioning of the new device and development of the necessary plasma scenarios took so long that no physics experiments could take place in 2020. Most of the planned AUG program could be executed despite the restrictions caused by the COVID-19 pandemic and lockdown of the IPP site for several weeks in April-May 2020 but fully utilizing remote participation. The main activity areas where the Finnish contribution was the most noticeable were studying erosion of plasma-facing components in H-mode conditions, modelling of fast ions using the ASCOT code, investigating particle and momentum transport, and SOLPS modelling to assess heat-flux profiles at the upper-divertor of AUG. On TCV, COVID-19 resulted in postponing the second half of the foreseen campaign, that with baffles in the vessel, into 2021. Consequently, the scope of the program was reduced by roughly 50% and of the proposed Finnish contributions only simulations of existing fast-ion experiments could be completed.

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

Investigating erosion of plasma-facing components in the outer divertor of AUG was continued also in 2020, with the help of a new experiment where various marker samples – with Au, Mo, and Re coatings (proxies for W) and with different surface morphologies – were exposed to H-mode plasmas exhibiting small and frequent ELMs. The aim was to extract net erosion profile for each marker material and determine deposition of various impurities on them to be compared with the existing datasets collected from earlier experiments in H-mode with large type-I ELMs and in L-mode. Due to the COVID-19 pandemic, post exposure analyses of all the samples is still pending and is expected to be completed by the end of 2021.

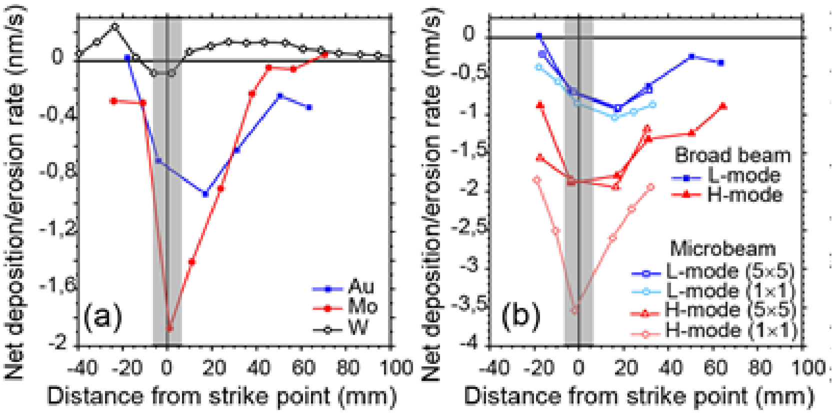

Figure 2.3. Net deposition/erosion rates (pos/neg values) of different marker samples as a function of poloidal distance from the applied strike point at the outer divertor of AUG: (a) Comparison between Au, Mo, and W markers in L-mode; (b) Comparison between 1×1 mm^2 and 5×5 mm^2 Au markers in L-mode and H-mode, data from both broad beam and microbeam measurements are shown.

In addition to the new experiment, progress was made in the analyses of old data from different erosion experiments, carried out since 2014. The results in Figure 2.3 (a) indicate that Au and Mo are eroded at 3-5 and up to 15 times higher rates, respectively, than W in comparable divertor conditions (here, in L-mode). Figure 2.3 (b), for its part, shows that in H-mode erosion is enhanced by a factor of 1.5-4 compared to L-mode and the smaller the marker, the better it will represent the results of primary sputtering of the material by plasma bombardment. However, the net/gross erosion ratio as determined from the graphs measured for the 1×1 mm^2 and 5×5 mm^2 Au markers in Figure 2.3 (b) is inconsistent with the value spectroscopically obtained, addressing the need to use submillimeter size marker spots for completely eliminating prompt re-deposition of the ejected particles.

2.3.3 Controlling Alfvenic instabilities by electron cyclotron current drive

During 2020, experiments at AUG were aimed at further studying the effect of ECRH/ECCD on the toroidal Alfven eigenmode (TAE) stability. The role of Antti Snicker from Aalto University within these experiments was to plan the optimal EC parameters to optimize the effect of EC on the TAEs, i.e. drive current at a specific location at the plasma. This was done running TORBEAM with the reference discharge and tuning the EC parameters to design the wishes current drive profile.

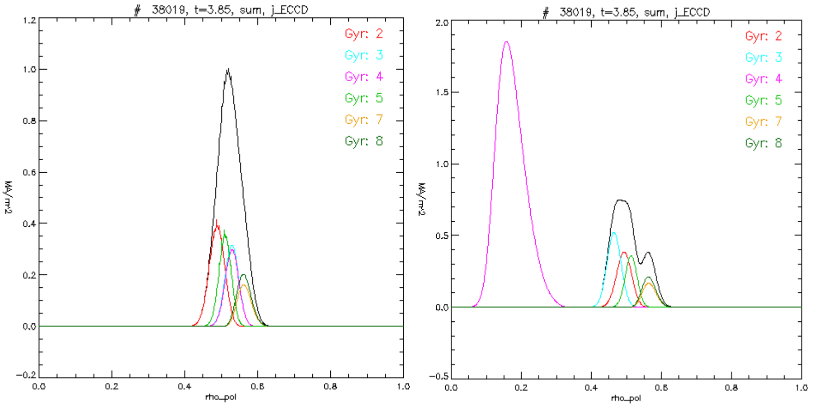

Figure 2.4. Typical (left) and corrected (right) electron cyclotron driven current density as a function of the normalized poloidal flux (radial coordinate). In the figure on the right real position of one mirror was not at the right position.

After the discharges, the same simulations were run but now using the data directly from the experimental database. A typical current drive profile is shown in Figure 2.4 (left) for discharge #38019. Here you see that all beams overlap nicely to generate a high peak in the current drive profile. The separation of the beams is given by the experimental uncertainties (in the planning phase the beams overlap perfectly). However, after these experiments it was noticed that one of the beam lines had a technical issue such that the real position of the mirror was not as recorded in the database but it was stuck at a wrong position. Therefore, correcting simulations were done to see how this technical problem reflected to the analysis. In Figure 2.4 (right), it is shown how much beam line #4 is shifted due to this technical issue and how much it changes the total current drive profile. As a result of the whole team working in collaboration, we were able to mitigate and even suppress certain TAEs due to the usage of local current via electron cyclotron systems.

2.3.4 Deputy Task Force Leadership activities

In 2020, Antti Hakola continued his activities as one of the MST1 Deputy Task Force Leaders (DTFL). The DTFL term lasted until the end of 2020 and, as in the past, consisted of coordinating specific experiments on AUG and TCV as well as planning, monitoring, and reporting the outcomes of experimental campaigns on the two devices. The responsibility areas of Antti Hakola were controlling core contamination and dilution by tungsten, preparing efficient operation for ITER and DEMO in terms of plasma-facing components (PFCs), optimising predictive models for the edge and divertor plasma conditions of ITER and DEMO, assessing the impact of error-field corrections on plasma confinement, as well as investigating the access to ELM suppression with the help of magnetic perturbations. The results have been presented in different review meetings and a number of conference contributions and journal articles have been submitted. The main highlights in 2020 were: (i) No threshold in plasma rotation or in the T_i/T_e ratio was observed for ELM suppression on AUG – contrary to reports from DIII-D and KSTAR - while the AUG results showed that the (electron or ion) pedestal collisionality by itself is not a critical access parameter for ELM suppression; (ii) Strong variations was measured for the erosion of the marker coatings along the surfaces of toroidal gaps in specific AUG outer divertor samples together with deep deposition inside the gaps, thus providing valuable input for the basis of ITER operations; (iii) Changes in the scrape-off layer (SOL) transport and the characteristics of plasma filaments on AUG and TCV can be best reconciled as a function of the neutral pressure at the midplane of the vessel.

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

Research scientists: M. Groth, A. Keitaanranta, H. Kumpulainen, R. Mäenpää, I. Paradela Perez, AU
T. Ahlgren, A. Lahtinen, K. Nordlund, K. Mizohata, J. Räisänen, T. Vuoriheimo, UH
M. Airila, A. Hakola, J. Likonen, VTT

2.4.1 Overview

The PFC Work Package aims at understanding the erosion, fuel retention and surface damage characteristics of different plasma-facing components (PFCs) in ITER or DEMO, both experimentally and with the help of numerical simulations. In 2020, the top objectives were: (i) Investigating plasma-wall interactions in helium plasmas in the full-W tokamaks AUG and WEST; (ii) Determining migration of carbon in the W7-X stellarator with the aid of $^{13}CH_4$ injections; (iii) Carrying out predictive modelling of W erosion/deposition in the W divertor of the DEMO reactor; (iv) Estimating the lifetime of W plasma-facing components in ITER with the help of high fluence experiments on MAGNUM-PSI; and (v) Assessing the feasibility of different laser-based spectroscopy methods for in-situ fuel retention investigations in future fusion reactors. The Finnish focus areas of PFC in 2020 were surface analyses of tokamak and laboratory samples and modelling of AUG experiments using the ERO and SOLPS codes, and assessing retention properties of Be and W plasma-facing components. Here, we highlight the results gathered from the analyses of wall tiles extracted from the W7-X stellarator and numerical ERO simulations of erosion experiments carried out on AUG.

2.4.2 Plasma-wall interaction studies in the W7-X stellarator

The focus in this area was on Secondary Ion Mass Spectrometry (SIMS) analyses of wall tiles extracted from W7-X after the completion of its operational period OP 1.2b and after the tracer isotope ^{13}C had been injected into the vessel during its last 30 discharges. The deposition patterns of ^{13}C and other light or metallic elements were measured on selected wall tiles removed from the half module 58.

The results generally show that deposition exhibits stripe like patterns in the poloidal direction. We found up to 3×10^{17} ^{13}C cm^{-2} accumulated in these stripes while very little was deposited on other areas nearby. The amount of ^{13}C measured using SIMS agrees with earlier ion beam measurements from other but comparable tiles. Most of the ^{13}C was found within the first 1 µm, the highest amount always being on the very surface.

Measurements focusing on other impurities showed layer like formations on some of the samples, see Figure 2.5 for an example. These complex impurity layers contained up to four distinct layers of different elements on the surface of the tile before reaching the bulk carbon substrate. Unlike ^{13}C which is seen mostly on the very top, the other impurities have resulted from earlier phases of OP 1.2b. The distinct layers found contained boron, sodium, chromium and molybdenum, each one having their own maximum at different depths on the tile.

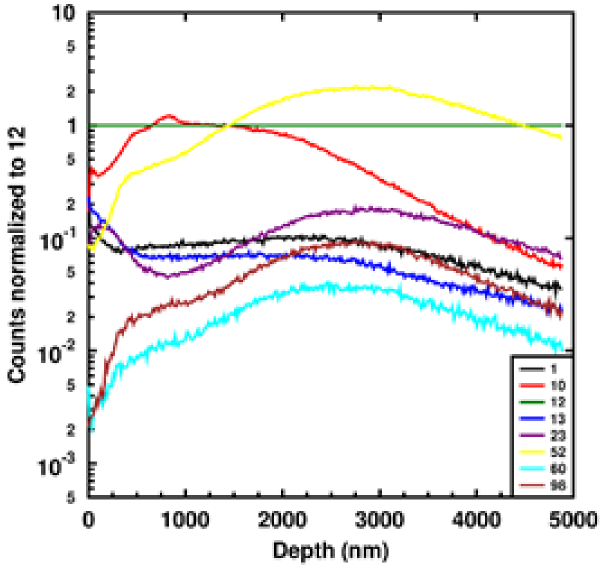

Figure 2.5. Examples of depth profiles of different elements (1=H, 10=B, 12 and 13=C, 23=Na, 52=Cr, 60=Ni, 98=Mo) measured on the W7-X tile HM58TM300hTE4.

2.4.3 Numerical modelling of erosion processes of plasma-facing components on AUG

ERO simulations of the erosion profiles extracted for Au and Mo marker coatings, resulting from their exposure to L-mode plasmas on AUG in 2019, were continued in 2020. In the case of Au, the markers were small spots (dimensions 1×1 and 5×5 mm^2) produced on top of an intermediate Mo layer. Of these, the smaller ones were designed to quantify the gross-erosion rate while on the bigger markers local prompt re-deposition of Au allowed obtaining data on net erosion. The experimental results indicated relatively uniform erosion profiles across the marker spots or coatings, very little re-deposition elsewhere, and the largest erosion taking place close to the strike point.

The ERO simulations with different background plasmas were able to reproduce the main features of the experimental net erosion profile of Au as Figure 2.6 shows. Of the studied parameters, electron temperature had the strongest impact on erosion: doubling the temperature enhanced erosion by a factor of 2.5-3. In contrast, for Mo, the simulated net erosion was ~3 times smaller than what experimental data indicate. The discrepancies can be attributed to the deviations of the background plasma profiles from the measured ones. In addition, the surrounding areas of the marker samples being covered with impurities and W from previous experiments may have considerably reduced the actual re-deposition of Mo.

All the simulations predicted a toroidal tail of re-deposited particles, downstream of the markers, but the particle density seemed to be below the experimental detection threshold. The comparison between the small and big marker spots further revealed that re-deposition dropped from >50% to <40% when decreasing the marker size. This indicates that small enough marker samples can be used for accurately determining gross erosion on AUG.

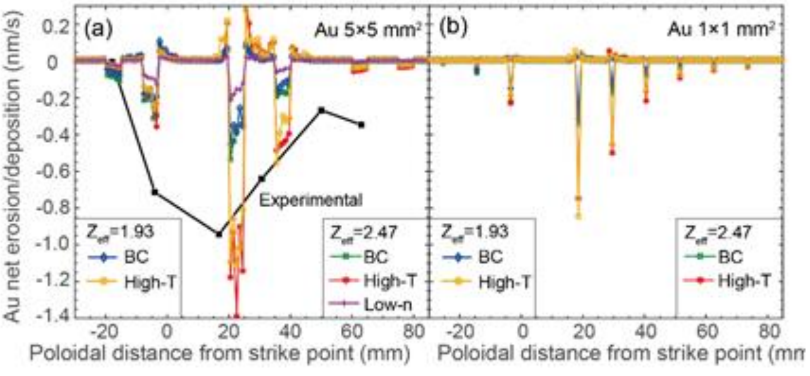

Figure 2.6. Net erosion/deposition (neg/pos) profiles for the (a) 5×5 mm^2 and (b) 1×1 mm^2 Au marker spots in different simulation cases; the legends BC, High-T, and Low-n refer to varying background plasma solutions applied.

2.5 WP S1: Fast ion behaviour in the Wendelstein 7-X stellarator

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

Collaboration between the ASCOT group and IPP Greifswald continued in 2020 with a focus on preparation for future operational campaigns, namely deuterium neutral beam injection (NBI) and ion cyclotron resonance heating (ICRH). The year 2020 also marked a significant increase in the number of people using ASCOT5 for stellarator simulation, with almost 10 regular collaborators at the end of the year. This increased activity allowed for the development of new wall load calculation and visualization features, while also requiring an increased focus from the ASCOT group on user support for new collaborators.

