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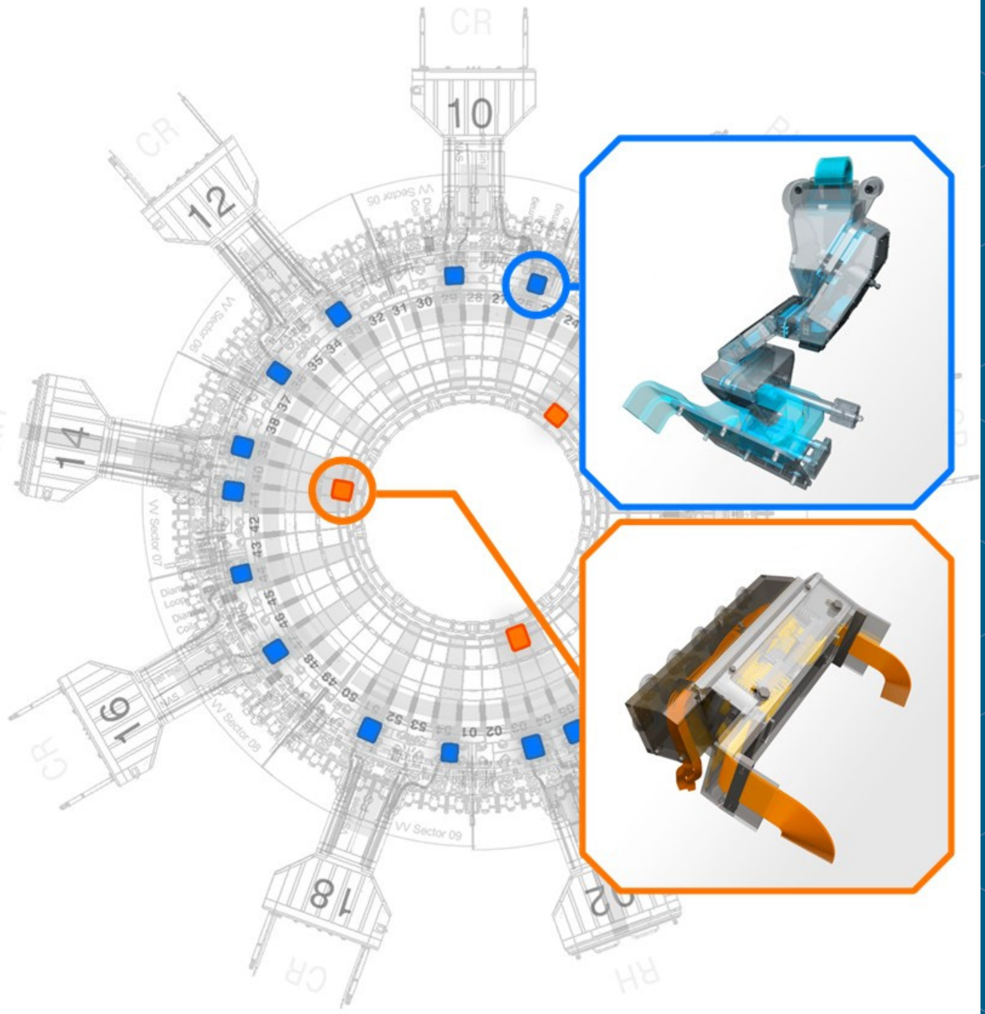
the obvious



FinnFusion Yearbook 2019

Jari Likonen (Ed.)

VTT TECHNOLOGY 375

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PunaMusta Oy, Helsinki 2020

Preface

“This is a great day for ITER, and a great day for the whole ITER team – you have built the main building of ITER to the point where we can install the core of the machine, starting with the Cryostat Base. To make it simple, the ITER tokamak building is completed, with some ‘small’ finishing works left.” This is citing Johannes Schwemmer’s words, the director of Fusion for Energy, on 30 March, 2020. This journey of constructing the tokamak building started in 2008, when the procurement arrangement was drafted with a small team of IO and F4E staff, followed by the technical specifications in order to put in place contracts to enable the ITER Buildings construction. One year ago, a Monte Carlo analysis of finishing the building project on schedule showed less than 1% of chance of success to meet this ITER Council milestone by the end of March 2020 – but still it happened! This was a very positive news from ITER as this 619M€ project is one of the largest projects during its construction phase.

It is fantastic to hear such good news in these times when uncertainties are all around, also in fusion research, due to worldwide COVID-19 pandemia. Most of the fusion labs are not operating their tokamaks or devices right now, and many sites are fully closed. We do not know when the already scheduled DT-operation in JET can take place. The European fusion research is stepping towards the Horizon Europe Framework Program in 2021-2027 under uncertain times. But as the fusion research community, we can try to exploit the new opportunities when many of our regular duties are not possible – we have more time to analyse data from past experiments and dedicate more time to writing scientific articles, and even more importantly, we have more time to think about something new and develop new ideas beyond the daily businesses. And this is certainly the approach we have taken here in Finland, to encourage to initiate interdisciplinary projects and challenges and further expand the FinnFusion collaboration into new areas of expertise.

What lies behind public acceptance of fusion? A European survey with some 20 000 citizens recruited from national online panels was carried out within EUROfusion to understand Europeans’ attitudes towards fusion energy research in 21 countries. The survey shows that the overall evaluation of fusion is partially independent from beliefs and emotions. It can be partially predetermined. Attitudes towards nuclear and towards science are very important determinants of attitude towards fusion. Finland turned out to be one of the three most supportive countries towards fusion research in Europe, which is a good piece of news to FinnFusion.

In June, the 3rd Joint Nordic Fusion Seminar was hosted by the Danish Technical University in Copenhagen. 21 participants from Finland and 75 participants in total were present to enhance the Nordic collaboration further in various fields of fusion research. In addition to the regular scientific and technical talks by researchers, there were talks from the Danish ministry and EUROfusion leadership. It was also possible to visit the NORTH tokamak. NORTH is a newly installed tokamak located in DTU and is also the most northern tokamak inside EU. FinnFusion started the fruitful collaboration with the NORTH team by testing temperature measurements with an optical fibre during the NORTH discharges in December 2019. FinnFusion organised the first DEMO workshop together with EUROfusion at VTT in Espoo in February. The goal of the workshop was to identify specific routes at making fusion commercially viable, programmatic risks associated with particular technologies, and remaining gaps between DEMO and a commercial fusion power plant. The workshop was by invitation only and had 52 participants including representatives from the EU Commission and most of the EUROfusion leadership. Moreover, FinnFusion organised the ITPA meeting on energetic particles in Rovaniemi in April. The exotic location attracted 40 participants to Lapland. In addition to 34 presentations on ITER physics topics, the participants enjoyed the Lappish winter by ice-hole swimming, cross-country skiing and photographing the northern lights.

Looking ahead toward the next European Framework Program FP9 in 2021-2027, there are many opportunities to take, but of course lots of uncertainties and challenges also to face. The FP9 budget is being discussed right now and the COVID-19 pandemia creates an extra complication there. On the other hand, the changeover of the framework program creates new possibilities to enhance our expertise and networks and initiate new projects and directions. Nationally we are working hard to gain more resources into fusion research and revive the F4E/ITER ILO activities so that both the Finnish fusion R&D and industry activities will have the optimum opportunities to maximize the benefits from the European fusion research.

Last but not least, stay healthy and energetic notwithstanding the current unusual circumstances, and enjoy all the opportunities we will have ahead in fusion research!

Tuomas Tala

Tuomas Tala
Head of Research Unit
FinnFusion Consortium

Contents

Abstract

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
DD	Deuterium-deuterium
DEMO	Future demonstration fusion power plant
DIV	Divertor
DONES	DEMO oriented neutron source
DT	Deuterium-tritium
DTP2	Divertor test platform phase 2 (test facility in Tampere)
EAST	Experimental Advanced Superconducting Tokamak
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

FT-2	Tokamak facility
HCPB	Helium Cooled Pebble Bed
HLT	High-level topic
HPC	High-performance computing
IAEA	International Atomic Energy Agency
ICRH	Ion cyclotron resonance heating
IFMIF	International Materials Irradiation Facility (under design)
IHTS	Intermediate heat transfer system
ILW	ITER-like wall
IMAS	ITER Integrated Modelling and Analysis Suite (collection of codes)
IPP	Institut für Plasmaphysik, Garching/Greifswald
ITER	Next step international tokamak experiment under construction in Cadarache, France (“the way” in Latin)
ITPA	International Tokamak Physics Activity
JET	Joint European Torus (tokamak facility)
JINTRAC	Set of plasma simulation codes
KSTAR	Korea Superconducting Tokamak Advanced Research (tokamak facility)
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)
MEAE	Ministry of Economic Affairs and Employment (in Finland)
NBI	Neutral beam injection
NJOC	New JET Operating Contract
OKMC	Object Kinetic Monte Carlo
PCS	Power conversion system
PDR	Preliminary Design Review
PFC	Plasma-facing component
PHTS	Primary heat transfer system
PIC	Particle-in-cell (plasma simulation method)
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
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.

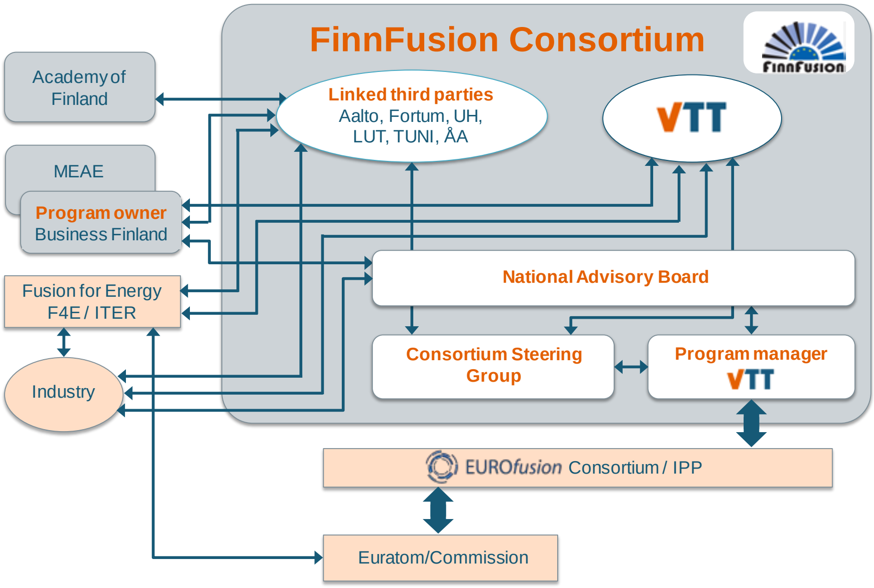


Figure 1.1. Organigram of Finnish Fusion Research Community in 2015–2020.