Calculation of 14.1 MeV neutron production rates from deuterium NBI was continued this year. The complete neutron production process from injection to fusion-born neutrons propagating to a detector was simulated for the first time using a combination of the ASCOT5, AFSI and Serpent 2 codes. For the Serpent 2 simulations, a detailed 3D neutronics model of W7-X was constructed. The results indicated that the amount of 14.1 MeV neutrons born should be sufficient for detection with a scintillating fiber detector in all magnetic configurations, given suitably high performance plasmas.

A combination of the SCENIC package (EPFL) and ASCOT5 allowed for predicting global ICRH ion wall loads that might pose a danger to plasma facing components. The SCENIC package was used to calculate ICRH ion distributions inside the plasma, while ASCOT5 was used to calculate the wall loads. It was found that the wall loads have similar features as NBI wall loads. NBI wall loads to the ICRH antenna were also evaluated in preparation for concurrent NBI and ICRH operation (see Figure 2.7). The heat load was found to be highly dependant on the magnetic configuration and the antenna insertion depth.

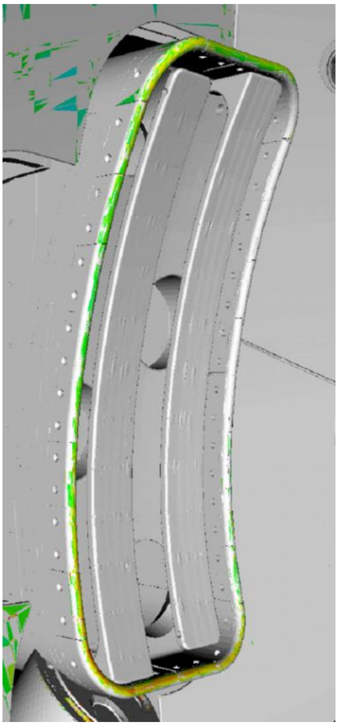

Figure 2.7. NBI heat load to the ICRH antenna in concurrent NBI and ICRH operation, simulated with ASCOT5.

2.6 WP CD: Code development for integrated modelling

Research scientists: S. Sipilä, J. Varje, AU

During 2020, work was initiated to benchmark BBNBI-ASCOT-AFSI simulation chain to the neutron spectrum code DRESS. Maintenance and user support was continued for the BBNBI, ASCOT and AFSI actors. A new IMAS tag 4.5 candidate revision of ASCOT4 was benchmarked against the previous tag 4.4.

The development of the ASCOT-RFOF actor was completed. ASCOT-RFOF is interchangeable with the basic ASCOT actor, but it is also capable of radiofrequency heating simulations in cases where ion cyclotron or lower hybrid wave data from a wave code are available.

2.7 WPDTT1-ADC: Fluid simulations of alternative divertor configurations

Research scientists: L. Aho-Mantila, VTT

Studies on alternative divertor configurations aim to optimize the exhaust strategy and expand the operational regime of DEMO. As a joint effort between engineers and physicists, we have explored geometric variations of the conventional, ITER-like single-null (SN) divertor. VTT has participated in these activities in 2020 by coordinating the work of the fluid modelling team, and by simulating the detailed exhaust processes in the double-null (DN) DEMO divertor configuration.

In 2020, we obtained significant understanding of the predicted characteristics of DEMO power exhaust. According to the SOLPS-ITER simulations, attached divertor regimes are prone to large asymmetries, which are driven and reinforced by geometrical effects, localization of the impurity radiation, and thermoelectric currents. Detached solutions show a smaller level of asymmetry, and they form an operative window that is sensitive to the details of the divertor geometry. Beneficial effects are observed when the connection length or the flux expansion is increased in the low-field-side divertor leg, whereas the benefits of increasing the number of X-points remain to be demonstrated, see Figure 2.8. The studies will continue in 2021 with more detailed physics models in the simulations.

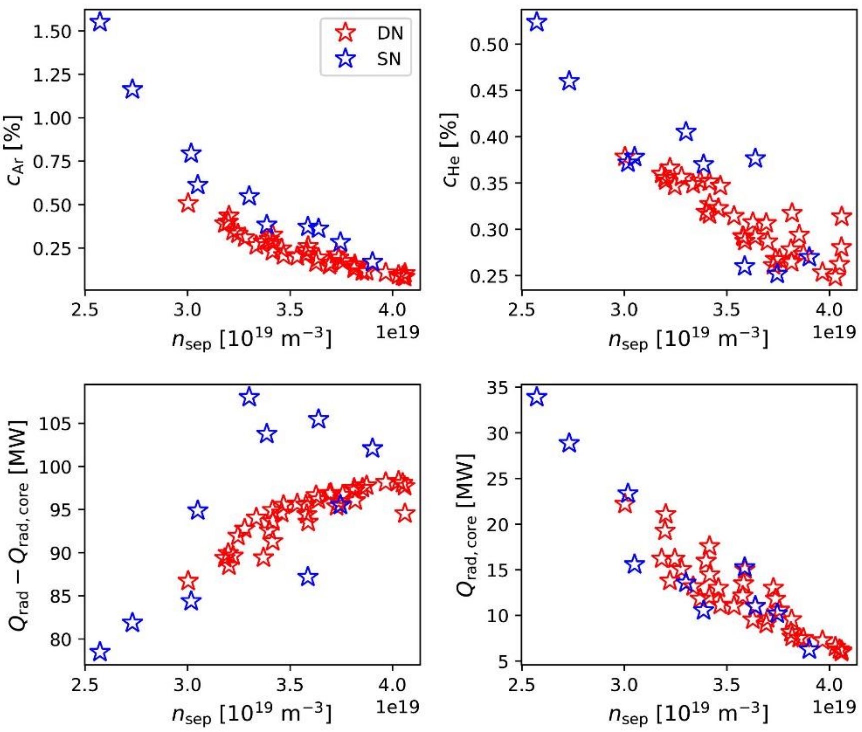

Figure 2.8. Comparison of Ar and He core concentrations (top row) and radiated power in the edge and core regions (bottom row) between the DEMO SN and DN configurations. Similar results are obtained in both configurations.

3. Power Plant Physics & Technology Work Programme 2020

3.1 WP PMI: Plant level system engineering, design integration and physics integration

Research scientists: T. Kurki-Suonio, L. Sanchis, S. Äkäslompolo, AU
M. Väänänen, J. Ylätalo, Fortum
S. Norrman, M. Szogradi, VTT

3.1.1 Introduction

FinnFusion activities within WP PMI cover the impact of low load operation on relevant plant components for the water cooled lithium lead (WCLL) plant variant with direct Coupling Option (Aux. Boiler)

3.1.2 WCLL BB PHTS&BOP Direct Coupling Option (Aux. Boiler) - Impact of low load operation on relevant plant components

The study concentrated on the improvement of the Apros model in particular to addresses and overcome some issues raised from the previous report PMI-3.2-T041-D002. The functionalities of the plant control system has been updated in the Apros model in accordance to Ansaldo Energia control system developed concept, from applicable parts. In addition, it tries to provide interesting insights on a specific technology, presented and discussed at last WPBOP Design Review, regarding the WCLL BOP Direct Coupling Option "No storage". In particular, the study gives an overview of the considerations for plant control, turbogenerator clutch (see Figure 3.1) and supporting grid connection. The possibilities and challenges related to proposed turbogenerator clutch operation with reference to the BOP "No Storage" has been discovered. Additionally some consideration covering battery storage possibilities supporting grid connection has been evaluated.

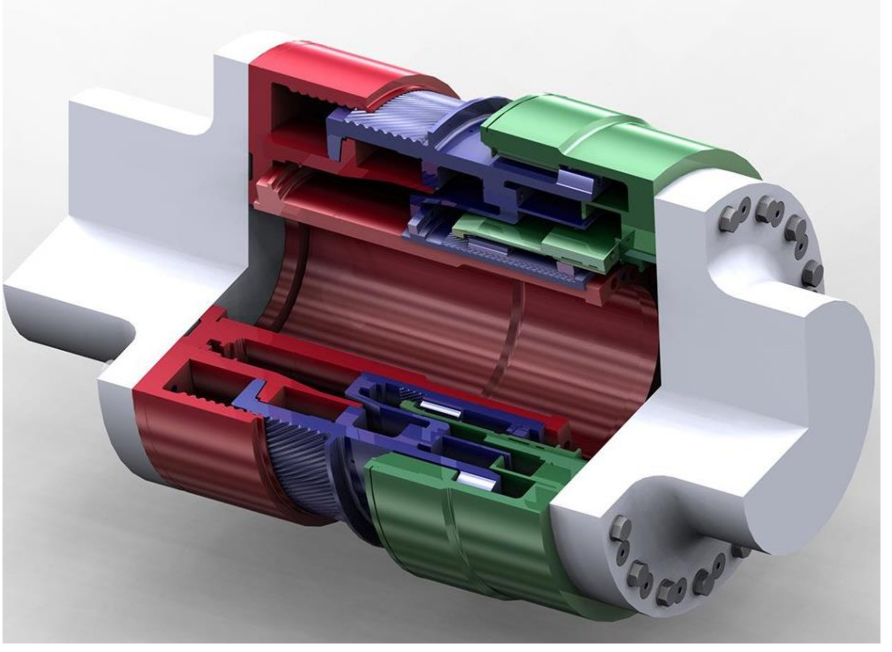

Figure 3.1. High capacity clutch candidate, model EVE from manufacturer SSS, considered for the “No storage” option.

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

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

The 2020 activities focused on the improvement of the small energy storage system (ESS) design of the Helium-Cooled Pebble Bed (HCPB) and Water-Cooled Lithium-Lead breeding blanket (WCLL BB) configurations for DEMO using the Apros software developed by VTT. Considering the HCPB layout a helical coil steam generator (HeSG) was designed and modelled with high pressure and temperature helium as primary and water as secondary coolant. The primary heat transfer system (PHTS) was coupled to the power conversion system (PCS) via eight HeSGs i.e. each PHTS loop featuring one SG, moreover, the integration of the small ESS was also realized by using such HeSG component with liquid Hitec salt on the primary and water on the secondary side.

Regarding the WCLL configuration two new once-through steam generators (OTSG) have been developed for the first wall (FW) and breeding zone (BZ) coolant loops of the BB. The refurbishment of the WCLL BB model entailed the construction of a 22.5° segment of the blanket consisting of two inboard (IB) and three outboard (OB) segments (see Figure 3.2). Each segment contained 7 poloidal regions, composed of a representative breeding unit (BU) and boundary condition interfaces of the given region. The poloidal distribution of radiative heat loads was obtained by utilizing results of transport codes such as ASTRA, SOLPS and the CHERAB Monte Carlo ray tracing code. The region-wise volumetric (nuclear) heating distribution was derived from relative power trends of MCNP simulations with respect to FW, PbLi and Eurofer compartments. The modular structure of the onion architecture-based BB enabled the user to define various power loads along three axes achieving more realistic thermalhydraulic feedback and transient behaviour from the reactor sector.

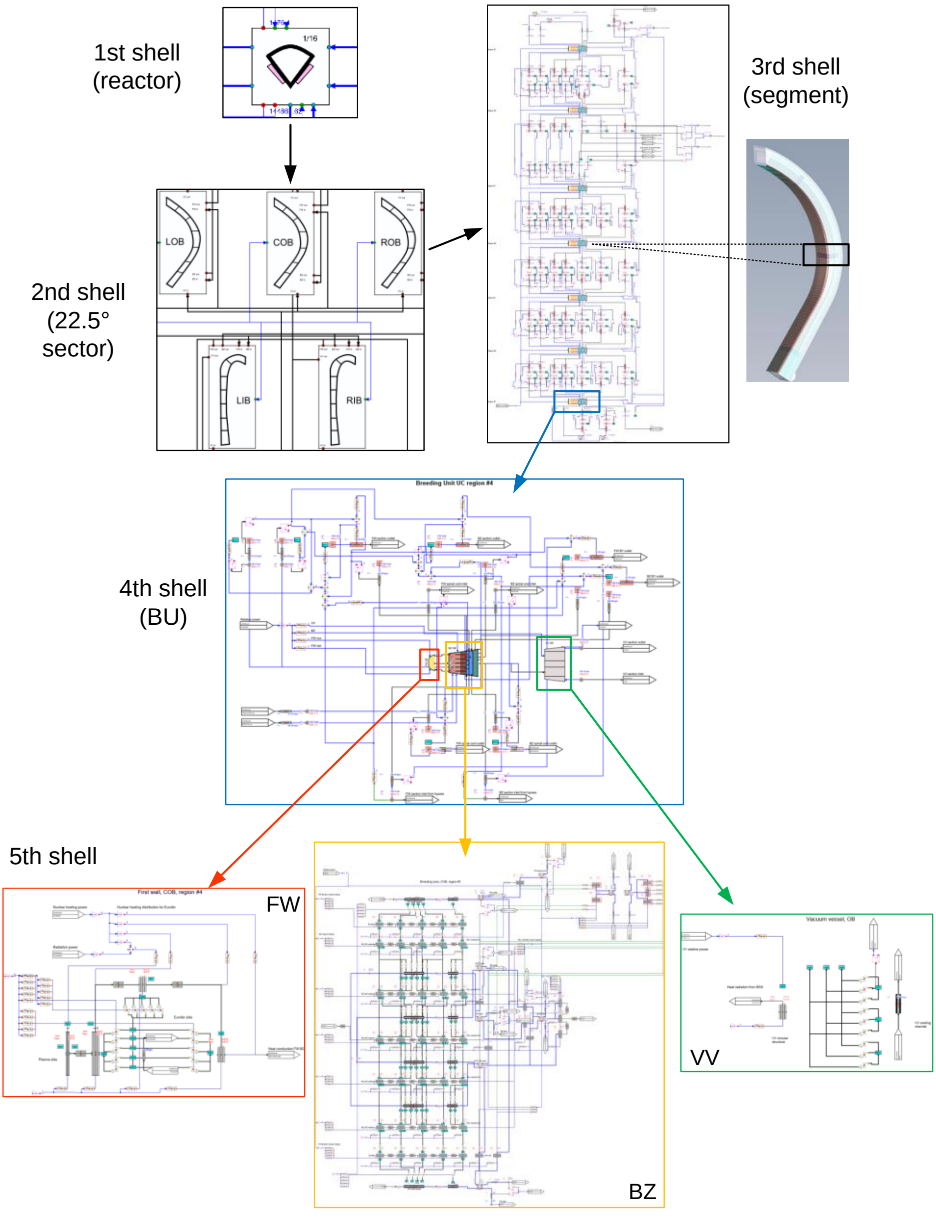

Figure 3.2. Onion structure of the BB.