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 2019:

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), MSc. Toni Kaltiaisenaho, Mrs. Anne Kemppainen (administration), Prof. Jaakko Leppänen, Dr. Jari Likonen, MSc. Sixten Norrman, Dr. Antti Salmi, Dr. Paula Sirén, Dr. Marton Szogradi

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

Activities: Remote handling, DTP2
Members: MSc. Jarmo Alanen (Project Manager), Dr. William Brace (Project Manager), Tech. Vesa Hämäläinen, MSc. Hannu Martikainen, MSc. Joni Minkkinen, Dr. Ali Muhammad, MSc. Teemu Mätäsniemi, Dr. Timo Määttä (Project Manager), MSc. Olli Rantanen, MSc. Hannu Saarinen, MSc. Karoliina Salminen, Lic.Tech. Mikko Siuko, MSc. Petri Tikka, Dr. Risto Tiusanen

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, Dr. Niels Horsten, Dr. Juuso Karhunen, Dr. Timo Kiviniemi, MSc. Joona Kontula, Dr. Taina Kurki-Suonio, Dr. Susan Leerink, Dr. Seppo Sipilä, Dr. Antti Snicker, MSc. Ivan Paradela Perez, Dr. Konsta Särkimäki, MSc. Vladimir Solokha, MSc. Jari Varje, MSc. Andreas Holm, MSc. Henri Kumpulainen, MSc. Patrik Ollus, MSc. Filippo Zonta
Students: Lukas Baker, Eerkko Ihalainen, Atte Keitaanranta, Joel Kilpeläinen, Markus Lehtisalo, Peetu Luotonen, Roni Mäenpää

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

Activities: Robotics
Members: Prof. Heikki Handroos (Project Manager), MSc. Changyang Li, MSc. Ming Li, Prof. Huapeng Wu, MSc. Shayan Moradkhani

Tampere University (TUNI)

Activities: Remote handling, DTP2
Members: MSc. Liisa Aha, MSc. Lionel Hulttinen, Dr. Janne Koivumäki, Prof. Jouni Mattila (Project Manager), MSc. Pauli Mustalahti, MSc. Longchuan Niu, MSc. Sergey Smirnov, MSc. Jyrki Tammisto, MSc. Jukka Väyrynen

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, Dr. Kenichiro Mizohata, Prof. Kai Nordlund (Project Manager), Prof. Jyrki Räisänen (Project Manager), Dr. Andrea Sand, Dr. Leonid Zakharov, MSc. Tomi Vuoriheimo

Fortum Power and Heat Ltd.

Activities: Power plant and safety engineering
Members: MSc. Sami Kiviluoto, 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 Parties 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
	Jukka Kolehmainen, Diarc/Oerlikon Balzers Coating
	Marjut Vähänen, Finnuclear
	Harri Sairiala, Fluiconnecto
	Jaakko Ylätalo, Fortum
	Ben Karlemo, Luvata
	Olli Kalha, Procurement and Contracting Consultant
	Mika Korhonen, Suisto Engineering
	Lauri Siivonen, Tamlink
	Liisa Heikinheimo, TEM
	Jarmo Lehtonen, Tevolokomo
	Arto Kotipelto, TVO
	Satu Helynen, VTT
	Johannes Hyrynen, VTT
	Timo Määttä, VTT
	Mathias Groth, Aalto
	Kai Nordlund, UH
	Kalevi Huhtala, TUNI
	Heikki Handroos, LUT
	Jan Westerholm, ÅA
Co-ordinator	Tuomas Tala, VTT
Secretary	Markus Airila, VTT

The FinnFusion advisory board had two meetings in 2019.

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 ITER Physics Project Boards

- WP JET2: Antti Hakola, VTT
- WP JET4: Jari Likonen, 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 2019

- 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 a member of the 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 Conference (Computer Simulation of Radiation Effects in Solids).
- 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 2019

2.1 WP JET1: Analysis and modelling tasks 2019

Research scientists:	L. Chôné, M. Groth, J. Karhunen, J. Kilpeläinen, H. Kumpulainen, S. Leerink, B. Lomanowski, V. Solokha, C. Stavrou, J. Varje, AU L. Zakharov, UH M. Airila, T. Kaltiaisenaho, A. Salmi, P. Sirén, T. Tala, VTT

2.1.1 Overview

JET operation and scientific campaigns started, after a shutdown, in summer 2019. The main focus was on establishing the necessary physics references, plasma operation scenarios and operational capability in view of the upcoming 100% tritum followed by the 50-50% DT campaigns continued over 2020-2021. In addition, preparation of the experiments together with analysis and modelling was executed in several two-week analysis campaigns, including activities on the preparation of key operational and analysis tools and on the extrapolation of recent JET results to ITER.

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 density peaking studies based on 2019 JET experiments with the scientific leadership provided by FinnFusion and using several computer codes in the detailed analysis.

2.1.2 Particle transport and sources

Several experiments, featuring gas puff modulations to study density peaking, particle transport and sources, have been planned and to be conducted on the JET tokamak.

(1) In preparation of the upcoming isotope campaign, deuterium reference discharges made. They will allow comparison of density peaking and particle

transport properties across the different hydrogen isotopes (H/D/T). This will provide important information and validation data for transport models to allow more confident extrapolation to fusion relevant D-T mixture plasmas.

(2) Three point gas scans both in Ohmic and in H-mode plasmas were made to study particle transport in LOC/SOC conditions and particle source / plasma fuelling through the ELMing H-mode pedestal. Further experimental time is being proposed to expand the limited scans to observe larger qualitative changes. Analysis of the data obtained so far in under way.

(3) Density peaking in deuterium plasmas with core fuelling (NBI) and without core fuelling (ICRH) were planned and executed with gas puff modulations in similar plasmas but with different heating schemes. Figure 2.1 shows the resulting electron density modulation in the transport coefficients. Work is under way to simulate these plasmas with the integrated transport code JINTRAC using both TGLF and QLK/QLK-nn models as well as with GENE and standalone TGLF for local turbulence characterisation.

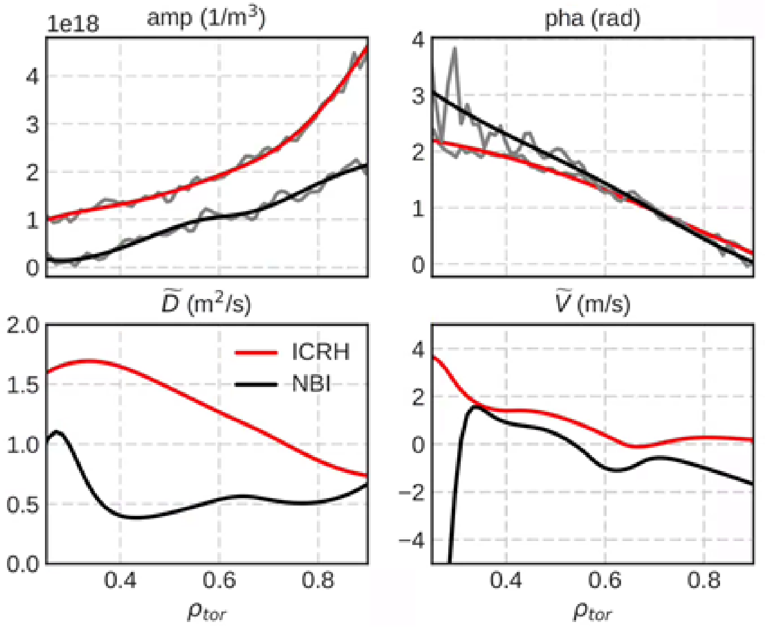


Figure 2.1. Electron density modulation amplitude and phase profiles at the 3Hz gas modulation frequency (top row) and the derived perturbative transport coefficients (bottom row) comparing NBI and ICRH heated plasmas with roughly similar density peaking.

2.2 WP JET2: Plasma-facing components

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

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

The JET2 programme focused on post-mortem analysis of divertor and wall components and in-vessel erosion-deposition probes (EDP) in 2019 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. The TDS measurements were made at CCFE.

Tritium removal by thermal outgassing will be used in ITER through the planned 350 °C divertor bake. In order to study the fuel outgassing efficiency W-coated divertor samples retrieved from JET-ILW were annealed at an ITER-relevant baking temperature. The W divertor samples were kept at 350 °C for 5 h, and the deuterium release was monitored with TDS. The samples were finally annealed up to 1000 °C to empty the samples of deuterium. The amount of deuterium released during the temperature increase from 350 to 1000 ^{o}C defines the remaining fraction. For the analysed ILW-3 samples the remaining fraction varied between 63 and 95 %. The highest remaining fraction was found for samples from the apron of Tile 1 but also for a sample from the top plasma facing surface of Tile 1. The remaining fraction is not directly related to the thickness of the co-deposited layer contrary to previous studies. Plasma parameters such as absorbed energy, surface temperature of the tiles, particle and heat fluxes also have a significant effect on the remaining fraction.

The experimental TDS spectra were simulated using the TMAP7 code with three traps for deuterium, resulting in good agreement with the experimental results. However, in the case of sample 1/6 from the top plasma facing surface of Tile 1 exposed in ILW-3 good agreement between TDS and TMAP could be obtained without the first trap at ~0.9 eV, but a lower diffusion coefficient was required. On the other hand, in the case of the ILW-1 sample 1/6 trap 1 was required. A possible explanation could be a higher deposition temperature during ILW-3 effectively emptying the first trap. The different diffusion coefficient might also be caused by slightly varying layer structures which could also be explained by the different deposition conditions. In the case of sample 1/11 from the apron of Tile 1 the TMAP model reproduces the experimental TDS spectra well (see Figure 2.2). The first trap was needed in the TMAP simulations for the ILW-3 sample but not for the ILW-1+2 sample which could be due a 2-week hydrogen campaign at the end of ILW-2 resulting in a reduced amount of D and a higher amount of H near the surface.

This and previous studies have indicated that the efficiency of the planned 350 °C divertor bake on ITER appears limited for thick (> 50 µm) co-deposits, and significant durations (~1 month) might be required to remove significant fractions of retained tritium.

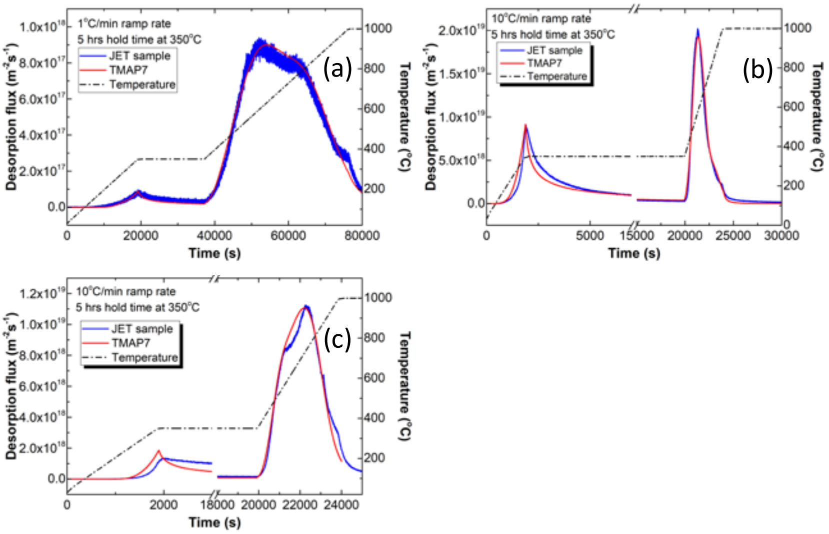


Figure 2.2. Comparison between the experimentally obtained TDS spectra for samples 1/11 from ILW-3 annealed with ramp rate 1 °C/min (a), 10 °C/min (b) and one exposed during ILW-1+2 (c) with ramp rate 10 °C/min, and simulations using the TMAP7 code.