3.3 Serpent 2 simulations of neutron fluxes and triton generation in the TBM mock-up

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

The PPPT task PMI-7.5 concerns tritium production in DEMO, with a WCLL (Water-Cooled Lithium-Lead) TBM mock-up built and experiments performed in Frascati, Italy, where the appropriate neutron source, FNG (Fusion Neutron Generator), is available. Within the task T008, we simulate neutron transport and tritium production in the new WCLL TBM mock-up using the Serpent code, developed and maintained at VTT (http://montecarlo.vtt.fi).

In 2020, a Serpent 2 model for the mock-up, including realistic geometry and material composition, was finalized. It consists of a Eurofer-steel box (supporting structure) and LiPb blocks (tritium breeder and neutron multiplier), interleaved with Perspex that serves as a neutron moderator. In addition, detectors were placed in two rows along 7 radial locations. Neutron flux in the mock-up was calculated at different radial locations to be compared with the MCNP6 code. Ten different reactions were compared, with variation less than 10% for most of the energy range. Tritium production ratio using perspex was 2.9%, but only 0.9% without the neutron moderator.

The COVID-19 situation did not allow the experiments as planned in 2020, so the project continues in 2021. As soon as the experimental data becomes available, they shall be compared against predictions from Serpent-2 simulations.

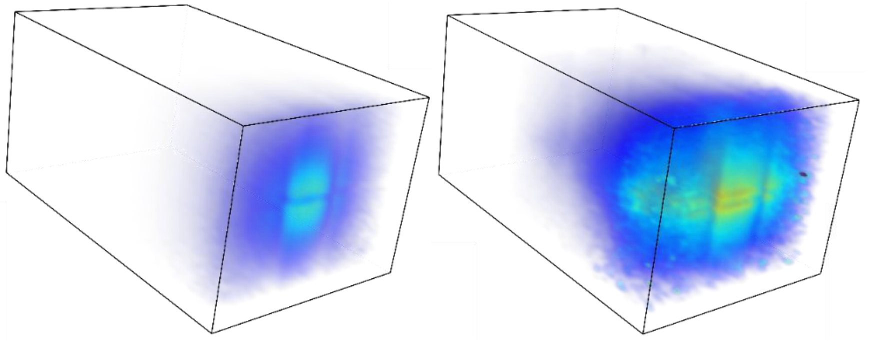

Figure 3.3. Illustration of the energy dependency of the ^{6}Li (n,T) ^{4}He cross-section. Left: neutrons with energy > 10 MeV. Right: neutrons with energy < 10 MeV. The need for a neutron moderator is clear.

3.4 WP RM: DEMO alternative Remote maintenance architectures

Research scientists: W. Brace, P. Kilpeläinen, H. Martikainen, O. Rantanen, J. Saukkoriipi, VTT
V. Puumala, P. Virtanen, S. Muhlig-Hofmann, Comatec Group

Building on previous blanket handling work and the conclusions from the DEMO RM project's pre-conceptual stage, there is a need to develop alternative maintainable architectures further in the DEMO 2020-2021 work package. The Single Null (SN) Proof of Principle (PoP) design review concluded that the Blanket Transporter presents a significant technical risk for further development for handling full-blanket segments within the SN vessel constraints. The following key issues require consideration to mitigate future architecture: complex hardware kinematics, inaccessibility to component Centre of Gravity (CoG) and high mass flexible payloads.

Therefore, alternative vessel architectures were assessed to establish a maintainable DEMO architecture. These included investigating ideas such as the impact and practicality of further blanket segmentation (DN or SN), the benefits of offsetting the lower inboard blankets in the Double Null (DN) vertical port configuration, or the benefits of alternative port or magnet positioning, and design of alternative remote handling (RH) systems.

The alternative architecture assessment was apparent; there is a benefit if the same RH system would be able to move not only the Lower Inboard blanket but also the outboard ones (Divertor and Lower Outboard Blanket) in a DN architecture. Therefore, a new RH system was designed that, by changing two different end effectors to a lifting mechanism's head and mover, all the different components are handled (see Figure 3.4).

This RH concept's basic design includes a mover trolley for transport through the lower port, a much more rugged and stable lifting mechanism including an adapter plate for the different end effectors, and two specialized end effectors with installed locks to pick up and secure the components to be moved. The alternative architecture and new RH concept mitigate the critical issues (complex hardware kinematics, inaccessibility to CoG, and high mass flexible payloads) required for future architecture.

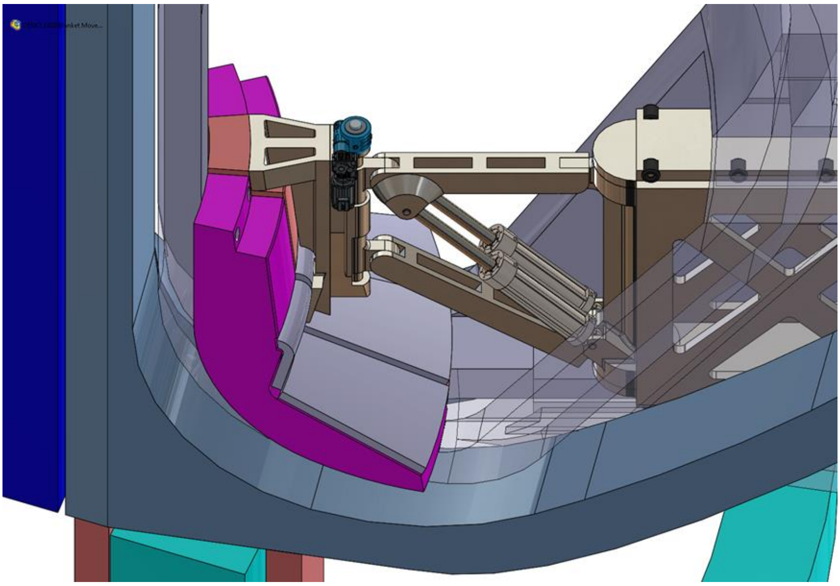

Figure 3.4. A concept of Remote Handling System for the Lower Horizontal Port area of the DEMO reactor.

3.5 WP PRD (Prospective R&D for DEMO): Materials

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

Tungsten is one of the main materials to be used in the highly demanding environment of fusion test reactors. Until recently, mainly primary damage caused by single particles have been studied in molecular dynamics simulations. Even though these simulations can give an excellent insight in the radiation response of a material, higher doses compared to reactors are not even closely reached. In the last years, massively overlapping cascades have been simulated to achieve higher doses, on the order of tenths of dpa. Still, this is not comparable with doses accumulated over decades of reactor use, as the simulations are needed to be run in a consecutive manner.

We have, in order to investigate how different possible speed-up techniques will effect the result, carried out both massively overlapping cascades close to 1 dpa. Additionally, we utilized several other techniques (Frenkel-pair insertion) to obtain doses close to 10 dpa, with atomistic resolution. Speed-up was obtained by inserting Frenkel-pairs and inserting Frenkel-pairs between cascades, to effectively increase the dose more with each CPU-demanding cascade simulation. We found that the methodology used did effect not only the defect number, but also the defect morphology. The latter can obviously have detrimental effects if the incorrect values/morphologies are utilized in other larger scale models and ultimately used for choosing the components in the reactor. In Figure 3.5 the number of vacancy cluster evolution is compared for different methodologies. Several aspects of the defect evolution can be compared (almost) directly with experiments, in order to validate or discard some of the results obtained in some of the methodologies.

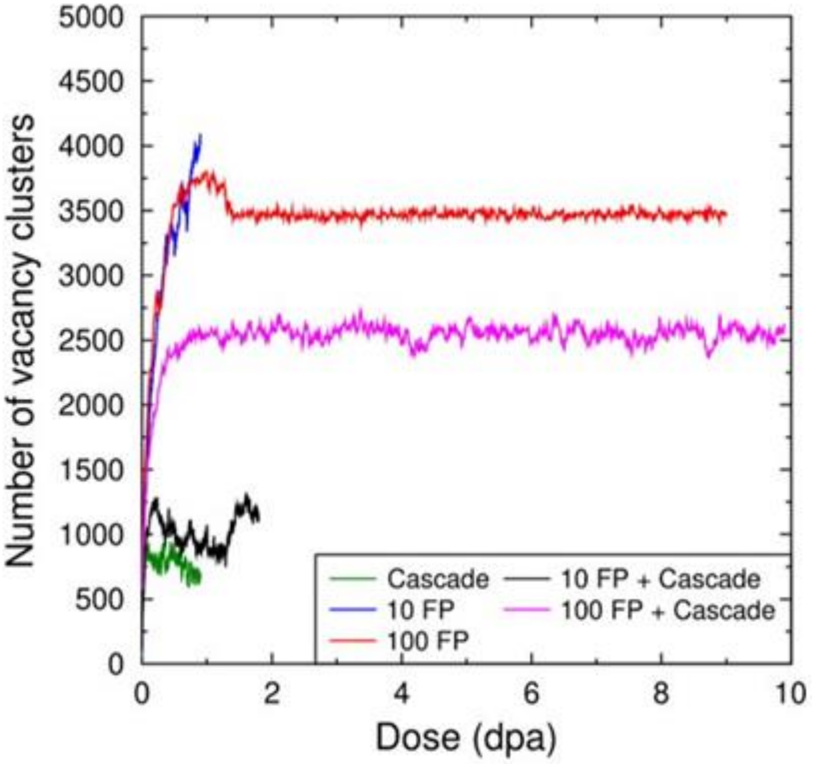

Figure 3.5. Number of vacancy clusters as a function of dose utilizing different simulation methodologies.

3.6 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.

In 2020, VTT work has concentrated on two tasks: 1) The finalisation of internal events PRA for IFMIF-DONES; and 2) Master's thesis on utilizing design phase PRA modelling to verify fulfillment of safety objectives found from the literature for IFMIF-DONES.

3.6.1 Internal events PRA of IFMIF-DONES

The internal events PRA includes event trees for six accident categories. In Figure 3.6 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.

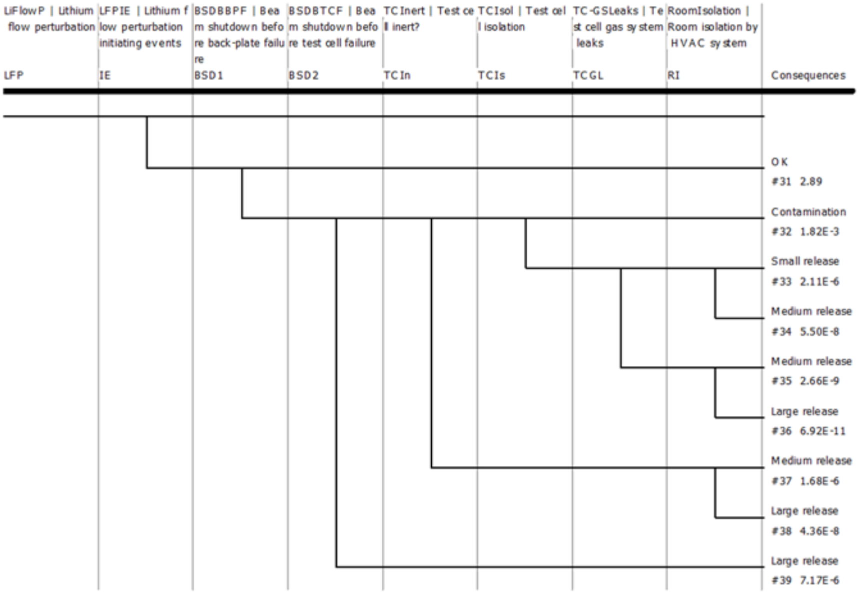

Figure 3.6. Lithium perturbation event tree

At the moment, the estimate on the frequency of large release of IFMIF-DONES is relatively high (1.2E-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.

3.6.2 Utilizing design phase PRA modelling to verify fulfillment of safety objectives

Based on literature references, the large release objective of IFMIF-DONES could be set to 10^{-6}/year. The preliminary risk estimate yields a proportionality factor of 0.08. Failure probabilities of safety systems are directly available from the PRA model and failure probability targets for the systems can be calculated by multiplying the estimate with the proportionality factor. How this would correlate with some of the safety systems' failure probabilities and the target failure probabilities are listed in Table 3.1.

Safety system / function	**Estimated failure probability (/yr)**	**Failure probability target (/yr)**
Safety beam shutdown signal 1	10^{-4}	$8x10^{-6}$
Test cell inertation	10^{-4}	$8x10^{-6}$
Room isolation by HVAC	$2.6x10^{-2}$	$2.2x10^{-3}$

Table 3.1. Safety system estimated and target failure probabilities.

Some of the safety systems already have small failure probabilities. Therefore, the large release risk could be decreased more efficiently by introducing modifications to the IFMIF-DONES safety design. The modifications should focus particularly on the beam shutdown and events that can cause perturbation to the lithium flow.

3.7 PPPT Industry task (Optioneering)

Research engineers: S. Mühlig-Hofmann, V. Puumala, K. Suominen, A. Timperi, Comatec Group

The objective of this industrial task is DEMO Remote maintenance systems technology support. DEMO design process shall maximize plant availability and minimizes downtime for maintenance. Therefore, there is a need to develop and substantiate remote maintenance concepts that will allow inspection, monitoring and replacement of a wide range of DEMO components. This work has identified several areas of high technical risk and more detailed concept studies have been performed in these areas to address these risks. A number of different optioneering approaches have been used to compare alternative designs and strategy choices. EUROfusion is keen to ensure greater engagement with industrial expertise to support and validate the development of feasible concepts to ensure that the design choices made are based on a sound, rigorous and repeatable methodology.

"Optioneering" means comparison of concepts meeting the design requirements and ranking of them according to the given criteria. Optioneering can be used to compare alternatives in different stages of the design process. EUROfusion was looking for an input from an industrial partner with experience of current best practice in optioneering to develop an agreed approach for optioneering and concept down selection, which can be implemented across DEMO remote maintenance system design. The scale and complexity of the above-mentioned conceptual designs in DEMO remote maintenance systems can be referenced with large and complex machinery applications in process plants. The concepts are typically related to remotely operated robotic systems used for plant maintenance. The target environment for the robotic systems imposes requirements on the technologies and materials to be used.

Comatec developed the optioneering methodology together with VTT and facilitated concept down selection workshops. Comatec also organized a two-day online training for the DEMO Work Package: Remote Maintenance team during COVID19 lockdown, in order to present the optioneering methodology and to train the team in its application.