2.3 WP MST1: Medium-size tokamak campaigns

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

2.3.1 Overview

In 2019, MST1 experiments were executed on ASDEX Upgrade (AUG) and TCV. The commissioning of MAST-U was further delayed, and the first physics campaign is now foreseen in the latter half of 2020. The plasma operations on AUG proceeded well, and almost the entire MST1 campaign could be completed by the end of the year. The main activity areas where the Finnish contribution was the most noticeable were studying erosion of plasma-facing components in different plasma scenarios, modelling of fast ions using the ASCOT code and controlling Alfvenic instabilities, investigating particle and momentum transport, and SOLPS modelling to assess heat-flux profiles at the upper-divertor of AUG. On TCV, the focus was on operating the machine with its newly installed baffles, and promising results were obtained, in line with the resuls of SOLPS simulations. The Finnish contribution on TCV was not that prominent as on AUG, and concentrated on fast-ion studies.

2.3.2 Controlling Alfvenic instabilities by electron cyclotron current drive

Within the MST1 program, Aalto University has for many years contributed to different fast-ion investigations on AUG and TCV. In 2019, in particular on AUG, research was carried out to identify a possible actuator for controlling Alfvenic instabilities by Electron Cyclotron Current Drive (ECCD). The method is based on modifying the current profile in the plasma, and consequently the q-profile and the shear, leading to complete elimination of the undesired Alfvenic modes by moving their frequencies to the continuum where the modes cannot exist anymore. It is therefore not a drive-damping type predator-pray algorithm but a way to get rid of the mode(s) for good.

In order to succeed, maximal change in the shear is needed. Therefore, one needs to pre-calculate EC parameters in order to drive the current in the correct radial location. Antti Snicker from Aalto University carried out TORBEAM analyses to address this issue (see Figure 2.3). The predictions were accompanied by intershot analyses since the plasma parameters were not exactly as predicted and, hence, also the current was not optimal. A novel method to move the current-drive profile across the mode spectrum was also introduced, which complicated the analysis considerably.

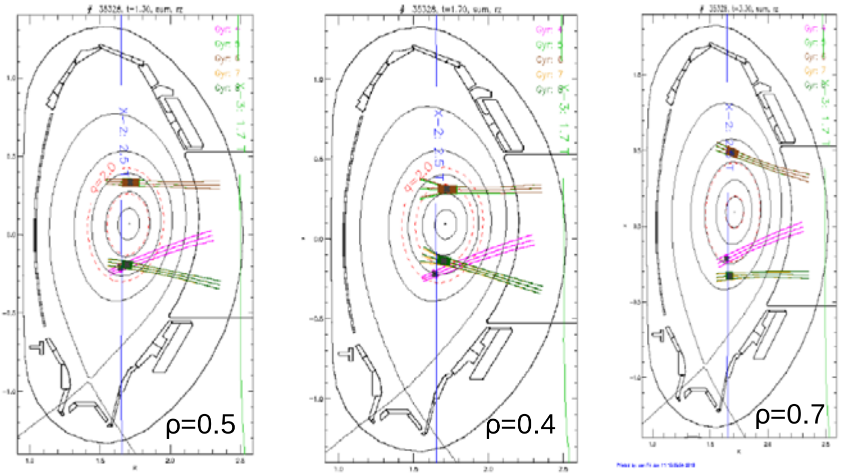


Figure 2.3. TORBEAM results for the poloidal view of EC beams driving current at different radial locations.

The results of these experiments were partly as expected: Some of the modes completely disappeared. However, some new modes appeared with certain EC settings. Moreover, many technical problems hindered the progress of the work. Future work in 2020, including modelling, will be necessary to understand what actually was happening in the studied plasmas.

2.3.3 ASCOT-RFOF studies of ion cyclotron heating and FILD signal in ASDEX Upgrade

ASCOT-RFOF studies of ion cyclotron resonance heating (ICRH) in ASDEX Upgrade discharge #33147 using ASCOT-RFOF have reached a new level of realism with a case-specific IC wave solution imported from TORIC wave code (see Figure 2.4). Stable IC power transfer from the wave to the assumed 5 % population of hydrogen at a prescribed level of 2.7 MW has been demonstrated. The related fast ion loss detector (FILD) signal simulations show a reasonable agreement with the measured signal from FILD1 as shown in Figure 2.5.

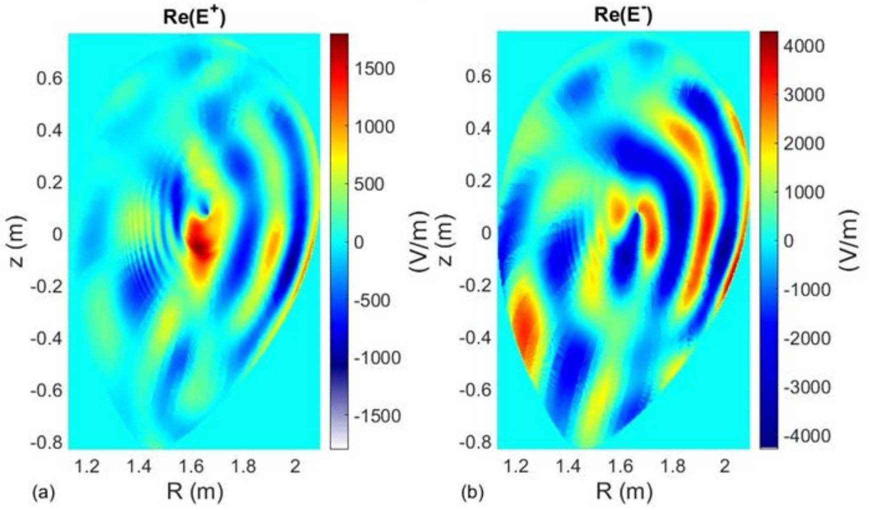


Figure 2.4. The left and right circularly polarized components E+ and E- of the IC wave electric field in ASDEX Upgrade discharge #33147 at t=1 s, imported to ASCOT-RFOF from TORIC.

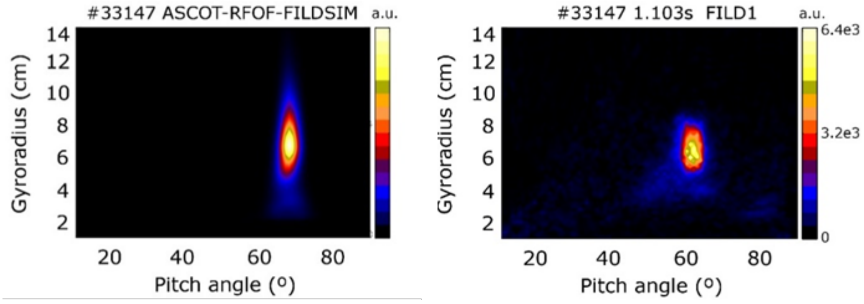


Figure 2.5. The simulated FILD1 signal assuming a 5 % H population (left), and the measured signal (right) as a function of pitch angle and gyroradius in discharge #33147. The simulation result has been postprocessed with the FILDSIM code to account for the instrument response.

2.3.4 Studying erosion of plasma-facing components in H- and L-mode deuterium and helium plasmas

Erosion of plasma-facing components in the outer divertor of AUG was studied in two different experiments in deuterium plasmas in 2019: One in L-mode and another one in H-mode with large type I ELMs and such that the electron temperatures (between ELMs in the H-mode experiment) in the outer divertor plasmas were comparable. Due to the full-W coverage of the AUG vessel, Au and Mo were used as marker materials instead of W. Despite their different sputtering yields, all the materials have comparable migration lengths. The analyses of the samples were carried out within WP PFC (see Section 2.4.3) and they indicate that gross erosion during ELMs is 1-2 orders of magnitude higher than in between ELMs while net erosion in H-mode is enhanced by a factor of 2-4 compared to the L-mode case.

Another important experiment was exposing W samples with nanostructured surfaces to helium plasmas also at the outer divertor of AUG. The idea was to assess if the nanostructures, referred to as W fuzz, are growing or being destroyed resulting from the accumulating He fluence. The results have revealed a complex erosion-deposition picture along the divertor surface, reflecting the variations in ion flux, surface temperature, and impact energy. An example of the measured erosion/deposition profiles can be seen in Figure 2.6. Close to the topmost strike point, new fuzz was formed on top of a deposited layer while especially in the private flux region (PFR) thick deposits containing W, Mo, and Ni that were affected heavily by arcing were measured.

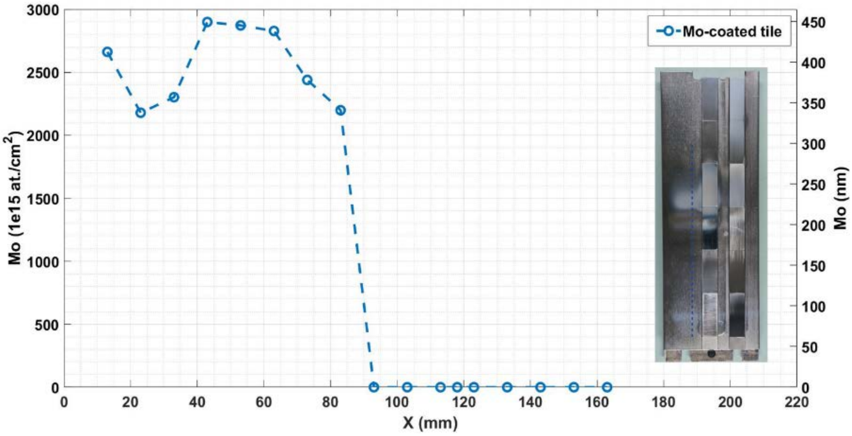


Figure 2.6. Thickness profile of the originally uniformly Mo-coated tile after its exposure to helium plasmas on AUG. The X coordinate starts from the PFR (bottom part of the tile). The strike point was located at ~90 mm in the first part and ~25 mm in the second part of the experiment.

2.3.5 Deputy Task Force Leadership activities

In 2019, Antti Hakola continued his activities as one of the MST1 Deputy Task Force Leaders (DTFL). The DTFL term lasts until the end of 2020 and, as in the past, has 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 are 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, and assessing the impact of error-field corrections on plasma confinement. 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 2019 are: (i) Optimal error-field correction methods can lead to the β_N of the plasma being increased by 10% and the plasma rotation by ~50%.; (ii) Strong difference in melting patterns of grounded and floating W samples was observed and such that the floating samples showed signs of slower melt motion and were heated up more rapidly; (iii) The database on the role of various plasma parameters in the characteristics of plasma filaments and the associated formation of density shoulder was complemented by results from H-mode discharges on AUG and TCV.

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 2019, 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 2019 were surface analyses of tokamak and laboratory samples, 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 laboratory made Be-containing deposited layers as well as from AUG samples.

2.4.2 Production of Be-containing deposited layers for fuel retention investigations

In 2019, the work initiated in 2018 to investigate retention in various beryllium-containing samples was continued and the results were reported in the PFMC 2019 conference. Focus was put on Be, Be-O, Be-O-C, and Be-N layers produced using High Power Impulse Magnetron Sputtering (HiPIMS) and Thermo-Vacuum Arc Deposition in Romania at different D partial pressures in the deposition chamber and altering the sample temperature between room temperature and 600°C. The main conclusions are that retention depends on the flux of D atoms on the growing film, but even more prominently on its composition, structure, and morphology. Especially, inclusion of carbon by 10-15 at.% in the layers can increase retention by a factor of 2-10. This is attributed to an increasing number of defects as well as aromatic and aliphatic C-D bonds in the samples. Other impurities do not significantly alter the D inventory while more D is retained in samples with rough or highly modified surfaces. The results also show that reproducing the reported D concentrations of ~5 at.% in layers resembling deposits on JET-ILW requires keeping the sample temperature at 100-200°C during the production phase and optimizing the uniformity of deposition fluxes. Data from D-containing Be samples further indicate that fuel retention in more ITER-relevant co-deposits would be around 1-2 at.%. The elemental compositions of D-containing Be and Be-C-O samples produced at different temperatures can be found in Figure 2.7.