3.8 PPPT Industry task (DEMO RH systems technology support)

Research engineers: V. Puumala, T. Ruonanen, T. Syrjänen, A. Timperi, P. Virtanen, V. Vanhatalo, Comatec Group

This industry task was a continuation of one of the six separate technology support cases for the DEMO power plant in 2018-2019. DEMO has many steel pipes and very limited space to install them. These pipes will undergo rapid cutting and welding processes during maintenance, and as a result, post weld heat treatment (PWHT) will be needed to restore the material properties. The aim of this task was to conceptualize an in-bore tool to carry out the PWHT.

Comatec was required to complete two tasks. Firstly, to develop a concept design for the in-bore PWHT tool, and secondly to design a proof-of-principle test setup. The electromagnetic, thermal and structural analysis using ANSYS finite element software were essential part of this task (see Figure 3.7). Comatec performed the work entirely at its own premises and in close co-operation with UK Atomic Energy Authority – RACE organization.

Comatec's engineering expertise is very well in line with the development needs of fusion technology remote handling systems (RH). One objective of this industry task was to describe and test the expertise that Comatec can offer for the demanding RH development and the planned execution of DEMO remote handling systems. This task showed that the partnership works very well.

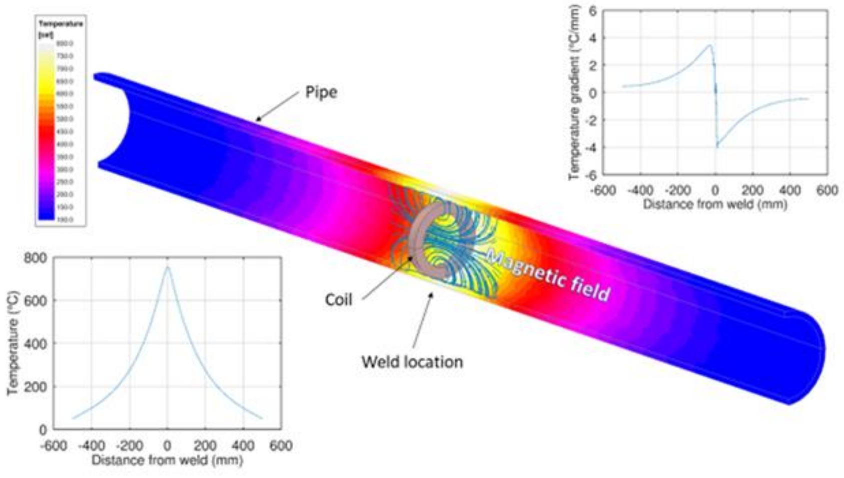

Figure 3.7. Heat treatment of pipes.

4. Communications

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 2019,* VTT Technology **375** (2020) 83 p., was published in May.

During 2020, Finnish media published several articles and interviews on the fusion research activities in Finland:

- Timo Määttä, Tamperelaisessa teollisuushallissa on kehitetty tekniikkaa, joka voi vielä pelastaa maailman öljykriisiltä ja ydinjätteiltä (Technology developed in an industrial hall in Tampere may save the world from the oil crisis and nuclear waste), interview with the national broadcast company YLE on 14 January 2020 (https://yle.fi/uutiset/3-11146330).

- Markus Airila, Taina Kurki-Suonio and Tuomas Tala, Milloin fuusiovoima tuottaa sähköä? (*When does fusion power produce electricity?*), interview with Tekniikan Maailma on 26 April 2020.

  https://tekniikanmaailma.fi/lehti/8a-2020/milloin-fuusiosta-sahkoa/

- National broadcast company YLE about ITER on 28 July 2020: Viimeinen etappi fuusiovoimala ITERin rakentamisessa alkaa – Alkaako energiantuotannon Graalin malja vihdoin siintää? (Starting the last leg towards fusion reactor ITER – is the Holy Grail now finally looming in the horizon?) (https://yle.fi/uutiset/3-11466676).

- Reaktorin rakentaminen suurimmassa fuusiovoimalassa alkoi, tarkoitus käynnistyä 2035 - Loputon energialähde askeleen lähempänä (*Construction in the largest fusion reactor began, intended to start in 2035 - Endless energy source one step closer*), article published in Tekniikka&Talous on 29 July 2020.

  https://www.tekniikkatalous.fi/uutiset/reaktorin-rakentaminen-maailman-suurimmassa-fuusiovoimalassa-alkoi-tarkoitus-kaynnistya-2035-loputon-energianlahde-askeleen-lahempana/b83577d0-403b-4088-ad36-b41761e41b81

- Simppa Äkäslompolo and Antti Snicker, Tehtävä: synnytä Aurinko maapallon pinnalle - mistä fuusiovoimassa on kyse ja miksi homma tökkii (*Mission: to bring the Sun to the surface of the earth - what is fusion power about and why it is so difficult to harness it*), interview with the national broadcast company YLE on 14 August 2020 (https://areena.yle.fi/audio/1-50547624).

- Timo Määttä, Ydinvoimaa ilman tuhansien vuosien ydinjäteongelmaa – onko fuusioenergia tiemme päästöttömään energiaan? (Nuclear power without a waste problem of thousands of years – is fusion our way to pollution-less energy?), interview with Kauppalehti Optio on 8 October 2020.

https://www.kauppalehti.fi/uutiset/ydinvoimaa-ilman-tuhansien-vuosien-ydinjateongelmaa-onko-fuusioenergia-tiemme-paastottomaan-energiaan/ef54cfd3-6332-4b18-ba3a-b4e6113a8fe7

- Hannu Saarinen and Mikko Siuko, Tamperelaisessa konehallissa tehtiin ällistyttävä keksintö maailman monimutkaisimpaan laitteeseen – Näin huolletaan ydinreaktoria, jonka sisällä on kuumempaa kuin Auringossa (*Astonishing invention from a machine hall in Tampere to the most complex device on Earth – So will be maintained the nuclear reactor with a core hotter than the Sun*), interview with Aamulehti on 9 October 2020 (https://www.aamulehti.fi/tiedejateknologia/art-2000007598678.html).

- Taina Kurki-Suonio and Mikko Siuko, Fuusioenergiasta on syntymässä kisa – Seuraavat 15 vuotta kertovat, onko fuusio-voimasta tulevaisuuden energianlähteeksi, arvioi tutkija (*A race towards fusion energy is emerging – Next 15 years will show if fusion is a viable energy source for future, estimates a scientist*), interview with Helsingin Sanomat on 28 October 2020 (https://www.hs.fi/tiede/art-2000006701247.html).

- MAST Upgrade starts up its first plasma, news release of Aalto University on 3 November 2020.

  https://www.aalto.fi/en/news/mast-upgrade-starts-up-its-first-plasma; https://www.aalto.fi/fi/uutiset/uusi-kokeellinen-fuusiolaite-on-kompaktin-kokoinen-ja-aiempaa-tehokkaampi

- Britannia alkaa etsiä tonttia kaupalliselle fuusioreaktorille - valmista tarkoitus olla 20 vuoden päästä (*Britain starts to look for a site for a commercial fusion reactor - expected to be ready in 20 years),* article published in Tekniikka&Talous on 2 December 2020.

  https://www.tekniikkatalous.fi/uutiset/britannia-alkaa-etsia-tonttia-kaupalliselle-fuusioreaktorille-valmista-tarkoitus-olla-20-vuoden-paasta/9ec14b4c-da27-46eb-ae93-f506f9fb2eca

- Taina Kurki-Suonio, MIT rakentaa pientä fuusiovoimalaa - apuna suomalaisohjelmisto (*MIT builds a small fusion reactor - Finnish simulation code is used in design*), interview with Tekniikka&Talous on 10 December 2020.

  https://www.tekniikkatalous.fi/uutiset/mit-rakentaa-pienta-fuusiovoimalaa-apuna-suomalaisohjelmisto/3bdf62a7-dd1a-47f0-831f-e9bc685af545

Lecture courses at Aalto University, School of Science:

- *Fusion Energy Technology (Mathias Groth, spring 2020).*

- *Advanced course in plasma physics with computational emphasis (L. Chôné, E. Hirvijoki, T. Kurki-Suonio, spring 2020)*
- *Introduction to plasma physics for fusion and space applications (T. Kurki-Suonio, autumn 2020).*

5. Education and training

5.1 WP EDU – FinnFusion student projects

5.1.1 Overview

After EUROfusion introduced the Education funding instrument, the FinnFusion consortium adopted the practice of nominating *FinnFusion students* to whom the Education funding is specifically directed. The selection is done by the FinnFusion Advisory Board after proposals from the university professors working in the programme. Such a selection is used as an incentive to the students and a strategic means to direct the programme in the long term.

During 2020, one doctoral dissertation and three Master's thesis were completed (see Section 11.3.4).

5.1.2 Doctoral students

Student: Henri Kumpulainen (AU)
Supervisor: Mathias Groth (AU)
Instructor: Mathias Groth (AU)
Topic: *Tungsten transport in JET*
Report: In addition to earlier work involving EDGE2D-EIRENE and DIVIMP simulations, the kinetic Monte Carlo trace-impurity erosion and migration code ERO2.0 has been applied to tungsten and beryllium transport studies in JET plasmas. The background plasma conditions are based on JINTRAC modelling of scenarios ranging from L-mode to ELMy H-mode hybrid plasmas with maximum heating power. Re-erosion of short-lived beryllium deposits at the divertor targets is predicted to contribute significantly to tungsten sputtering in L-mode and inter-ELM scenarios. However, due to efficient divertor screening, most of the tungsten in the L-mode confined plasma is predicted to originate from erosion by deuterium charge-exchange atoms near the divertor entrance. During ELMs, both the predicted erosion and influx of tungsten are dominated by sputtering due to main ions at the targets.

Student: Patrik Ollus (AU)
Supervisor: Mathias Groth (AU)
Instructors: Antti Snicker (AU)
Topic: *Charge exchange losses of beam ions in MAST-U*
Report: In the ASCOT fast-ion code, an atomic reactions module was implemented to allow the modelling of neutralizing charge exchange (CX) reactions that cause transport and loss of fast ions. Beam ions were simulated in the presence of CX reactions in a

high-density scenario of the MAST-U spherical tokamak. CX reactions induce an estimated loss of 20 % of the injected beam power, reducing heating and current drive outside the plasma core. Because of the large magnetic field gradient and open wall design, beam ions lost through CX are deposited mostly on the outer midplane vacuum vessel and nearby poloidal field coils, with wall power loads estimated to reach the order of 100 kWm^{-2}.

Student: Vladimir Solokha (AU)
Supervisor: Mathias Groth (AU)
Instructors: Mathias Groth (AU)
Topic: *Isotope effect on the JET divertor plasmas*
Report: The isotope effect in the JET-ILW divertor during the L-mode pulses was investigated. The pumping system pumps more efficiently light hydrogen isotopes due to the dependence of the conductivity on the thermal velocity of the molecule. The EDGE2D-EIRENE simulations allowed to quantify the isotope separation due to pumping between the core and the divertor, and to explain the dependence of the measured isotope ratio on the input power and line-averaged electron density. The dedicated set of EDGE2D-EIRENE simulations and solutions of the Modified Rutherford Equation clearly shows that temperature drop at q=2 radius is approx. two times larger in the deuterium case than in the hydrogen case, which causes 50% larger islands and a higher risk of disruption and lower density limit. This data can be used to optimise the fuelling scenario for the mixed isotope pulses in ITER and DEMO.

Student: Changyang Li (LUT)
Supervisor: Huapeng Wu (LUT)
Instructor: Huapeng Wu (LUT)
Topic: *Multi-objective optimization of a 6-DoF parallel manipulator for fusion reactor*
Report: The work introduces multi-objective optimization algorithm for designing of parallel manipulator. Depending on the parallel manipulator purposes in a fusion reactor environment, the objective functions related to workspace, dexterity, stiffness and force capacity are defined respectively, which are further integrated into a cost function with different weights allocated on each objective function. The design variables are the geometry of the parallel manipulator and the location of the universal joints on the platforms. Several algorithms are used to obtain the optimized results. The analyzed results are validated by simulation using another computational software. This algorithm is also suitable to optimize

the design of the general parallel manipulator with changing constraints, design variables and cost function.

Student: Shayan Moradkhani (LUT)
Supervisor: Huapeng Wu (LUT)
Instructor: Huapeng Wu (LUT)
Topic: *Condition monitoring of a fusion reactor vacuum vessel assembly robot*
Report: A parallel manipulator has been designed for the assembly of the vacuum vessel of a fusion reactor. This assembly process comprises material handling, machining and welding process. The machining and welding processes use standard G- and J-codes as for CNC machines and welding robots, and they also use point-to-point motion and an interpolation to maintain the speed of the axes.

Student: Ruochen Yin (LUT)
Supervisor: Huapeng Wu (LUT)
Instructor: Huapeng Wu (LUT)
Topic: *Fusion environment reconstruction molding and visual servoing for the remote handling system*
Report: Main goal of this topic is to realize three-dimensional reconstruction of the inside of the vacuum vessel. When the remote handling system is changing the plasma-facing components during the maintenance, the Multi-Purpose Deployer (MPD) will produce bending deformation due to the huge mass of the components. The position of end effector calculated by forward kinematics would have an unignorable error, the precise position of the end effector needs to be obtained by using a real-time positioning algorithm based on a three-dimensional model. Meanwhile, it is necessary to use visual servoing to ensure that the end effector can accurately approach the task target.

Student: Lionel Hulttinen (TUNI)
Supervisor: Jouni Mattila (TUNI)
Instructor: Jouni Mattila (TUNI)
Topic: *Parameter Identification and Compensation for Actuator Nonlinearities for Remote Handling Manipulator Control*
Report: In the ITER vacuum vessel, precise motion and force control of the slave devices are a necessity 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 and 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 ratios and associated static nonlinearities. Additional key area of this study is force reflecting bilateral master-slave control for these manipulators.

Student: Longchuan Niu (TUNI)
Supervisor: Jouni Mattila (TUNI)
Instructor: Jouni Mattila (TUNI)
Topic: *Computer Aided Teleoperation utilizing 3D scene construction by stereo camera with marker*
Report: The research on development and integration of 3D Machine Vision for HLCS modules and GENROBOT at DTP2 continues with the aim to implement an improved and more robust version of the 3DNode software developed earlier. In this study, we have presented a marker based pose estimation tool for use under the strict requirements of the ITER environment. To comply with the vacuum class 1A material restrictions, we have created a custom design for a retro reflector, which utilizes only glass and stainless steel, avoiding the use of typical adhesive and plastic materials commonly found in commercial, off-the-shelf retro reflectors. An automated camera calibration routine was designed to perform calibration of both the cameras and the hand-to-eye transform between the camera and the robotic manipulator. We have presented the algorithms needed to detect the retroreflectors from camera images and to perform the camera localization from different amounts of images: single capture, single camera; single

capture, two cameras; multiple captures, single camera. The developed algorithm has been tested both with synthetic and real data. Different approaches to pose estimation were developed during the project, comprising methods based on a single camera, a stereo camera and a scanning camera. Various experiments show that the use of markers embedded within the target greatly increases the reliability and precision of the system. The system developed within this grant is considerably more precise and reliable than its previous version. The project was finalized during 2020. The recipient publically defended his dissertation in December 2020.