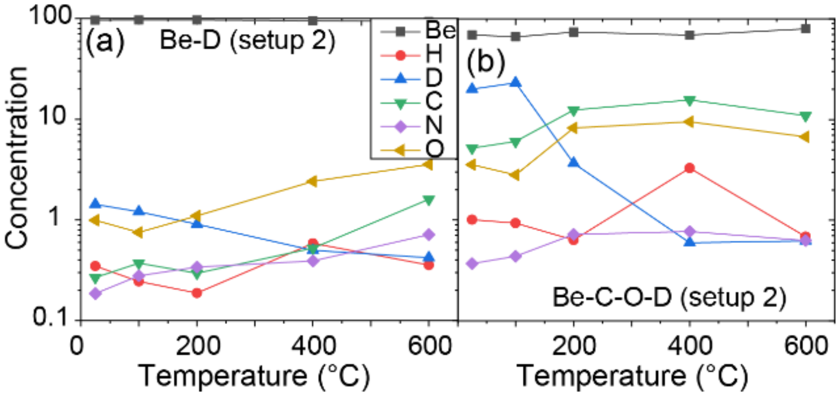


Figure 2.7. Elemental composition for different (a) Be-D and (b) Be-C-O-D layers produced at different surface temperatures. Here, setup 2 refers to the optimized deposition geometry and conditions of the HiPIMS method.

2.4.3 Studying erosion of plasma-facing components in ASDEX Upgrade

A large part of the work under WP PFC in 2019 concentrated on surface analyses of outer divertor samples resulting from L- and H-mode plasma experiments on AUG (see Section 2.3.4). All the analyzed samples had a graphite substrate on which a 100 nm thick Mo layer and some 20-30 nm thick Au marker spots (sizes 1×1 mm² and 5×5 mm²) had been produced. The 1×1 mm² spots provided information on gross erosion and samples with 5×5 mm² Au spots on net erosion.

The 5×5 mm² spots showed that the net erosion rate of Au during L-mode plasmas is almost nonexistent in the PFR, up to 0.8 nm/s at the strike point area and ~0.3 nm/s in the scrape-off layer (SOL). In H-mode plasmas, the erosion rates are clearly higher: ~0.8 nm/s in the PFR, ~1.9 nm/s at the strike point, and some 1.0 nm/s in the SOL. See Figure 2.8 for the measured erosion/deposition profiles. On the L-mode samples, redeposition of Au between the marker spots is below the detection limit while on the H-mode samples, larger migration and thus redeposition of Au was observed, up to 0.1 nm/s.

In the absence of ELMs, simulations with the ERO code predict impurities to have the largest effect on net erosion in regions where the electron temperature drops below 20 eV. However, without any impurities, erosion would be almost two orders of magnitude lower. The simulated erosion profile is typically more peaked than the experimental one and it exhibits a faint toroidal tail of redeposited particles downstream of the markers.

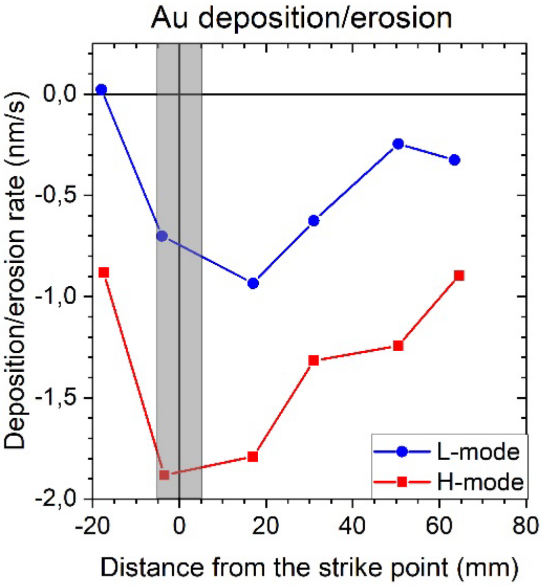


Figure 2.8. Net erosion/deposition profiles of Au markers resulting from L- and H-mode experiments on AUG. The gray bar denotes the strike point, the PFR is to the left and SOL to the right of the strike point.

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

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

In 2019, the installation of the new water cooled divertor of the Wendelstein 7-X (W7-X) stellarator excluded all plasma operations. Thus, work concentrated in analyzing the results from the 2018 NBI experiments while preparations for future campaigns are also under way. The work is in support of the W7-X high-level goal of demonstrating the improved fast ion confinement at high plasma pressure in W7-X and was performed in close collaboration with Wendelstein personnel.

The main analysis goals were comparisons to various measurements: NBI orbit loss wall loads as measured with infrared cameras, NBI current drive and NBI fast ion population contribution to diamagnetic energy as measured with coils, and finally fast ion hydrogen line-radiation (FIDA).

The modelling of future campaigns concentrated on deuterium operation. ASCOT was used to study the effects of changing one or both of the injected species and the plasma from hydrogen (H) to deuterium (D), also making D-D fusion reactions possible. The slowing down NBI deuterium population was calculated with the ASCOT code. The AFSI code was used to calculate the resulting D-D fusion reactions, which produce 2.45 MeV neutrons and tritons. The triton population was further modeled with the ASCOT code to calculate the triton slowing-down population. AFSI was then used to calculate the D-T fusion products, giving the 14.1 MeV birth rate (see Figure 2.9). The neutron yields were used as inputs to Serpent neutronics code to predict the performance a planned scintillating fiber neutron detector. Based on the total neutron rates, time resolved measurements of 14.1 MeV neutron flux to the detector would be possible, but detailed neutronics calculations are still pending.

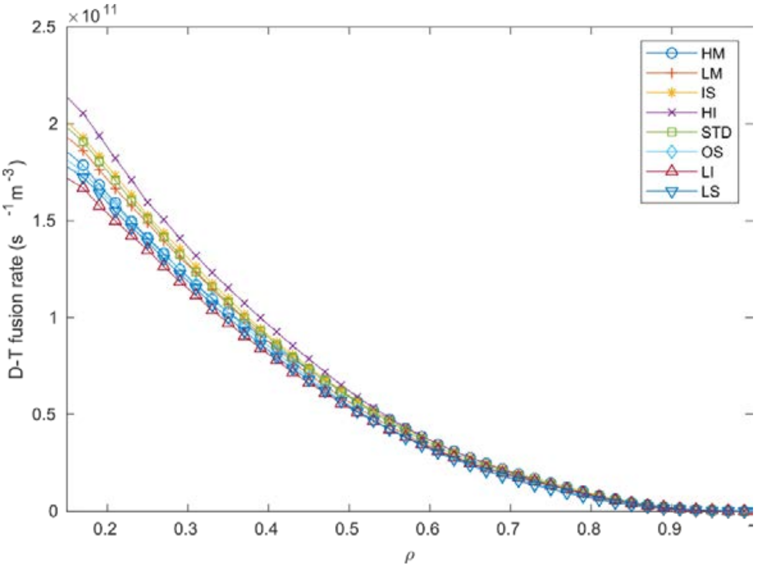


Figure 2.9. Radial profiles of deuterium-tritium fusion rates in the different W7-X reference magnetic configurations as calculated with ASCOT and AFSI.

2.6 WP CD: Code development for integrated modelling

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

During 2019, maintenance and user support was continued for the BBNBI, ASCOT and AFSI actors. The AFSI fusion source IMAS actor was extended to use the Monte Carlo model for calculating anisotropic thermal, beam-thermal and beam-beam 4D (R,z,pitch,E) sources with realistic spectra, including neutrons and alphas.

The actor writes the source distributions into IDS's using GGD and generates markers for subsequent FP simulations. Also, a simple synthetic neutron camera diagnostic was implemented as IMAS actor. Development was initiated for the ASCOT-RFOF actor, capable of ion cyclotron heating simulations.

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 explore geometric variations of the conventional, ITER-like single-null (SN) divertor. VTT participated in these activities in 2019 by simulating the exhaust processes in the so-called double-null (DN) divertor configuration, in which a second magnetic X-point and divertor are formed at the top of the machine, inside the first wall.

Using the state-of-the-art edge plasma fluid code SOLPS-ITER with a fluid description also for the neutrals, hundreds of parameter variations were carried out to identify possible operational regimes in the DN configuration. The results suggest an increased operational space and smaller requirements for edge radiated power exhaust compared to the conventional SN configuration, resulting from geometrical effects (see Figure 2.10). Drifts were found to impact the solutions, requiring further investigations in 2020. In 2020, we will also verify these initial results using a more credible, kinetic neutral model.

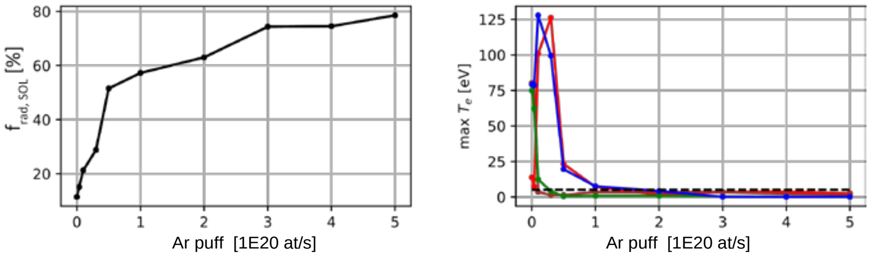


Figure 2.10. Simulated radiated power fraction in the scrape-off layer ($f_{rad,SOL}$, left) and maximum target temperatures (right) in the DN DEMO configuration. Target temperatures drop below 5 eV as required for detachment when $f_{rad,SOL}$=65% is reached, but $f_{rad,SOL}$ can be increased further up to at least 80% of the power entering the scrape-off layer.

3. Power Plant Physics & Technology Work Programme 2019

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

Research scientists:	T. Kurki-Suonio, L. Sanchez-Sanchis, J. Varje, 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

This study performed during 2019 by Fortum and VTT collaboration focused on technical aspects of low load and cycling operation on WCLL BB option with auxiliary boiler. The study reveiled that various issues should be taken into account during conceptual design due to the pulsed operation of DEMO plant. Potential failure risks and mechanisms were investigated and improvement proposals for illustrated WCLL BB with auxiliary boiler Apros heat balance was presented. The study was based on the operating experience with Loviisa PWR nuclear power plant and the literature on flexible operation of fission NPPs. Main conclusions of this report were that the PCS cycle is just as important as PHTS cycle; this is proven by experience from EDF that had challenges with combining produced power output values between the primary and secondary systems operating NPPs in load-following mode. Second conclusion was that a well-designed plant control and online monitoring system of critical components/parts are key to maintain process conditions stable during the dwell and pulse phases and the transitions. Many components will operate in off-design conditions. This may cause aggravated aging combined with cycling operation to be accounted during design. It was also determined that large pressure variations should be generally avoided in the plant components. Moderate temperature variation is allowed (see Figure 3.1) but a monitoring criterion for the temperature variance cycles should be set and coupled with fatigue analysis. Finally, the PCS should be designed taking into account the pulse-dwell turbine operation, moisture removal, reheating and condenser operation.

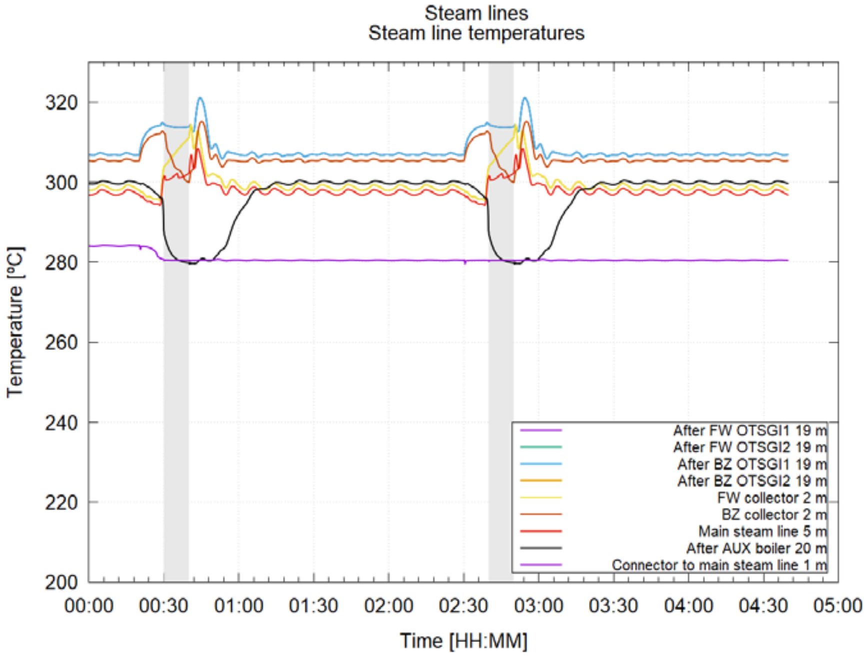


Figure 3.1. Example of the main steam line material temperature variation during pulse and dwell cycles from Apros analysis.

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

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

Early 2019 VTT took over work from CCFE related to dynamic analyses of the water-cooled lithium-lead (WCLL) concept of DEMO. The development of two Apros WCLL-model variations continued. The first model comprised an indirect coupling of the breeding blanket primary heat transfer system (PHTS) to the power conversion system (PCS) via an intermediate heat transfer system (IHTS), embracing a large Hitec (molten salt) energy storage system (ESS). The second model had a direct coupling between the PHTS and the PCS, and equipped with an auxiliary boiler for steam production during dwell. In WP BOP the indirect coupling concept was further analysed with updated information on key components and configurations of the PCS. Additionally, stability analyses related to the capability of the PHTS to damp fusion power fluctuations was conducted with the model. Also preliminary work with a direct coupling of the PHTS and PCS equipped with a small ESS system started. Work with the helium cooled pebble bed (HCPB) DEMO design also continued. The main achievement was a more accurate modelling of the breeding blanket, the vacuum vessel and the divertor units with respect to structural mass and heat capacity (see Figure 3.2), which is important for capturing the thermal inertia of the system when cycling between burn and dwell operations.

Transient analyses with the indirect coupling concept were analysed with the updated model and preliminary power fluctuation analyses were performed. The different configurations of both the WCLL and HCPB options will undergo a gate review during 2020, afterwards the viable, safe and economic alternatives will move on to the conceptual phase.

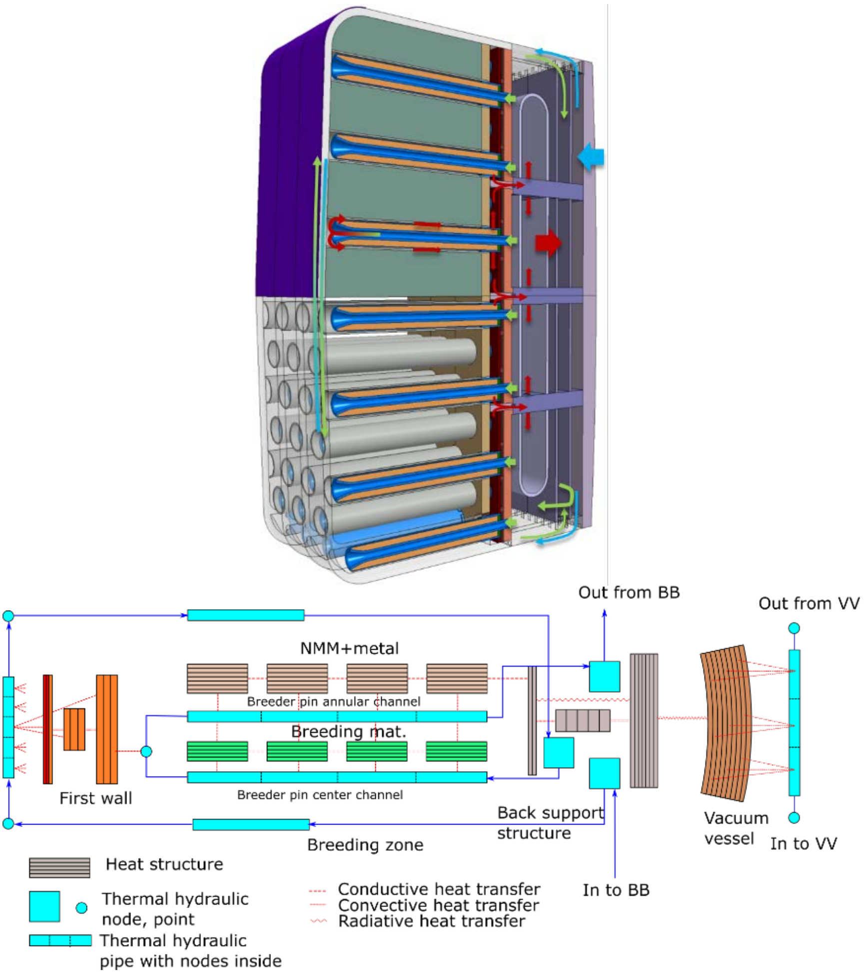


Figure 3.2. HCPB breeding blanket and principal modelling of structure and cooling channels.

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

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

The 2-year PPPT task PMI-7.5 concerns tritium production in DEMO, with a TBM mock-up to be built and experiments performed in Frascati, Italy, where the appropriate neutron source, FNG (Fusion Neutron Generator), is available. The new mock-up is called WCLL (Water-Cooled Lithium Lead), and it is the follower of the earlier version, HCLL (Helium-Cooled Lithium Lead), which was found not to be compatible with the DEMO environment. 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.

Serpent is a Monte Carlo neutron transport code, widely applied to reactor physics applications as well as coupled thermohydraulic calculations. The code has recently been extended to fusion applications. Serpent includes a built-in burnup calculation capability, and the code can directly import CAD and unstructured mesh based geometries. The code applies advanced weight window variance reduction techniques and is highly parallelized for modern supercomputers.

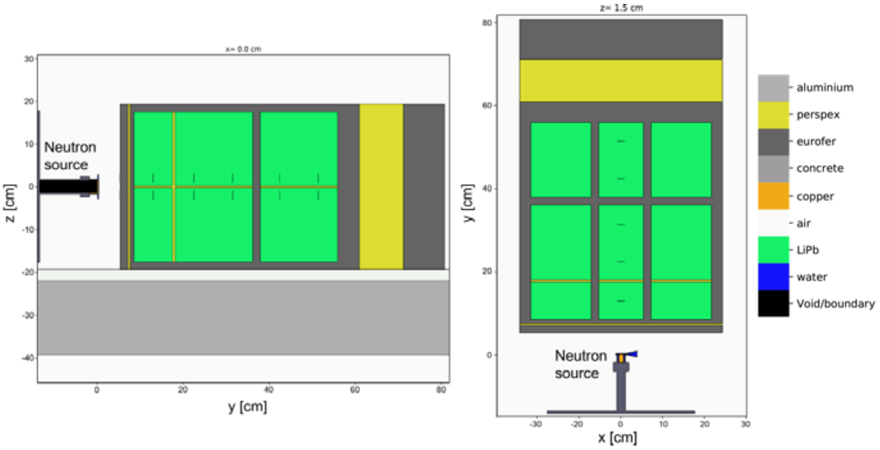


Figure 3.3. Side (left) and top (right) view of the WCLL TBM mock-up showing also the component materials of the setup.

In task T008, the Serpent code will be used throughout the WCLL neutronics mock-up experiment. Year 2019 was assigned to simulations in the preanalysis phase, with a preliminary mock-up model, against which a thorough benchmarking with the existing MCNP model and its results could be carried out. Due to manpower issues, however, only importing and verifying the geometry of the MCNP model, shown in Figure 3.3, could be accomplished in 2019, while the actual simulations of neutron fluxes and tritium productions were shifted to the first quarter of 2020.

3.4 Investigation of alpha particle losses in NT DEMO with ripple

Research scientists: T. Kurki-Suonio, J. Varje, AU

It has been shown that natural type-I ELMs are not tolerable in DEMO, due to the extreme temperature excursions at the divertor target they can cause. A range of candidates among ELM-free regimes for DEMO has been identified. Among these, the negative triangularity (henceforth NT) exhibits some interesting features that are attractive for a reactor.

Nevertheless, questions related to the applicability of NT for DEMO have to be addressed. In particular, the effect of magnetic ripple on energetic particle losses is expected to be more relevant than in positive triangularity (PT), as particles in NT “spend more time” on the low field side, where the role of ripple is most effective.

The goal of the PPPT task PMI-5.2.1-T011 was thus to evaluate the alpha particle losses in a DEMO NT 3D magnetic equilibrium. The generation and slowing down of fusion alpha particles was simulated with the ASCOT suite-of-codes using magnetic and plasma inputs, provided by EUROfusion, that corresponded to negative triangularity configuration in DEMO. The emphasis was on the confinement of fusion alphas, which was found embarrassingly good. Unfortunately, this turned out to be a trivial result since, with the given plasma, fusion reactions would essentially only occur in the very center of the plasma, $\rho < 0.5$, see Figure 3.4. Also other problems with the given scenario were identified.

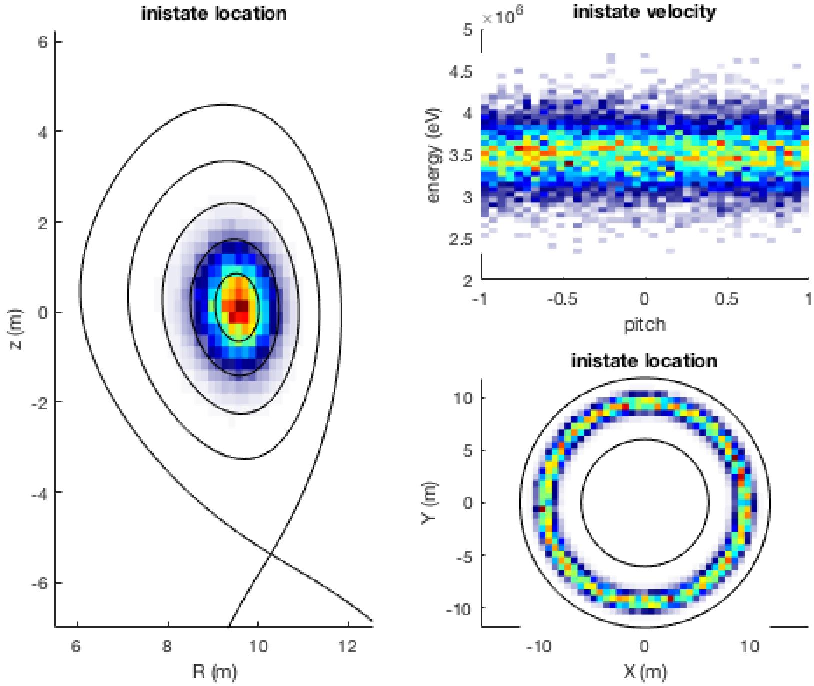


Figure 3.4. The birth profile of thermonuclear alphas.