Student: Jesper Byggmästar (UH)
Supervisor: Kai Nordlund (UH)
Instructor: Kai Nordlund (UH)
Topic: *Multiscale modelling of radiation effects in fusion reactor materials*
Report: We continued developing highly accurate machine-learning interatomic potentials for body-centred cubic metals and alloys. The potentials are applicable to radiation damage simulations and are accurate to within a few meV/atom of the underlying training data from density functional theory calculations. Potentials for pure W, Mo, Nb, Ta, and V are published and a potential for the complete quinary Mo-Nb-Ta-V-W system is now complete and ready to be used in molecular dynamics simulations.

Student: Emil Levo (UH)
Supervisor: Kai Nordlund (UH)
Instructor: Kai Nordlund (UH)
Topic: *Multiscale modelling of radiation effects in fusion reactor materials*
Report: In 2020 we studied how temperature affects radiation damage in NiFe and NiCoCr equiatomic multicomponent alloys. Massively overlapping cascades were simulated, with molecular dynamics, in the alloys and reference Ni, at 138-800 K. The simulated samples were analyzed for point defects, defect clusters and dislocations. Rutherford backscattering in channeling conditions (RBS/c) simulations were performed to obtain RBS/c spectra of the samples, and to enable better comparison with experiment. The alloys were superior compared to Ni at all temperatures in terms of radiation tolerance. The RBS/c calculations deemed useful for comparison with experiment and all the results are to be published.

Student: Aki Lahtinen (UH)
Supervisor: Jyrki Räisänen (UH)
Instructors: Antti Hakola (VTT), Jari Likonen (VTT)
Topic: *Plasma-wall interactions in fusion devices*

Report: In 2020, the work focused on the analysis of the IBA data collected from the samples exposed in the ASDEX Upgrade tokamak during 2019 experiments. The experiments studied nitrogen-15 migration, effect of the surface roughness on the erosion and deposition during L-mode plasma discharges, gross and net erosion during L- and H-mode plasma discharges, and plasma-wall interactions during helium plasma discharges. NRA was used to study deposition of nitrogen-15 during the L-mode experiment and deposition of deuterium, boron, and carbon impurities during all the experiments. RBS was used to study erosion of molybdenum samples with different surface roughnesses, and erosion and deposition of different molybdenum and tungsten samples exposed to the helium plasma discharges.

Student: Anna Liski (UH)
Supervisor: Filip Tuomisto (UH)
Instructors: Tommy Ahlgren (UH)
Topic: *Irradiation Effects on Hydrogen Retention in High Entropy Alloys*
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. This makes HEAs interesting class of materials in extreme environment applications like fusion reactor first wall. Our project is evaluating the suitability of WMoNbTaV alloy as a plasma facing material by experimentally characterizing the defect types of hydrogen trapping and quantifying the amount of hydrogen trapped by each defect.

The studied alloy was prepared by National Tsing Hua University and each of its constituents obtained as an individual element sample. Alloy and pure samples have been implanted with 20keV deuterium with the dose of $5x10^{16}$ at/cm^2. The amount of retained deuterium was then measured by Elastic Recoil Detection Analysis (ERDA) and Secondary Ion Mass Spectrometry (SIMS) revealing a lower retention of hydrogen in the WMoNbTaV- alloy than tungsten, which is currently used wall material in the reactor. The binding energies of hydrogen are now being under investigation with TDS.

Student: Tomi Vuoriheimo (UH)
Supervisor: Filip Tuomisto (UH)
Instructors: Kalle Heinola (IAEA), Tommy Ahlgren (UH)
Topic: *Deuterium retention and removal in tungsten*
Report: In 2020 we made low energy implantations with deuterium into tungsten. The energies were chosen based on JET ELM data taking into account both inter-ELM energies (100 eV/D) and intra-ELM energies (5 keV/D). Implantations with estimates for ITER

ELM energies were also made with 20 keV/D. Implantations with different energies were done sequentially. The goal was to compare D retention during a single ELM in JET and ITER. We found that with higher energies (ITER) the D retention is more than the sum of the two implantations alone. With JET energies this was not seen.

Student: Anu Kirjasuo (VTT)
Supervisor: Filip Tuomisto (UH)
Instructors: Antti Salmi (VTT)
Topic: *Particle source impact on density peaking in JET experiments*
Report: Particle source impact on plasma density profile peaking was examined in a database study of 165 JET H- and L-mode plasmas, utilizing a formula derived from particle continuity equation, presented by Fable et al. {Nuclear Fusion, 59(7):076042, 2019} in relation to an ASDEX Upgrade experiment. The results obtained were compared both to the ASDEX Upgrade experiment, and to recent dedicated gas modulation experiments (two three-point collisionality scans) in JET, where particle source impact on density peaking was examined in detail both experimentally and with simulations by Tala et al. {Nuclear Fusion, 59(12):126030, 2019}. The source ratio of density peaking values were broadly in line with expectation, although at the higher end, indicating that a coefficient fitted to ASDEX Upgrade experiment might change for these JET experiments. Also, approximations made by Fable et al. might need to be revisited for the JET experiments that cover a wider parameter space. In particular for the H-mode plasmas in the database it seems the turbulent regime would have to be included to increase the accuracy of the approximation. The research continues in 2021 with simulations in order to try and find an appropriate parametrization to improve the formula for increased accuracy.

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. This approach facilitates to incorporate multiple microscopic processes and complex geometries. However, the kinetic MC approach leads to a tremendous computational cost for high-collisional reactor-relevant regimes. Therefore, different computationally much cheaper fluid neutral models have been developed during the last decades.

The main shortcomings of a purely fluid description for neutrals are the fact that they are usually restricted to the plasma grid that does not extend up to the real vessel wall, the fact that the fluid approach is not valid in some low-collisional regions of the plasma edge, and the fact that a fluid approach is typically also not valid for the hydrogen molecules. Therefore, we have developed a spatially hybrid approach that consists of a fluid model for the hydrogen atoms in the plasma edge region coupled to a kinetic model for atoms sampled at the boundary of the plasma grid and coupled to a kinetic model for the hydrogen molecules. The main benefit is the fact that the hybrid neutral model facilitates to incorporate the complex vessel geometry.

Applying the hybrid method to JET L-mode plasmas leads to a significant reduction of the fluid-kinetic discrepancies, as can be seen in Figure 5.1. The computational cost of the hybrid approach is on average 7-14 times lower than a simulation with fully kinetic neutrals for the same statistical error on the relevant quantities of interest.

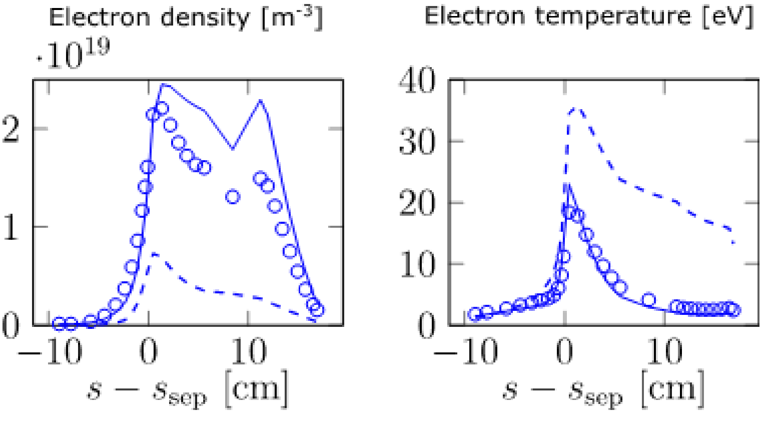

Figure 5.1. Outer divertor target profiles: fully kinetic neutrals (solid lines), purely fluid neutrals (dashed lines), and hybrid neutrals (circular marks).

6. Enabling Research

Research scientists: L. Chôné, T. Kiviniemi, A. Virtanen AU
T. Ahlgren, F. Djurabekova, F. Granberg, K. Heinola, E. Levo, A. Liski, A.E. Sand, UH
A. Laukkanen, J. Likonen, VTT

FinnFusion participated in five Enabling Research projects in 2020:

- ENR-MFE19-CCFE-03: Atomic Resolution Advanced Microstructure Characterisation Techniques for Radiation Damage (AtomCRaD)
- ENR-MFE19-CCFE-04: Model for reactor relevant pedestals
- ENR-MFE19-VTT-01: High Entropy Alloys as DEMO First Wall material: from irradiation effects to fuel retention
- ENR-MFE19-MPG-04 MAGYK: Mathematics and Algorithms for GYrokinetic and Kinetic models
- ENR-PRD-MAT-IREMEV-1: Models for primary radiation damage

In this report, we highlight the ENR projects coordinated by CCFE and University of Helsinki.

6.1 Atomic Resolution Advanced Microstructure Characterisation Techniques for Radiation Damage

The Enabling Research project AtomCRaD addresses the question of whether it is possible to observe radiation-induced defects in structural materials with atomic scale resolution, using aberration corrected scanning transmission electron microscopy (STEM). We investigate the possibility of identifying and characterizing in detail the morphology of individual defects, in particular from high-angle annular dark-field (HAADF) images, where the atoms are enhanced rather than the strain fields of defects. The project is carried out in collaboration with researchers from CCFE and the University of Manchester in the UK.

While atomic columns of the tungsten lattice can be readily identified in experimental micrographs, interpreting the disordered regions in order to identify the underlying atomic structure is less straightforward, due to the complex interaction of the electron beam with the material as it travels through the sample. For the purpose of supporting the interpretation of experimental images, as well as finding the optimal imaging conditions, we have simulated STEM images of both ideal tailored dislocations loops, and disordered defects obtained through molecular dynamics simulations of collision cascades giving rise to radiation-induced damage (see Figure 6.1). We have found that under certain conditions, it is possible to differentiate between vacancy and interstitial type dislocation loops, a task that is extremely challenging and often impossible using conventional TEM. The Burgers vector and habit plane of the dislocation loops are found to be easily identifiable and not sensitive to the imaging conditions. These results indicate that the use of STEM can greatly improve our understanding of the radiation-induced microstructure of materials for fusion applications.

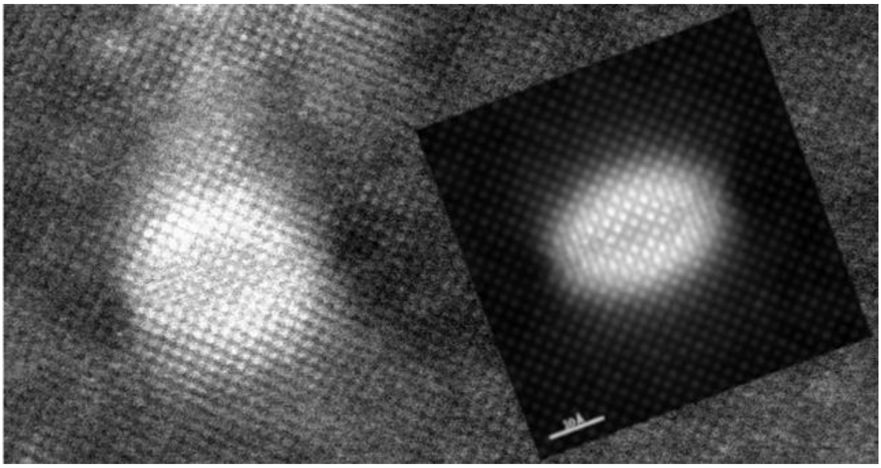

Figure 6.1. An experimental image (left) of a dislocation loop in tungsten, compared to a simulated image (right) computed for identical imaging conditions. We can conclude that the defect in the experimental image is a loop with Burgers vector **b**=<100>. The image was obtained with a 100 keV electron beam, which based on our simulation results falls slightly short of the contrast needed to differentiate between vacancy and interstitial type loops. The simulated image shows an intersitial type loop.

6.2 Model for reactor relevant pedestals

The physics of the tokamak pedestal is a key element for improving our confidence in designing potential fusion power plants. The aim of the present enabling research project is to contribute to development of fully predictive model for the pedestal height and width. One key component here is bootstrap current which is a self-generated current parallel to the magnetic field in toroidal geometries which is predicted by neoclassical transport theory. Role of Aalto University in the project was to study accuracy of these predictions.

The bootstrap current profile has been studied in the pedestal region numerically with neoclassical simulations using parameters similar to those in JET tokamak. The simulations have been performed with the plasma simulation code ELMFIRE and results were compared to two different analytical estimates with good agreement but importance of taking into account Shafranov shift was pointed out. The effect of poloidally localized atom source on the bootstrap current has been studied while assuming that the ionization takes place in the pedestal region. Clear effect of poloidal location was found for thermal particles within one poloidal Larmor radius of source location (see Figure 6.2) but for cold particles the poloidal dependence mostly disappears.

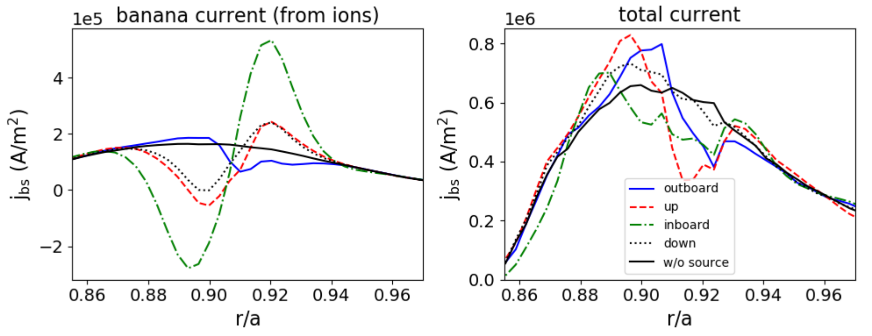

Figure 6.2 Scan of a) banana current and b) total bootstrap current as a function of radius for thermal particle source located at four different poloidal angles.

6.3 High Entropy Alloys as DEMO First Wall material: from irradiation effects to fuel retention

The High Entropy Alloys (HEA) are a promising new class of metal alloys. This project is a study of the defect evolution and fusion fuel retention properties of HEA materials under DEMO-relevant irradiation conditions.

Diffusion, trapping and retention of deuterium was studied by 20 keV 5x10^{16} D/cm^2 implantation to the MoNbTaVW HEA. Same implantation was also performed to the single HEA constituents Mo, Nb, Ta, V, and W, to compare the effect of each element, see Figure 6.3.

Initial results show that:

1) D diffuses fast at room temperature in the HEA material (migration barrier less than about 0.3 eV)

2) Trapping energies of D to vacancy type defects in HEA are larger than about 0.5 eV.