3.5 WP RM: Remote maintenance systems

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

The DEMO divertor remote maintenance (DRM) development work package for 2019-2020 comprises of system design activities within the lower-port of the Double Null (KDI-4) tokamak. KDI-4, the Key Design Integration work of the Double Null (DN) deviates from the Single Null Blanket Transporter design due to high-level constraints (high mass and kinetics of blanket). The DN design means the divertors are installed on the upper and the lower areas of the Tokamak ring. Also, the breeder blankets are divided into upper and lower parts to be removed and installed through their vertical ports.

The double null KDI-4 development work includes the engineering design of many systems within the lower port. The task includes the design of the deployment system specialized as the lower port transport system consisting of the vertical transporter and intermediary lifting system (see Figure 3.5). The Vertical Transport System (VTS) performs the crucial part of the lifting operation in the hot cell under the lower port, and the Intermediate Lifting System (ILS) performs the final lifting operation inside the lower port chamber, as well as some limited tilting of the payload.

Dedicated systems for interfacing the divertor and lower outboard breeding blankets (OBB) are also designed to be attached to the ILS during transport operations. The divertor end-effector system consists of a support structure as a connecting point to ILS and for mounting the trolley and hydraulic power units for lifting and moving the divertor radially and toroidally. The end-effector system for the OBB consist of the support interface to the ILS, radial movement platform, lower and upper trolleys, and height adjustment system for the upper trolley.

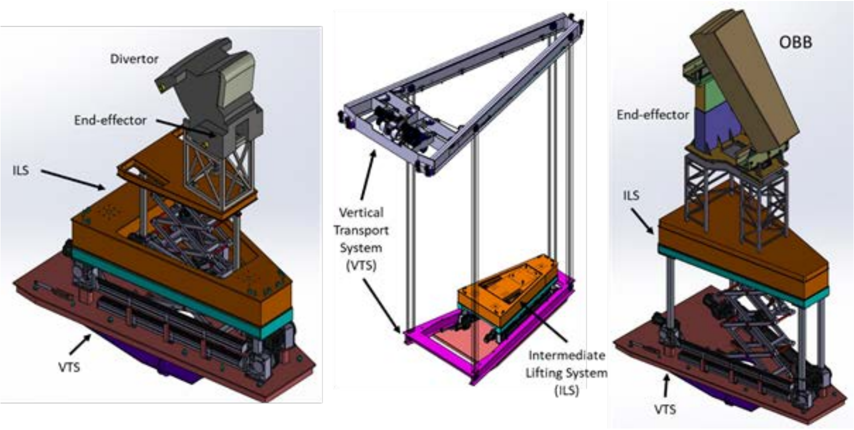


Figure 3.5. DEMO Remote maintenance double null lower port maintenance systems.

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

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

Iron, iron alloys and tungsten are the main materials of choice in many parts of nuclear power plants, both current and proposed ones. The defect production and evolution will affect their properties and can render them unusable for different applications. In previous years, the cascade overlap with previous existing debris have been parametrized for both Fe and W, and results are now published. In addition, the massively overlapping cascades in FeCr alloys have been published. In 2019 we focused on the stability of certain defects found in Fe, massively overlapping cascades in W and the implementation of the knowledge into OKMC, to reach longer relaxation times.

We found that the C15 Laves phase cluster in Fe, the most energetically stable interstitial type defect for small cluster sizes, can upon growth collapse into dislocation loops of different Burgers vectors, shown in Figure 3.6. We found that the energetically less favorable <100> loop can form as observed earlier. However, its probability should be lowered drastically compared to earlier studies, as they used questionable interatomic potentials for this kind of study. The massively overlapping cascades in W revealed the shortcomings of several commonly used interatomic potentials, where the evolution was drastically affected by the incorrect stability of certain dislocation structures. The implementation of cascade overlap and the collapse of C15 into OKMC showed that the evolution in the material was affected by both of these factors, showing to the importance of including atomistic phenomena into these kinds of simulations.

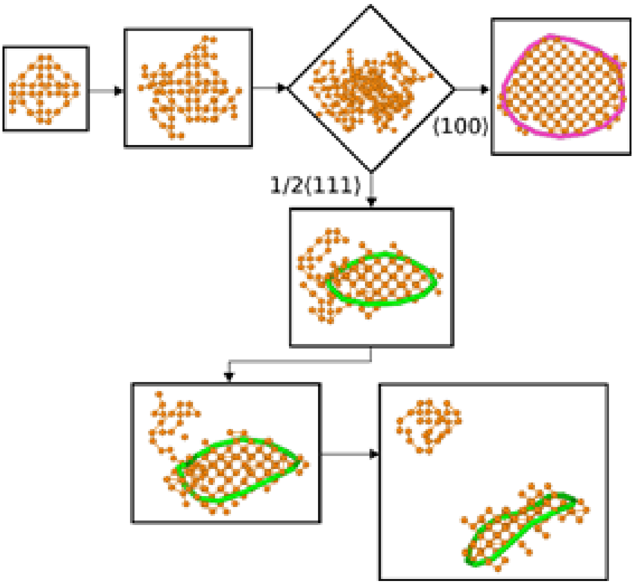


Figure 3.6. Collapse of C15 into different dislocation loops.

3.7 WP ENS: Early Neutron Source definition and design

Research scientists: A. Helminen, E. Immonen, I. Karanta, T. Tyrväinen, VTT
A. Rantakaulio, O. Suurnäkki, Fortum

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. It is expected that the construction phase of IFMIF-DONES will start within a couple of years. The location candidate for IFMIF-DONES in Europe is Granada, Spain (see Figure 3.7).

The design of IFMIF-DONES is conducted in the project called Work Package Early Neutron Source (WPENS). From Finland, VTT and Fortum have participated in WPENS in 2019. The Finnish contribution to WPENS has been in the areas of safety engineering and probabilistic risk assessment.

3.7.1 Safety engineering

Fortum has conducted feasibility studies on how to apply the safety engineering and requirement management practices of fission nuclear power plants to the safety design of IFMIF-DONES. The objective has been to give guidance on the functional safety design and how to ensure the requirement traceability of IFMIF-DONES. The guidance will help identifying systems participating in each safety function, how they are actuated and how the systems interoperate during the performance of a function. The information is used in the licensing to demostrate and validate the functional safety design of IFMIF-DONES.

3.7.2 Probabilistic risk assessment

VTT has prepared a probabilistic risk model for the lithium related accidents of IFMIF-DONES. The lithium related accidents are the most severe accidents and create the biggest share of overall risk for IFMIF-DONES. The model can be used to estimate the overall risk and to identify possible weaknesses in the design. The information is used in the following design rounds to improve the safety design of IFMIF-DONES.

Figure 3.7. The location candidate for IFMIF-DONES in Granada, Spain.

3.8 PPPT Industry task (DEMO remote handling systems technology support)

Research engineers: M. Erkkilä, S. Mühlig-Hofmann, V. Puumala, A. Timperi, P. Virtanen, Comatec Group

This industry task consisted of six separate technology cases for the DEMO power plant. Comatec performed the work in close co-operation with VTT and UK Atomic Energy Authority - RACE organizations. The six cases support the planning of DEMO remote handling systems:

Task 1. Carry out a feasibility study of the suitability of induction heaters for in-bore weld heat treatment (see Figure 3.8).
Task 2. Investigation options for a miniaturized and quick-release laser fibre connection.
Task 3. Compatibility of COTS water hydraulic components.
Task 4. Power and data connection for remote-controlled devices in fusion environment.
Task 5. Carry out a feasibility study for the high payload cranes.
Task 6. Standard and OTS remote operated connections and robotic connectors (tool changers) for In-vessel and Ex-vessel use, for Fluids, Electrical (power, data) and Mechanical (Tool changer locking, connector locking, component locking).

The tasks were finalized in the spring of 2019. For the Task 1, the work continued as a new task for RACE and was supposed to be ready by March 2020.

Comatec's engineering expertise is very well in line with the development needs of fusion technology remote handling systems (RH). One object 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 has shown that the partnership works very well.

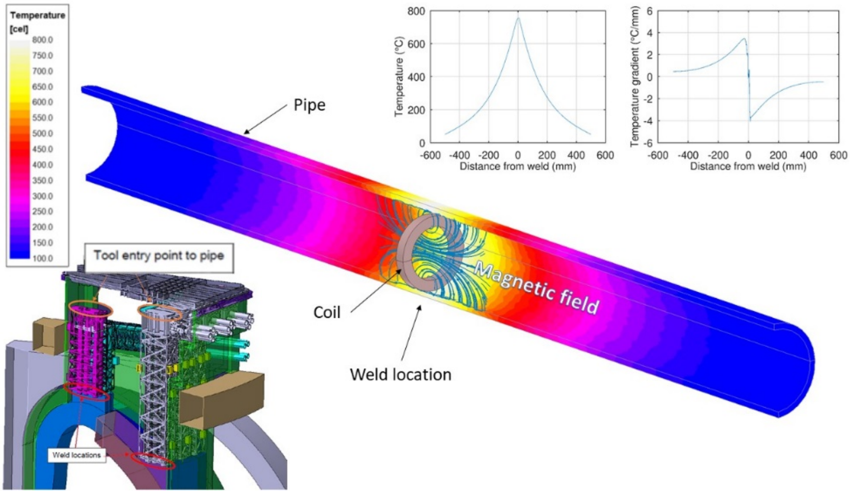


Figure 3.8. In-bore post weld heat treatment of DEMO pipes with electromagnetic induction.

4. Communications

The FinnFusion Annual Seminar was organised by DTU Physik, Denmark, and held at Schaeffergaarden, as a 3rd joint Nordic seminar with the Danish and Swedish Research Units on 11–12 June 2019. Invited speakers were Lars Christensen, Division at Danish Agency for Science and Higher Education, Lorne Horton, JET, United Kingdom, Hartmut Zohm, IPP Garching, Germany, Niels Bech Christensen, DTU, Denmark, and Odd Erik Garcia, The Arctic university of Norway. The number of participants was 75. The Annual Report, *FinnFusion Yearbook 2018,* VTT Technology **352** (2018) 77 p., was published for the Annual Seminar.

During 2019, Finnish and international media published several articles and interviews on the fusion research activities in Finland:

- Tuomas Tala, Fuusioreaktori lähestyy todellisuutta – energiaongelmat ratkaiseva voimalatyyppi tuottaa sähköä verkkoon jo 2050-luvulla (*Fusion reactor approaching reality – the power plant solving energy issues will produce electricity already in the 2050's*), interview on DEMO in Tekniikka & Talous on 10 January 2019.

  https://www.tekniikkatalous.fi/tekniikka/energia/fuusioreaktori-lahestyy-todellisuutta-energiaongelmat-ratkaiseva-voimalatyyppi-tuottaa-sahkoa-verkkoon-jo-2050-luvulla-6754642

- Tuomas Tala, Markus Airila, Mikko Siuko, Kai Nordlund and Taina Kurki-Suonio provided material to Supergraafi – Fuusiovoimalan seuraava vaihe (*Supergraph – Next phase of fusion power plant*), Tekniikka & Talous on 8 February 2019.
- A. Hakola, Fuusioenergia ePlaneetan sähköntarvetta ruokkimassa (*Fusion energy feeding the electricity need of ePlanet*), Sytyke 2/2019, p. 20.