The implications of the results are very interesting and promising concerning the tritium (T) retention in the HEA material as the fusion first wall material. T diffuses quite fast meaning that the probability for tritium build-up and possible hydride formation in the surface layer is small. This together with the literature data that the HEA material shows smaller amounts of defects and material degradation due to irradiation might make the HEA material superior to the presently planned W first wall in the ITER and DEMO machines.

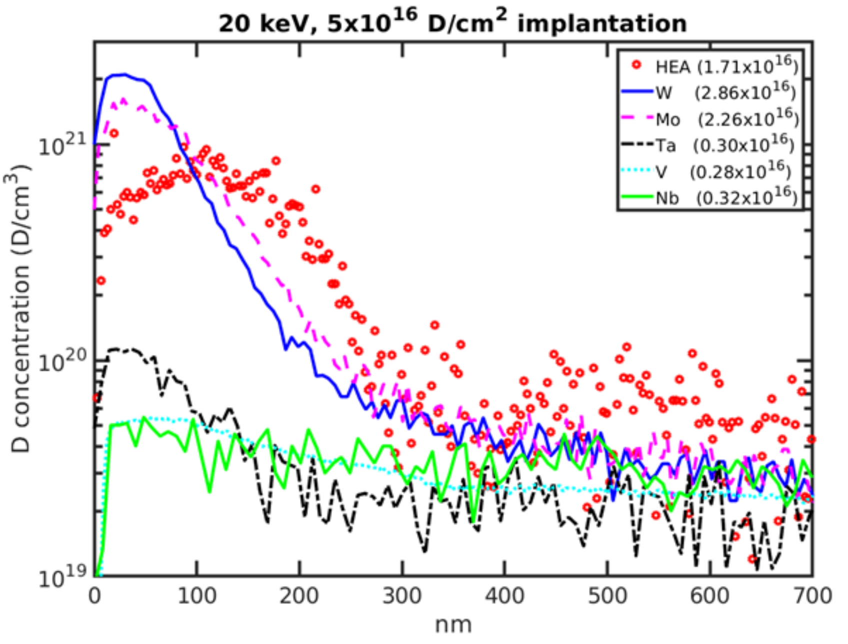

Figure 6.3. SIMS and TOF-ERDA D depth profiles (amounts in parenthesis) in the HEA and single HEA elements.

7. NJOC and PMU

7.1 Overview

Two FinnFusion scientists were seconded to work in the JET operating contract team (NJOC) in 2020. This section highlights the NJOC projects:

- NJOC Viewing and thermal measurements diagnostician, Juuso Karhunen, AU
- NJOC ASCOT Code Responsible Officer, Paula Siren, AU

7.2 NJOC Viewing and thermal measurements diagnostician

Estimation of local plasma conditions in the JET divertor from tomographic reconstructions of deuterium Balmer line emission

Research scientist: J. Karhunen, AU

The Monte Carlo methodology for estimating 2D distributions of the electron density (n_e) and temperature (T_e) from intensity ratios of reflection-corrected tomographic reconstructions of filtered camera images of deuterium Balmer line emission in the JET divertor has been modified to yield also an estimate for the atomic deuterium density (n_0). The knowledge of n_e, T_e and n_0 allows further analysis of the ionization (S_{ion}) and recombination rates (S_{rec}), enabling more accurate local inspection of the divertor plasma conditions between experiments and divertor modelling. The experimental estimates for an L-mode density ramp have been compared to predictions of an EDGE2D-EIRENE density scan during the process of outer divertor detachment.

The experimental estimates and the EDGE2D-EIRENE simulations show qualitative agreement in the behaviour of the divertor conditions at the outer strike point and the sequence of events leading to detachment, marked with points A—E in Figure 7.1 in terms of increasing upstream n_e and decreasing strike-point T_e. The onset of detachment, with the outer target ion current (Φ_{ot}) plateauing at its peak, is observed to coincide with strong decrease in S_{ion} and emerging increase in n_e, n_0 and S_{rec} (point A). This is followed by roll-overs of first Φ_{ot} and n_0 (point B), then n_e (point C) and finally S_{rec} (point D) with deepening detachment. Near the end of the n_e ramp, increases in n_e, n_0, S_{ion} and S_{rec} are observed also above the X-point due to the poloidal extension and shift of their spatial distributions.

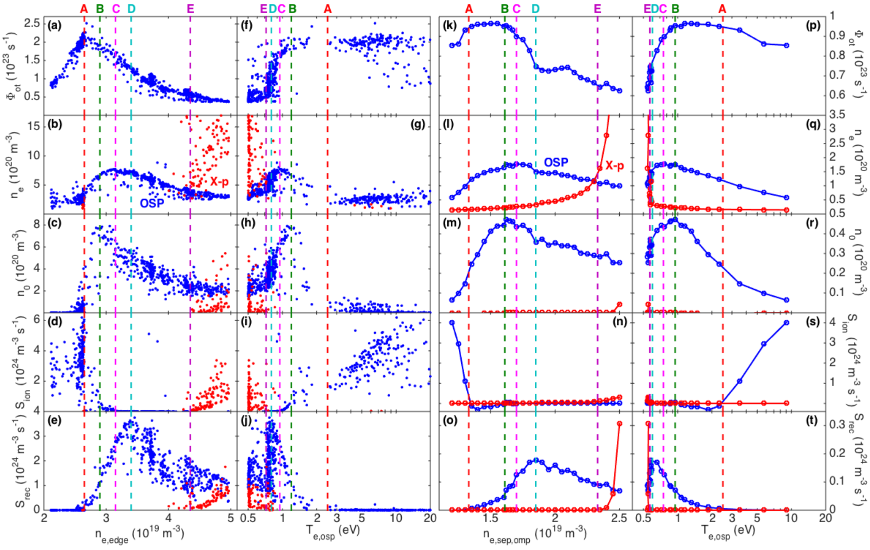

Figure 7.1. Evolution of local plasma conditions at outer strike point (blue, OSP) and above the X-point (red, X-p) is resolved experimentally (a—j) in qualitative agreement with EDGE2D-EIRENE simulations (k—t).

7.3 NJOC ASCOT Code Responsible Officer

Updates for automatic analysis and post-processing of JET neutral particle analysers for TT and DT campaigns

Research scientist: P. Siren, AU

The data processing from both JET neutral particle analyser systems (NPA) have been updated for needs of operating in different scenarios with mixed isotopes in tritium and deuterium plasmas in 2021 campaigns. NPA systems provide the information of neutralised fast ion populations in different energy ranges for H, D, T, ^{3}He and ^{4}He particles and can be used for cross-checking the efficiency of external heating, especially in different RF scenarios with the minor population of energetic particles. Additionally, low energy NPA system is one of the key diagnostics for isotope ratio monitoring in TT and DT campaigns (DTE2). Its capabilities for isotope analysis have been demonstrated during H plasma experiments in 2016 and 2019 and data processing was updated to easy-to-use option during 2020 for fluent process by control room diagnostics experts.

NPA data analysis workflow was systematically applied and demonstrated in scenario development experiments in 2020. Automatic processing includes the data monitoring, neutral particle flux per energy channel (Figure 7.2) and high energy tail temperature fitting. Flux and tail temperature fitting is performed via JETPEAK multipurpose database and modelling environment which provides the pre-checked and filtered information of essential plasma diagnostics. One of its most important benefit is that it is combining the postprocessed information from diagnosticians and modellers for more reliable analysis and tools development.

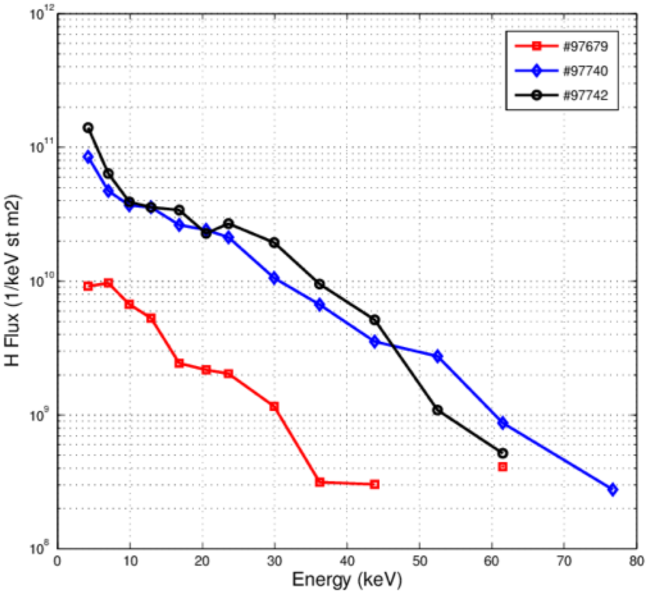

Figure 7.2. High energy H flux in JET hybrid plasma reference pulses estimated based on the low energy NPA data (source: JETPEAK database) used to compare the efficiency of H minority RF heating.

8. International collaborations

8.1 DIII-D tokamak

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

The primary purpose of participating in International Collaborations with DIII-D was to utilise a new, high-resolution ultraviolet (HR-UV) spectrometer in DIII-D, with a single view chord across the outer divertor leg, in planned experiments to resolve deuterium Lyman-Werner band emission. These measurements are critical in determining the impact of ion-molecular interaction on the onset of detachment. Experiments in JET-ILW were performed in 2019 to attempt measuring the Lyman-Werner bands. However, in these JET experiments Lyman-Werner emission remained unresolved due to either the resolution of the UV spectrometer being too low or the bands are not sufficiently excited. The project is part of the Finland-US Fulbright sponsorship and PhD thesis of MSc. Andreas Holm of Aalto University with Lawrence Livermore National Laboratory, California, USA and DIII-D (August 2019 – July 2020).

Due to COVID-19 restrictions and several interventions of DIII-D due to water leaks, the installation and commissioning of HR-UV could not be carried out. Hence, the dedicated experiment to measure the Lyman-Werner bands was postponed until 2021. An analysis tool (CRUMPET) in the edge fluid code pyUEDGE was developed by Andreas Holm to account for both atomic and molecular processes in divertor detachment. For initial test cases, CRUMPET simulations indicate vibrational H_2 populations become comparable to the ground-state H_2 population for plasma temperatures below 6 eV and densities above $1x10^{18}$ m^{-3}.

8.2 JT-60SA

Diagnosing fast ions via fusion neutrons in JT-60SA (part of SA-M.A06-T003-D001)

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

JT-60SA with its cutting-edge NNBI (Negative Neutral Beam Injection) will be invaluable in predicting the performance of the negative beams. Therefore it is of utmost importance that the dynamics of the beam particles can be accurately modelled. The purpose of the SA-M.A06-T004-D001 task, carried out jointly between Aalto University, EPFL and ENEA, was to establish the ASCOT suite of codes as a reliable tool for beam ion simulations in non-trivial magnetic configurations, e.g., in the presence of 3D perturbations, and to evaluate signal to the FILD detector to be installed in the device.

The vacuum magnetic fields were calculated from the geometries and currents in the CS and TF coils using the BioSaw code. The Error Field Correction Coils

(EFCC) perturbations were likewise calculated from the geometries and currents for n = 1, and for different phasing between the three rows. The plasma response was evaluated with the MARS-F code.

The simulations were carried out separately for the NNBI and PNBI systems. Unfortunately, for the fully inductive Scenario-3 where the effect of EFCC was studied, the plasma response was accidentally calculated for a different scenario. Thus this work merely serves the purpose of verifying the procedure. The beam-ion birth distributions calculated for the advanced inductive Scenario 4 are illustrated in Figure 8.1, showing the different deposition from the NNBI (500 keV) and PNBI (85 keV) systems.

ASCOT features a synthetic FILD detector, which allowed a series of simulations where the detector head was moved radially and the sensitivity of losses as well as velocity space coverage were estimated. Furthermore, 'worst-case –scenario' simulations were carried out to estimate maximal beam power loads to the probe head.

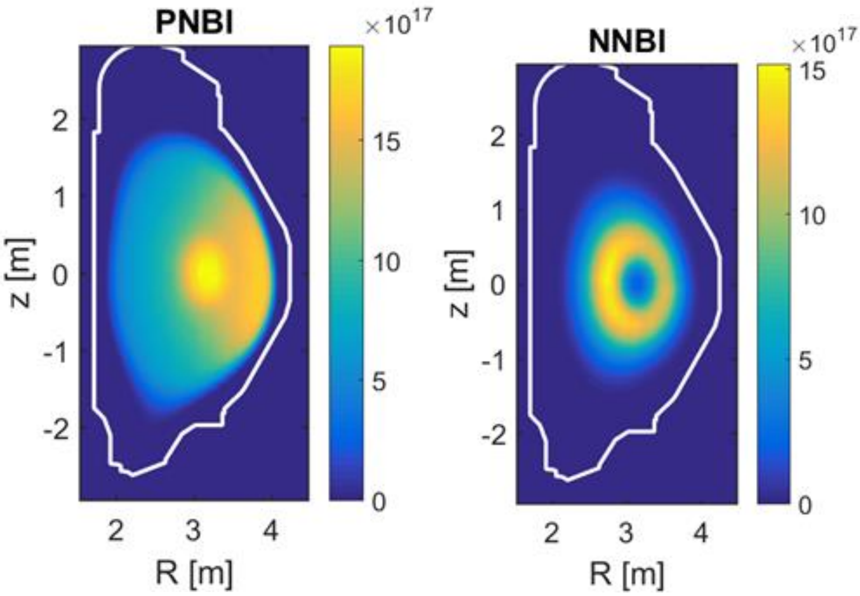

Figure 8.1. Deposition of ions from the 85 keV positive neutral beams (left) and from the 500 keV negative neutral beams (right).

8.3 KSTAR tokamak

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

Capability to externally drive toroidal rotation in larger future fusion devices such as ITER will be significantly smaller than in present day experiments. Since rotation has been found beneficial for stability and confinement it is important to be able to predict and optimize plasma intrinsic rotation. Intrinsic rotation has been observed to appear spontaneously without any external torque sources but its physics and scaling towards ITER are still very much uncertain. Estimations from minute to significant rotation in ITER have been presented. To clarify the situation, ITPA Transport and Confinement group is advocating multi-machine experiments to investigate the ρ^* scaling of the intrinsic torque (TC-17) to enable more confident rotation extrapolations and predictions for ITER.

Previously ρ^* scans between JET, DIII-D and AUG, at matched β_N, q and υ^*, have been performed. This year, the first successful perturbative momentum transport on Korean super conducting KSTAR tokamak was achieved. The experiment utilized modulated neutral beam (NB) torque to create a small but measurable rotation modulation in plasmas with >5s of steady state. Careful analysis using the perturbed data and high resolution TRANSP calculated NBI torque will be used to infer the plasma intrinsic torque causing intrinsic plasma rotation. Should the proof-of-principle analysis show sufficient promise future experiments, with scans in relevant dependent parameters, will be proposed to allow more elaborate physics insights.

9. Fusion for Energy activities

9.1 Preliminary Design of Remote Handling Connector and Ancillary Components

F4E grant: F4E-OPE-0829

Research scientists: J. Alanen, T. Avikainen, P. Kilpeläinen, J. Koskinen, J. Lyytinen, T. Malm, H. Martikainen, T. Määttä, J. Pennanen, S. Rantala, H. Saarinen, P. Tikka, VTT

Remote Handling Connector (RHC) system is part of ITER in-vessel diagnostics system. RHC is located in the inboard position for the central divertor cassettes and in the outboard position for the other divertor cassettes. Mineral insulated cables route the electrical diagnostics sensor signals from the divertor area to the diagnostic hall. The operating space of RHC is limited and the environmental conditions include ultra-high vacuum, baking temperature of 350 °C, irradiation and challenging electromagnetic forces. The system is connected via remote handling.

VTT has continued the work on the Preliminary Design of Remote Handling Connector and Ancillary Components. The preliminary design is based on the conceptual design of Outboard and Inboard Configurations pictured in Figure 9.1. The design was presented at the Virtual Symposium on Fusion Technology (SOFT) 2020 conference and a paper was accepted for Fusion Engineering and Design journal published in 2021.

The developed system was evaluated at a preliminary design review meeting. The current focus of the project continues in the closure of the PDR phase by resolving chits raised during the review meeting. The main challenges in the development are in the analysis of the connector structure and the flexible cables. The design is balancing between contradictory requirements such as thermal management and electromagnetic forces, as well as the space for remote handling and space for cable routing. The aim is to provide the baseline for the final design of the RHC system estimated to start in 2021.

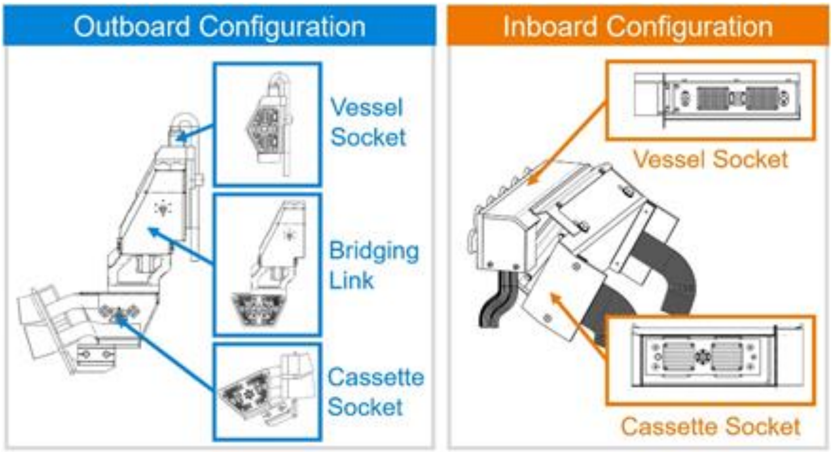

Figure 9.1 Architecture for Outboard and Inboard Configuration.

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

F4E grant: F4E-GRT-0901

Research scientists: J. Alanen, J. Minkkinen, O. Rantanen, H. Saarinen, VTT
L. Aha, I. Ali, M.M. Aref, L. Gonçalves Ribeiro, A. Gotchev, L. Hulttinen, J. Mattila, M. Mohammadkhanbeigi, J. Mäkinen, L. Niu, O. Suominen, 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. The development tasks are coordinated and carried out by VTT. The RDS is used to investigate the health of the RH devices based on diagnostics rules created by the operators, and to archive the diagnostics data. The Remote Diagnostics Application software was released in the end of 2019. The C&C is the operator user interface application to control the movement of the RH robots. During 2020, the C&C was implemented by GTD, a Spanish system and software engineering company, and ported to VTT for integrating it into the control system of the Cassette Multifunctional Mover (CMM) at the Divertor Test Platform (DTP2) hosted by VTT. The VR application is used to monitor the movements of the CMM robot in real-time, especially where camera views are not possible. In 2020, the legacy VR application was integrated into CMM Control Network.

A development of another RHCS subsystem, Computer Assisted Teleoperation, was coordinated by Tampere University. The purpose of this task was to further develop the 3D Node system designed and demonstrated in the previous Grant F4E-GRT-0689. The 3D Node system detects a target, e.g. the Remote Handling (RH) Equipment, and recognizes its position and orientation in a relation to its environment using camera images. The study aimed to recognize the RH Equipment with high accuracy (< 3mm). Also a study on the usage of radiation tolerant markers was included in the task. The Tampere University studies ended at the end of 2019, and from the management point of view the Tampere University task ended in the beginning of 2020.

9.3 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

A novel control technique of hydraulics, namely water hydraulics, has been developed at Tampere University. It is called “digihydraulics”. This far accurate control of hydraulic actuators has been done using servovalves, which are sensitive to temperature, impurities (size > 3 µm) and many others. They can in many cases be replaced with a group of redundant, fault tolerant On-Off -valves, which can be set to produce needed servo-like output flow. The group of valves is called “digivalve”. However, the technology is not mature yet. Some oil hydraulic applications have been made but commercial water hydraulic applications or components do not exist yet. F4E is interested in digihydraulics for some high-precision devices, like ITER divertor cassette maintenance system and hydraulic manipulators.

In VTT laboratory, DTP2 -platform, divertor maintenance system for ITER fusion device has been tested and developed further. The system was originally made to operate with typical water hydraulic valves, also with servo valves. The servo valves have sometimes jammed and caused problems, so they are now replaced with digivalves.

On DTP2 platform, the transportation robot carries the divertor cassette in to the reactor vessel and moves it sideways, about one cassette width, away from the reactor “door”. For correct, pre-planned and safe motion trajectory, the cassette is lifted, the cassette “nose” is rotated up a bit, and the cassette is moved sideways. All those motions take place at the same time and planned speed, so that the trajectory of the cassette motion follows the pre-planned path.

Original system with servovalves was able to follow planned trajectory within a couple of millimetres accuracy; the maximum error was 3 mm. Next test drives will show how accurately the hydraulic system with digivalves will follow the trajectory (see Figure 9.2). The digivalves under testing have been developed, tested and improved in various test installations, or as a plain digivalve, at Tampere University since 2017. The tests have shown very good performance.

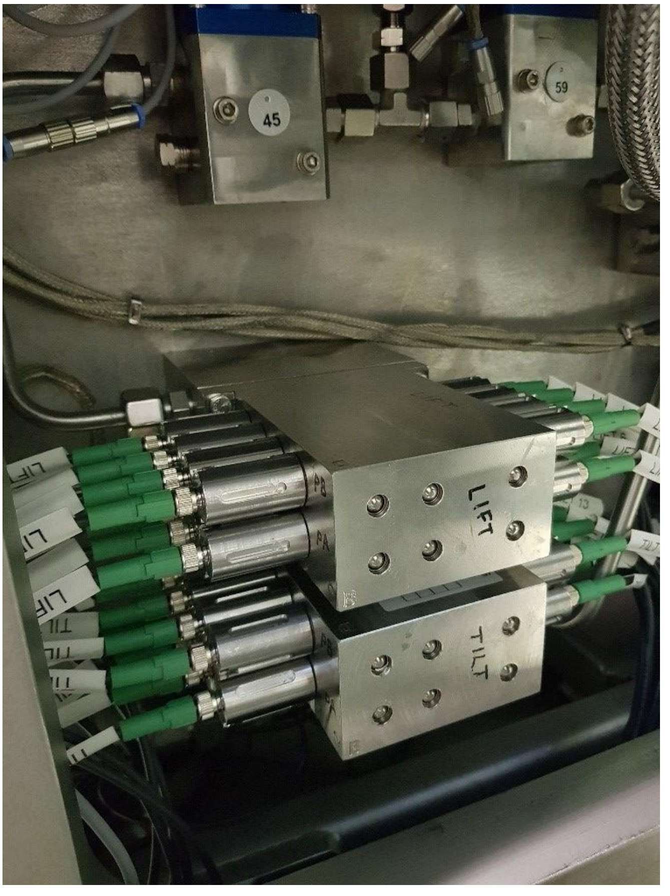

Figure 9.2. Two servovalves have been replaced by two digivalves (steel blocks). Each valve block consists of 16 separately controlled on-off -valves.

10. Code development in FinnFusion

10.1 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, moreover reactor models together with corresponding automation systems have been thoroughly tested for a variety of nuclear units. The simulation model is configured with a graphical user interface (see Figure 10.1).

Within EUROfusion, several alternatives of Balance-of-Plant (BoP) configurations have been developed and investigated during the Pre-conceptual Design Phase of DEMO. Dynamic simulations with Apros have played an important part in this development process and in the down-selection of alternatives moving into the Conceptual Design Phase. BoP design alternatives comprise large or a small energy storage system (ESS) with molten salt (HITEC) between the Primary Heat Transfer System (PHTS) and the Power Conversion System (PCS), or a direct coupling between the PHTS and PCS, equipped with auxiliary power generating or power storage systems for both breeding blanket options, WCLL and HCPB. The analyses have been concentrated on normal operation of the main systems of BoP during the pulsed operation of the tokamak, where the integrated operation and feasibility of the design alternatives have been evaluated.

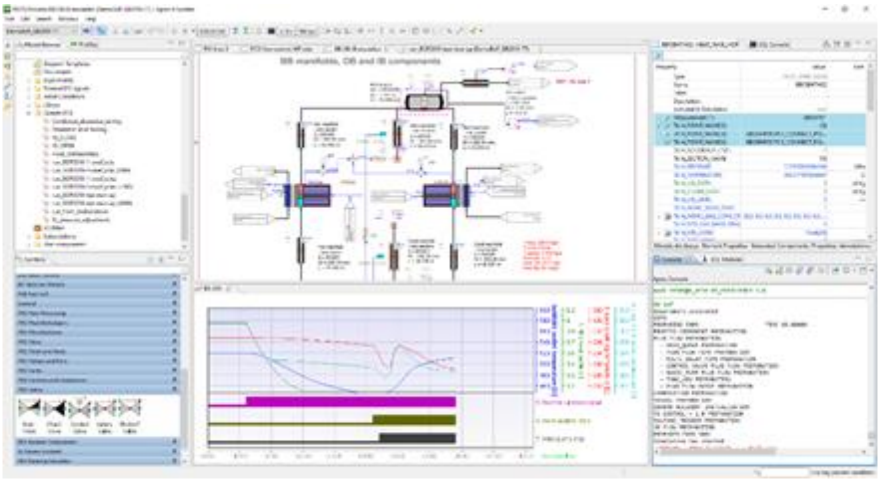

Figure 10.1. Apros user interface

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

Research Scientists: T. Kurki-Suonio, S. Äkäslompolo, AU

The code development in the ASCOT group continues on several fronts. Multiple incremental enhancements have been made to the new ASCOT5 suit of codes. A major endeavour is the pursuance of GPU porting of ASCOT5 in collaboration with the EUROfusion high level support team (HLST). Currently, ASCOT5 is parallelized using OpenMP and MPI libraries. The feature to offload computations to GPUs with OpenMP is a new and developing feature in the compilers, and the work done is at the very cutting edge of the available technology. Thus, each step in the porting process needs research and testing. At the end of the year, ASCOT5-GPU was performing adequately on the EUROfusion Marconi100 GPU platform with the xlC compiler. Other tested compilers did not seem to provide satisfactory performance. At the moment, ASCOT5-GPU seems suitable for short simulations of a very large number of markers.

10.3 Full-f gyrokinetic turbulence code ELMFIRE

Research scientists: L. Chôné, E.Hirvijoki, T. Kiviniemi, A.Virtanen, AU

Development of ELMFIRE code has focused on building a new 6-D electromagnetic particle-in-cell code. The code is based on variational discretization of the Vlasov-Maxwell action principle and a metriplectic discretization of the Landau collision operator. Consequently, the Vlasov-Maxwell solver guarantees long-term stability for both energy and local charge conservation and the Landau solver guarantees discrete-time energy and momentum conservation and entropy dissipation. Both parts have been tested as separate GPU implementations and work is on-going to develop a high-performance version compatible with the new CSC LUMI machine. Two publications have already emerged from this development work and initial physics benchmarks have been performed (see Figure 10.2 for temporal evolution of ETG turbulence in slab geometry).

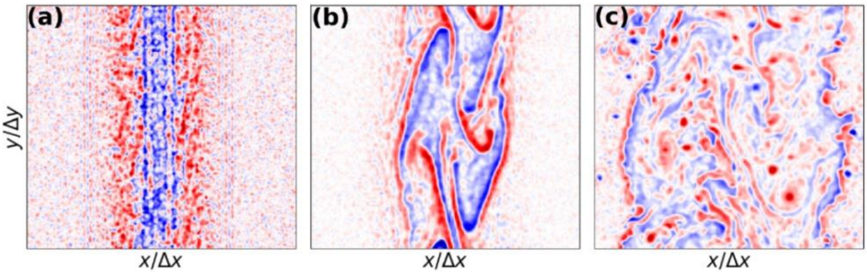

Figure 10.2. Temporal evolution of density fluctuations in ETG turbulence.

10.4 Molecular Dynamics

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

The long-running work on using molecular dynamics to model plasma-material interactions in fusion reactors reached a really important new result in 2020. Working closely together with the Max-Planck Institute for Plasma physics in Garching and the Technical University of Vienna, we showed that in metals, the local micrometer-scale surface crystal orientation can have a strong (around a factor of 5) effect on surface erosion rate (see Figure 10.3). This can make the materials roughen and cause local differences in sputtering yields, factors that may affect the planning of how to control precisely the edge plasma and materials erosion in fusion reactors.

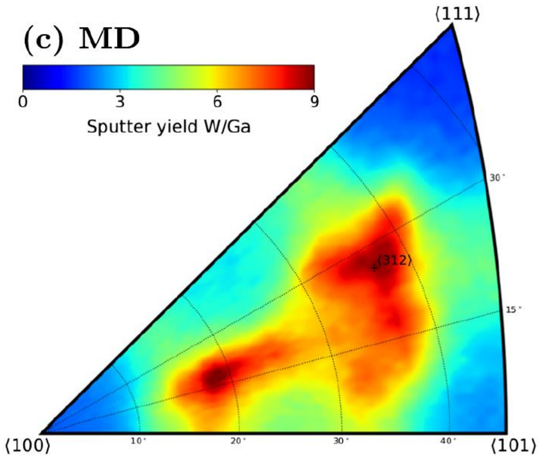

Figure 10.3. Dependence of sputtering yield on surface crystal orientation determined from molecular dynamics simulations. Experiments gave essentially identical results.