Presentations in the member event of the Finnish Nuclear Society on 21 May 2019:

- Rainer Salomaa, Non est ad astra mollis e terris via (*There is no easy way from the earth to the stars*), review of development of fusion devices over several generations.
- Taina Kurki-Suonio, Fuusiovoimala ja ITER (*Fusion power plant and ITER*).

Lecture courses at Aalto University, School of Science:

- *Fusion Energy Technology (Mathias Groth, spring 2019).*
- *Fundamentals of Plasma Physics for Space and Fusion Applications (T. Kurki-Suonio, autumn 2019).*
- *Advanced Plasma Physics with Computational Emphasis (L. Chôné, E. Hirvijoki, T. Kurki-Suonio, spring 2019)*

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 2019, one doctoral dissertation and two Master's thesis were completed (see Section 11.4.4).

5.1.2 Doctoral students

Student: Henri Kumpulainen (AU)
Supervisor: Mathias Groth (AU)
Instructor: Mathias Groth (AU)
Topic: *Tungsten transport in JET*
Report: The erosion and transport of tungsten (W) in JET L-mode and H-mode plasmas have been modelled using the multi-fluid/kinetic neutral code EDGE2D-EIRENE and the Monte Carlo trace-impurity code DIVIMP. The code predictions agree within a factor of 2 with the spectroscopic measurements of neutral and singly-ionized W line emission in the divertor and with the experiment-based estimates of the main plasma W density. In the studied L-mode scenarios, inclusion of the cross-field drifts in the simulations was found to have only a minor impact on the W density profiles, whereas in H-mode both the W erosion and the transport are significantly affected by the drifts.

Student: Vladimir Solokha (AU)
Supervisor: Mathias Groth (AU)
Instructors: Mathias Groth (AU)
Topic: *Isotope effect on the JET divertor plasmas*
Report: Experiments in JET-ILW Ohmic confinement mode show that deuterium discharges have a lower detachment onset density than hydrogen discharges. The experimental data showed that the magnitude of the isotope effect depends on the divertor geometry, the magnetic configuration and the pumping efficiency of the subdivertor/divertor cryopump system (Solokha et al 2020 Phys. Scr. 2020 014039). Simulations with the edge fluid code

EDGE2D/EIRENE revealed that pumping at JET is effective near the divertor outer target only. Therefore, the magnitude of the isotope effect, which depends on the pumping efficiency, is sensitive to the molecular pressure in the pumping plenum. According to experiments and simulations, closer proximity of the strike point to the pumping plenum in horizontal configurations, and operating in vertical configurations, increase the molecular pressure (and thus pumping efficiency) by up to 30% and thus produce a stronger isotope effect on the detachment onset density than in the nominal horizontal divertor plasma configuration. Similarly, EDGE2D-EIRENE predicts that plasma and thus neutral re-distribution due to ExB drifts in reversed B_t configurations (ion BxGradB out of the divertor) increase the deuterium molecular pressure in the pumping plenum and thus lead to an increase of the isotope effect by 5%.

Student: Konsta Särkimäki (AU)
Supervisor: Mathias Groth (AU)
Instructor: Taina Kurki-Suonio (AU)
Topic: *Modelling and understanding fast particle transport in non-axisymmetric tokamak plasmas*
Report: A modern orbit-following code ASCOT5 was developed which was used to study fast ion transport in the presence of static magnetic perturbations. It was shown that mapping losses in a specific phase-space allows one to identify different collisionless loss-processes. Furthermore, the regions in phase-space from which losses occur can be estimated directly without orbit-following simulations. This allows for a fast estimate on losses and also provides independent verification for the results of orbit-following simulations. It was also shown that ITER fast ion transport due to ELM control coils can be modelled as an advection-diffusion process. This fact will be used to scan fast ion losses in different coil current configurations.

Student: Changyang Li (LUT)
Supervisor: Huapeng Wu (LUT)
Instructor: Huapeng Wu (LUT)
Topic: *Dynamic analysis and multi-objective optimization of a 6-DoF parallel manipulator*
Report: The work introduces the optimal design of parallel robot machine based on multi-objective optimization integrated with parallel manipulator dynamic models. The parallel robot machine will carry out the machining and welding for the assembly of fusion reactor vacuum vessel. The tasks will be performed inside of the vacuum vessel remotely. In the structural optimization design of the robot,

the objective function is considered as a combination of workspace volume, kinematics, dynamic dexterity and global mass index. The design variables include radius of top and bottom platforms, actuator maximum load and length of the actuators. In addition, the variables are subjected to the boundary conditions, such as limited parallel manipulator size in vacuum vessel, etc. An evolution optimization algorithm is studied, which can guarantee the global solution and accuracy.

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: 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 with a high-precision force/motion control. However, the dynamic behaviour of manipulators with nonlinearities of the gears make control design and their stability analysis an extremely challenging task. This study focuses on developing model-based control methods for heavy-duty RH manipulators subject to high-gear rations and associated static nonlinearities. Additional key area of this study is force reflecting bilateral master-slave control for these manipulators.

Student: 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.

Student: Jesper Byggmästar (UH)
Supervisor: Kai Nordlund (UH)
Instructor: Kai Nordlund (UH)
Topic: *Multiscale modelling of radiation effects in fusion reactor materials*
Report: This year focused on developing better interatomic potentials to more accurately simulate radiation damage in iron and tungsten. In particular, using a new potential for iron, we investigated the stability, growth, and collapse of the C15 Laves defect clusters. We also started exploiting machine learning methods to develop interatomic potentials with accuracies comparable to quantum-level calculations. Our machine-learning potential for tungsten is published and can be used to simulate radiation damage in tungsten with unprecedented accuracy.

Student: Aki Lahtinen (UH)
Supervisor: Jyrki Räisänen (UH)
Instructors: Antti Hakola (VTT), Jari Likonen (VTT)
Topic: *Plasma-wall interactions in fusion devices*
Report: In 2019, the work focused on the investigation of gross and net erosion in the outer strike point (OSP) region of ASDEX Upgrade tokamak (AUG) during L- and ELMy H-mode plasma discharges using marker samples and AUG's divertor manipulator. On the L-mode samples, high erosion, up to 0.8 nm/s, was observed at the OSP and low erosion in the private flux region (PFR) and in the scrape-off layer (SOL). On the H-mode samples, erosion was higher. The maximum erosion rate, up to 1.6 nm/s, was similarly at the OSP, but now high erosion rate, up to 0.75 nm/s, was observed also both in the PFR and in the SOL. Another contributed research topic in 2019 was impact of helium operation on tungsten plasma-facing components in AUG.

Student: Anna Liski (UH)
Supervisor: Kai Nordlund (UH)
Instructors: Fredric Granberg (UH)
Topic: *Non-recursive Sink Strengths for Rate Equations Simulations of Defect Dynamics in Solids*
Report: Monte Carlo simulations were performed to model the trapping of migrating point defects in the systems with different trapping sites. The sites considered were voids (spherical traps), edge dislocations and grain boundaries. The goal of this work is to develop a simple way of calculating one input parameter required for mean-field rate equation simulations: the sink strength. It is commonly solved through iteration due to its self dependency: every individual sink strength is a function of the total sink strength.

In our work we have used a novel approach by describing the parameter as a function of the total sink volume fractions. Unlike total sink strength, volume fraction is always known. During this year we have modified the simulation program to fit the needs of this project and conducted majority of required calculations. Our work is now at its final stage of selecting functions describing data most accurately.

Student: Alvaro Lopez-Cazalilla (UH)
Supervisor: Kai Nordlund (UH)
Instructors: Fredric Granberg (UH)
Topic: *Molecular dynamics simulation of ripple formation and propagation*
Report: The purpose of the work is to study sputtering of tungsten under different conditions by means of molecular dynamics (MD). The different orientation, the surface configuration such as adatoms, vacancies, mounds and the energy of the incoming ions may play an important role in the surface modification. In our case, we have studied the modification of W under Ar irradiation at different low-medium energies and angles. Besides, we have developed a tungsten fuzz which has been used as well to follow the erosion process. The results will be compared with experimental data.

Student: Tomi Vuoriheimo (UH)
Supervisor: Jyrki Räisänen (UH)
Instructors: Tommy Ahlgren (UH)
Topic: *Deuterium retention and removal in tungsten*
Report: In 2019 we investigated isotope exchange by implanting hydrogen into tungsten and annealing the samples in deuterium atmosphere under various temperatures. Reference samples were annealed in vacuum. From these and from our previous results of replacing implanted deuterium with hydrogen, we confirmed that isotope exchange is a statistical effect and its efficiency depends on the concentration of free solute isotopes in the tungsten lattice. This information can be useful when improving the efficiency of tritium removal from fusion reactor first wall materials. In addition to the work discussed above we made low energy deuterium implantations into tungsten with JET and ITER relevant energies and fluences.

5.2 WP TRA – EUROfusion Researcher Grant

Assessing synergestic effects of internal MHD modes and 3D fields on fast-ion transport

Research scientist: A. Snicker, AU

Antti Snicker finished his Eurofusion Research Grant end of May 2019. The contribution for 2019 mainly consisted of active participation to MST1 experiments (see chapter 2.3). Here is additional work that was carried out in 2019.

A comparison of guiding-center and full-orbit transport in the full TAE spectra expected in ITER was carried out. The idea was to verify the usage of guiding-center following in the simulations with MHD modes included. The existing publication (A. Snicker et al 2013 Nucl. Fusion 53 093028) was used for the TAE spectra, note should be made that these spectra contain only one toroidal mode number but is already computationally heavy especially for full-orbit particle tracing. This result is already several years old and orginally carried out with older version of the ASCOT code. However, the current version was used to successfully reproduce the old result (within the estimated errorbars, since only 10% of the initial particle ensemble were used to save CPU time).

Two modification were done to facilitate the comparison with minimized CPU resources. Firstly, rather than solving the full slowing down distribution function, an initial particle ensemble was sampled from the 4D slowing-down distribution and then followed for a rather short time period. The resonance between the fast-ions and the TAEs are located at around 1 MeV and this approach saves a lot of CPU time. Secondly, the amplitude of the waves was articially increased in order to get better statistics.

As shown in Figure 5.1, the particle distribution in the presence of TAE modes is very similar between guiding center and full-orbit tracing options. In fact, the differences inside the plasma where alpha particle distribution is non-zero, are within 2-3 percent. Towards the edge of the plasma, where the alpha particle density is very small, larger relative differences are observed, although the absolute difference is very marginal.

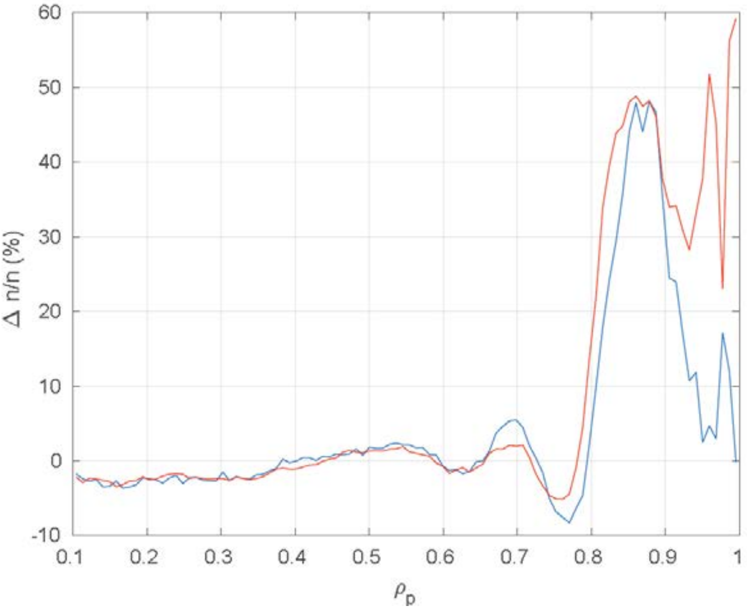


Figure 5.1. Relative alpha particle redistribution in the presence of TAE mode in ITER. The Blue line corresponds to guiding center simulation and red line to full-orbit simulation. Note that the simulation set-up is non-physical (to intensify the effect of the modes).