10.5 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 2020 Serpent has been used under PPPT task PMI-7.5 (see chapter 3.3). Main aim was to simulate neutron transport and tritium production in the new WCLL TBM mock-up. A Serpent 2 model for the mock-up, including realistic geometry and material composition, was finalized.

11. Other activities

11.1 Missions and secondments

Antti Hakola to IPP Garching, Garching, Germany, 13–15 January 2020 (WP MST1).

Tuomas Tala and Antti Salmi to NFRI/KSTAR, Daejeon, Korea, 15–24 January 2020 (WPIC).

Antti Hakola to IPP Garching, Garching, Germany, 20–23 January 2020 (WP MST1).

Jari Likonen to IPP Garching, Garching, Germany, 3–5 February 2020 (WP MST1).

Antti Hakola to IPP Garching, Garching, Germany, 3–6 February 2020 (WP MST1).

Tuomas Tala and Antti Salmi to DIFFER, Eindhoven, the Netherlands, 9–11 February 2020 (WPENR).

Jari Likonen to JET facilities, United Kingdom, 11– 20 February 2020 (WP JET2).

Mathias Groth to DIII-D/General Atomics, San Diego, California, USA, 13 Febuary – 3 March 2020 (International Collaborations).

Antti Hakola to IPP Garching, Garching, Germany, 17–20 February 2020 (WP MST1).

Antti Hakola to IPP Garching, Garching, Germany, 25 February–5 March 2020 (WP MST1).

Tuomas Tala and Antti Salmi to JET, Culham, UK, 8–12 March 2020 (WPJET1).

11.2 Conferences, seminars, workshops and meetings

Mathias Groth participated in the 28th ITPA Divertor and Scrape-Off Layer and the PSI 2020 Program Committee meetings in Jeju, South Korea, 13–17 January 2020.

Leena Aho-Mantila, Markus Airila, Fredric Granberg, Mathias Groth, Antti Hakola, Etienne Hodille, Niels Horsten, Henri Kumpulainen, Roni Mäenpää and Kai Nordlund participated in the EUROfusion Joint Working Session on SOL and PSI Modelling, Tervaniemi, Finland, 28–21 January 2020.

Jari Likonen participated in the WPJET2 Meeting on Ion Beam Analysis of Plasma-Facing Components from JET-ILW, Instituto Superior Técnico Lisbon, Bobadela Campus, Portugal, 3–4 March 2020 (WP JET2).

Tuomas Tala participated in the F4E Governing Board meeting (virtual), 3 April 2020.

Tuomas Tala participated in the EUROfusion General Assembly meeting (virtual), 7–8 April 2020.

Seppo Sipilä participated in the second week of the WPCD Summer General 2020 Code Camp (virtual) 15–19 June 2020 (WPCD).

Tuomas Tala participated in the ITPA Transport and Confinement meeting (virtual), 29 June–3 July 2020 (WPIC).

Tuomas Tala participated in the EUROfusion General Assembly meeting (virtual), 6–7 July 2020.

Tuomas Tala participated in the F4E Governing Board meeting (virtual), 9–10 July 2020.

Tuomas Tala participated in the F4E Governing Board meeting (virtual), 29 September 2020.

Eero Hirvijoki participated in the Theory of Fusion Plasmas: Joint Varenna-Lausanne International Workshop (virtual), 12–16 October 2020.

Antti Hakola participated remotely in the ASDEX Upgrade Programme Seminar, 12–16 October, 2020.

Mathias Groth, Antti Hakola and Jari Likonen participated in the 29th ITPA Divertor and Scrape-Off meeting (virtual), 12–22 October 2020.

Eero Hirvijoki participated in the Numerical Methods for the Kinetic Equations of Plasma Physics (NumKin 2020) workshop (virtual), 19–23 October.

Tuomas Tala participated in the ITPA Transport and Confinement meeting (virtual), 19–23 October 2020 (WPIC).

Tuomas Tala participated in the EUROfusion General Assembly meeting (virtual), 27–28 October 2020.

Antti Hakola and Jari Likonen participated remotely in the WP JET2-WP PFC Annual Meeting, 9–10 November 2020.

Antti Hakola participated remotely in the EFPW meeting, 2–4 December 2020.

Antti Hakola and Jari Likonen participated remotely in the WP TE Programme Meeting, 7–9 December 2020.

Laurent Chôné participated in the Supercomputing 2020 conference (virtual), 9–19 November 2020.

Tuomas Tala participated in the F4E Governing Board meeting (virtual), 9–10 December 2020.

Tuomas Tala participated in the EUROfusion General Assembly meeting (virtual), 14–15 December 2020.

Publications 2020

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

11.3 Publications

11.3.1 Refereed journal articles

1. H. Q. Wang, H. Y. Guo, G. S. Xu, A. W. Leonard, X. Q. Wu, M. Groth, A. E. Järvinen, J. G. Watkins, T. H. Osborne, D. M. Thomas, D. Eldon, P. C. Stangeby, F. Turco, J. C. Xu, L. Wang, Y. F. Wang, J. B. Liu, First Evidence of Local E x B Drift in the Divertor Influencing the Structure and Stability of Confined Plasma near the Edge of Fusion Devices, Physical Review Letters **124** (2020) 195002.

2. K. Schlueter, K. Nordlund, G. Hobler, M. Balden, F. Granberg, O. Flinck, T. F. da Silva and R. Neu, Absence of a Crystal Direction Regime in which Sputtering Corresponds to Amorphous Material, Physical Review Letters**125** (2020) 225502.

3. F. Tuomisto, I. Makkonen, J. Heikinheimo, F. Granberg, F. Djurabekova, K. Nordlund, G. Velisa, H. Bei, H. Xue, W. J. Weber, Y. Zhang, Segregation of Ni at early stages of radiation damage in NiCoFeCr solid solution alloys, Acta Materialia **196** (2020) 44.

4. A. Hamedani, J. Byggmästar, F. Djurabekova, G. Alahyarizadeh, R. Ghaderi, A. Minuchehr and K. Nordlund, Insights into the primary radiation damage of silicon by a machine learning interatomic potential, Materials Research Letters **8** (2020) 364.

5. N. Vianello, D. Carralero, C. K. Tsui, V. Naulin, M. Agostini, I. Cziegler, B. Labit, C. Theiler, E. Wolfrum, D. Aguiam, S. Allan, M. Bernert, J. Boedo, S. Costea, H. De Oliveira, O. Fevrier, J. Galdon-Quiroga, G. Grenfell, A. Hakola, C. Ionita, Scrape-off layer transport and filament characteristics in high-density tokamak regimes, Nuclear Fusion **60** (2020) 16001.

6. A. Hollingsworth, M. Lavrentiev, R. Watkins, A. Davies, S. Davies, R. Smith, D. Mason, A. Baron-Wiechec, Z. Kollo, J. Hess, I. Jepu, J. Likonen, K. Heinola, K. Mizohata, E. Meslin, M.-F. Barthe, A. Widdowson, I. Grech, K. Abraham, E. Pender, Comparative study of deuterium retention in irradiated Eurofer and Fe–Cr from a new ion implantation materials facility,Nuclear Fusion **60** (2020) 16024.

7. H. Weisen, E. Delabie, J. Flanagan, C. Giroud, M. Maslov, S. Menmuir, A. Patel, S. Scott, P. Sirén P and J. Varje, Analysis of the inter-species power balance in JET plasmas, Nuclear Fusion **60** (2020) 36004.

8. A. E. Järvinen, S. L. Allen, D. Eldon, M. E. Fenstermacher, M. Groth, D. N. Hill, C. J. Lasnier, A. W. Leonard, A. G. McLean, A. L. Moser, G. D. Porter, T. D. Rognlien, C. M. Samuell, H. Q. Wang, J. G. Watkins, Progress in DIII-D towards validating divertor power exhaust predictions, Nuclear Fusion **60 (**2020) 56021.

9. S. Mordijck, T. L. Rhodes, L. Zeng, A. Salmi, T. Tala, C. C. Petty, G. R. McKee, R. Reksoatmodjo, F. Eriksson, E. Fransson and H. Nordman, Collisionality driven turbulent particle transport changes in DIII-D H-mode plasmas, Nuclear Fusion **60** (2020) 66019.

10. H. Reimerdes, R. Ambrosino, P. Innocente, A. Castaldo, P. Chmielewski, G. Di Gironimo, S. Merriman, V. Pericoli-Ridolfini, L. Aho-Mantilla, R. Albanese, H. Bufferand, G. Calabro, G. Ciraolo, D. Coster, N. Fedorczak, S. Ha, R. Kembleton, K.

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11.3.2 Conference presentations

69. V. Solokha, M. Groth, S. Brezinsek, M. Brix, G. Corrigan, C. Guillemaut, D. Harting, S. Jachmich, U. Kruezi, S. Marsen and S. Wiesen Isotope effect on detachment in JET-ILW Ohmic plasmas, 28th ITPA-DSOL meeting, Jeju, South Korea, 13–16 January 2020.

70. V. Solokha, M. Groth, S. Brezinsek, M. Brix, G. Corrigan, C. Guillemaut, D. Harting, S. Jachmich, U. Kruezi, S. Marsen and S. Wiesen Isotope effect on detachment in JET-ILW Ohmic plasmas, EUROfusion Joint Working Session on SOL and PSI Modelling Tervaniemi, Finland, 28–21 January 2020.

71. L. Hulttinen and J. Mattila, Flow-limited path-following control of a double Ackermann steered hydraulic mobile manipulator, The 2020 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM 2020), Boston, USA, 6–10 July 2020, virtual.

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74. N. Christen, M. Barnes, H. Weisen, P. Siren, Reconstructing NBI-driven rotation profiles with the local gyrokinetic code GS2, 62nd Annual Meeting of the APS Division of Plasma Physics, 9–13 November 2020, virtual, paper VP14.00013.

11.3.3 Research reports

75. J. Likonen (ed.), FinnFusion Yearbook 2019, VTT Technology **375** (2020).

11.3.4 Academic theses

76. Jesper Byggmästar, Analytical and machine-learning interatomic potentials for radiation damage in fusion reactor materials, Doctoral Thesis, University of Helsinki, Helsinki 2020.

77. Longchuan Niu, Improving the Visual Perception of Heavy Duty Manipulators in Challenging Scenarios, Doctoral Thesis, Tampere University, Tampere 2020.

78. Essi Immonen, Utilizing design phase PRA modelling to verify fulfillment of safety objectives of Fusion Materials Irradiation Facility, MSc thesis, Aalto University, Espoo 2020.

79. Henrik Nortamo, Implementation of structure-preserving plasma simulatíon using a scalable framework, MSc thesis, Aalto University, Espoo 2020.

80. Antti Virtanen, ELMFIRE predictions of the bootstrap current profile in the JET pedestal region, MSc thesis, Aalto University, Espoo 2020.

81. Henri Brax, Interpretive ERO Modelling of Beryllium Migration in the JET Divertor, BSc thesis, Aalto University, Espoo 2020.

82. Atso Ikäheimo, Fast-ion heat load on ICRH antenna in W7-X stellarator, BSc thesis, Aalto University, Espoo 2020.

83. Heikki Systä, Simulating the effect of a poloidally localized neutral particle source on bootstrap current in the pedestal region, BSc thesis, Aalto University, Espoo 2020.

84. Lauri Toivonen, Simulating charge exchange losses of beam ions in the TCV tokamak, BSc thesis, Aalto University, Espoo 2020.

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Title	**FinnFusion Yearbook 2020**
Author(s)	Jari Likonen (Ed.)
Abstract	This Yearbook summarises the 2020 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 with projects focusing on tokamak experiments and modelling; (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, CSC - IT Center for Science Ltd.,Fortum Power and Heat Ltd., Lappeenranta-Lahti University of Technology, 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, materials research, plasma-facing components and remote maintenance. F4E projects in 2020 focused on system level design for ITER Remote Handling Connector, 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 15 PhD students in FinnFusion member organizations. In addition, one EUROfusion post-doctoral research and engineering fellowship was running in 2020. In 2020, FinnFusion organized a EUROfusion working session on edge plasma modelling in Tervaniemi. The FinnFusion annual seminar was cancelled due to the COVID-19 pandemic.
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Tiivistelmä	Tähän vuosikirjaan on koottu FinnFusion-konsortion vuoden 2020 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 tarjoamalla erityisesti tokamak-kokeisiin ja mallinnukseen liittyvää osaamista; (iii) seuraavan sukupolven eurooppalaisen DEMO-fuusiovoimalan konseptikehitys. FinnFusion-konsortion muodostavat Teknologian tutkimuskeskus VTT Oy, Aalto-yliopisto, CSC - Tieteen tietotekniikan keskus Oy, Fortum Power and Heat Oy, Helsingin yliopisto, Lappeenrannan-Lahden teknillinen yliopisto, Tampereen yliopisto ja Åbo Akademi. FinnFusion-konsortio osallistuu useisiin EUROfusion-projekteihin. Suurin työpanos kohdistuu JET- ja ASDEX Upgrade -koelaitteissa tehtäviin kokeisiin ja analyyseihin, materiaalitutkimukseen, ensiseinämäkomponentteihin ja etäkäsittelyyn. FinnFusionin F4E-työt liittyivät ITERin etäkäsittelyn järjestelmätason suunnitteluun (Remote Handling Connector, Digivalve) ja etäkäsittelyn ohjelmistokehitykseen. EUROfusion tukee jatko-opiskelua omalla rahoitusinstrumentillaan, jonka turvin FinnFusion rahoitti osittain 15 jatko-opiskelijan työtä jäsenorganisaatioissaan. Lisäksi vuoden 2020 aikana oli käynnissä yksi EUROfusionin rahoittama tutkijatohtorin projekti. FinnFusion järjesti Suomessa v. 2020 EUROfusionin reunamallinnukseen liittyvän kokouksen Tervaniemessä. COVID-19 pandemian vuoksi vuosittainen fuusioalan vuosiseminaari jouduttiin peruuttamaan.
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FinnFusion Yearbook 2020

Jari Likonen (Ed.)

This Yearbook summarises the 2020 research and industry activities of the FinnFusion Consortium. FinnFusion participates in several EUROfusion work packages, the largest being experimental campaigns at European Medium-size tokamaks and JET and related analyses, as well as materials research, plasma-facing components and remote maintenance.

EUROfusion supports post-graduate training through the Education work package that allowed FinnFusion to partly fund 15 PhD students in FinnFusion member organizations. In addition, one EUROfusion post-doctoral research and engineering fellowship was running in 2020.

F4E projects in 2020 focused on system level design for ITER Remote Handling Connector, on the development of the High Level Control System subsystems for ITER Remote Handling System and on the development of digihydraulics for the divertor maintenance system for ITER.

In 2020, FinnFusion organized a EUROfusion working session on edge plasma modelling in Tervaniemi. The FinnFusion annual seminar was cancelled due to the COVID-19 pandemic.

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