5.3 WP TRA – EUROfusion Researcher Grant

Modelling interactions of deuterium with beryllium in presence of oxygen and oxide layer with molecular dynamics for fusion applications

Research scientist: E. Hodille, UH

In this project, we assess with molecular dynamics (MD) the sputtering and reflection processes of beryllium oxide irradiated by deuterium ions. In 2018, we carried out MD simulations to estimate the sputtering yield of BeO by D at 300K with D incident energy between 10 eV and 200 eV. The year 2019 was dedicated to the estimation of the sputtering yield of BeO at different temperatures (300K to 800K) for the same energy range.

The calculation of the sputtering yield is done in two steps. First, cumulative irradiation (up to 500 impacts) is carried out to build a D-rich layer in the material. Then, 10,000 non-cumulative impacts are simulated to estimate the sputtering yields. The concentration of D in BeO depends on the temperature as shown experimentally [Roth et al. J. Nucl. Mater. 453 (2014)]: between 300 K and 500 K, it is 0.12 at.fr. and it drops to 0.02 at 800 K. Thus, the amount of impacts to create the

D-rich layer is higher at low temperature than at higher temperature, which induces more damages. In addition, for a constant D concentration, the surface damage increases with temperature, i.e. there is more damage in the simulation cell at 500 K than at 300 K.

The MD estimated sputtering yield of BeO is given as function of temperature for six different incident energies between 10 eV and 200 eV in Figure 5.2. For all energies, the sputtering yield increases from 300K to 500K at constant D concentration. When the D concentration decreases, the sputtering yield decreases as well. We also investigated the sputtering products, i.e. either single atom (physical sputtering) or molecules (mainly OD_z and $Be_xO_y(D_z)$). At 10 eV, the temperature dependence is only due to OD_z production: for higher concentration of D, there are more O-D bonds on the surface, which eases the swift chemical sputtering (SCS) mechanism. For other energies, the temperature dependence is explained by the evolution of the production of $Be_xO_y(D_z)$ with temperature. At high temperature, i.e. low D concentration and low D surface damage, the mechanisms leading to such molecules are mainly of physical nature. At low temperature, i.e. high D concentration, the high amount of surface damage triggers new sputtering mechanisms that creates $Be_xO_y(D_z)$ molecules. For energy between 30 eV and 80 eV, there is an increase in the sputtering yield from 300K to 500K as the amount of damage increases with the temperature (for constant D concentration). At higher energy, the D atoms stop deeper below the surface and the damage is also located deeper below the surface and impact less the sputtering. This also explains the fact that $Be_xO_yD_z$ molecules are produced at low energy while only Be_xO_y molecules are produced at high energy.

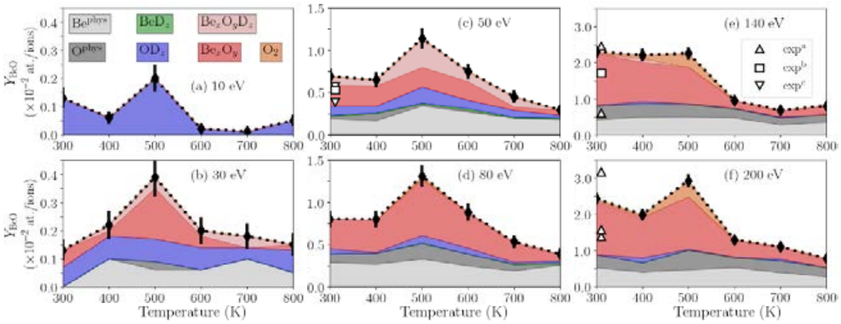


Figure 5.2. Evolution of the MD sputtering yield with temperature. The contributions of single Be atoms (Be^{phys}), single O atoms (O^{phys}), BeD_z, OD_z, $Be_xO_y(D_z)$ and O_2 are also shown.

6. Enabling Research

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

FinnFusion participated in five Enabling Research projects in 2019:

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

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

6.1 Model for reactor relevant pedestals

The pedestal plays an important role in determining the confinement in tokamak H-mode plasmas. However, the steep pressure gradients in this transport barrier also lead to edge localized modes (ELMs). Since type I ELMs are known to damage plasma facing components future large tokamaks must operate with small or no ELMs. Aim of the project is to develop a capability to predict the pedestal heights for these regimes based on an improved understanding of the underlying pedestal physics. The role of Aalto University in the project is to understand the limits of present analytical models of bootstrap current in pedestal regime as well as to study the effect of turbulence on bootstrap current using gyrokinetic full-f code ELMFIRE.

The neoclassical bootstrap current simulations are found to agree with the analytical estimates of Sauter and Hager within a few percent. No large deviation between the two analytical models is observed for the low-collisionality regime, and both models match the simulation results within numerical accuracy, even when approaching the limit where the neoclassical approximations start to break down (see Figure 6.1). However, discrepancies as large as 20% between the numerical simulation and the analytical estimates by the models are introduced when the collision grid used by ELMFIRE is made sparser, resulting in inaccuracy in the collision operator. With Shafranov shift analytic estimates were shown to disagree but this can not be studied with ELMFIRE.

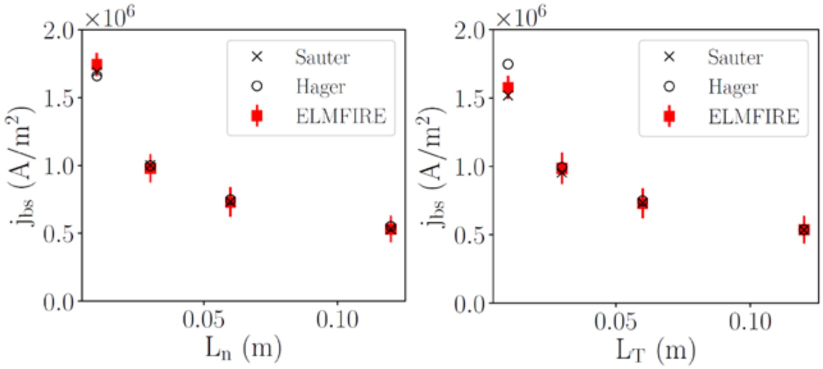
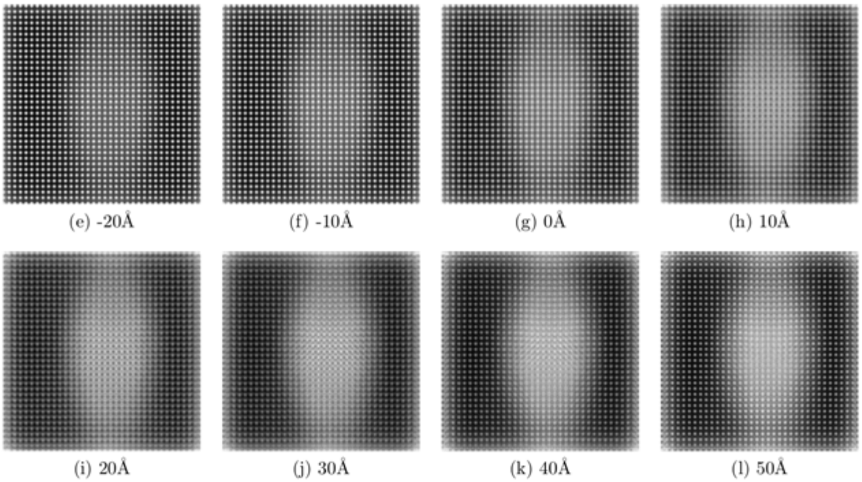


Figure 6.1. Bootstrap current as a function of the gradient scale lengths for (a) density L_n and (b) temperature L_T.

6.2 Models for primary radiation damage

The ENR AtomCRaD project tackles the question of achieving atomic scale resolution in scanning transmission electron microscopy (STEM) images of radiation-induced defects in tungsten, for the purpose of identifying and characterizing the microstructure of the irradiated material. The project is carried out in collaboration with researchers from CCFE and the University of Manchester in the UK, with the WP3 subtask, comprising a total of 11 pm/year, being carried out by researchers at the University of Helsinki.

Achieving atomic resolution of nano- and subnanoscale defects, including dislocation loops and small voids, in metals involves many challenges, from sample preparation to finding optimal microscope settings and imaging conditions, to interpreting the resulting intensity distribution that is measured. For the purpose of supporting the interpretation of experimental images, and finding the optimal image conditions, the WP3 task focuses on numerical simulations of micrograph images. These are calculated from atomic coordinates of radiation damage predicted by molecular dynamics simulations of collision cascades. Using a computational method, called the multislice method, for calculating the transmission of the electron beam through the sample, images are acquired (see Figure 6.2) that will later be compared to experimental images from the other WPs in the project. In particular, we aim to identify conditions that maximize the contrast of signals related to the atomic misalignment and local strain surrounding the defect.



(e) -20Å (f) -10Å (g) 0Å (h) 10Å

(i) 20Å (j) 30Å (k) 40Å (l) 50Å

Figure 6.2. A defocus series of a dislocation loop, showing the change in contrast as the focal plane is adjusted to different depths

7. Code development

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

Research Scientists: K. Särkimäki, J. Varje, AU

A new orbit-following code ASCOT5, which was developed at Aalto University, was officially released. The code has been developed for modern supercomputer architectures using a hybrid MPI+OpenMP approach with highly parallelized multithreading and vectorization. The modular structure of the code has been designed for extendability and ease of maintenance.

The code has immediately gained international interest: by the end of the year 2019, the user license had been signed by eleven universities, institutes and companies, and the user base consists of over 30 people. First publications, where the code has been utilized, have already come out, and the ASCOT5 reference paper was submitted for publication.

In ongoing development, new physics are implemented in the code: beam ionization, charge-exchange reactions, test particle response to MHD, time-dependent EM-fields, and new runaway electron physics.

In the end of November 2019, an official, EUROfusion-supported ASCOT5 training session was organized at Aalto University, with 10 participants from EU and one from U.S. Since we could not accomodate all interested in this first ASCOT Training Session, all sessions were broadcasted (and recorded for later viewing) for those not selected as well as for colleagues overseas.

Figure 7.1. Paticipants of the EUROfusion-supported ASCOT5 training session.

7.2 Full-f gyrokinetic turbulence code ELMFIRE

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

Elmfire work has contributed to two enabling research projects “MAGYK: Mathematics and Algorithms for GYrokinetic and Kinetic models” and “Model for reactor relevant pedestals”. In the atter one, we have shown that the Hager and Sauter bootstrap formulae agree with the ELMFIRE code without Shafranov Shift. The two analytic formulas differ when the shift is included but this cannot be studied with ELMFIRE. The accuracy of ELMFIRE simulation of bootstrap current was shown to decrease when binary collision cell width was more than $L_T/100$ where L_T is temperature gradient scale length.

In context of MAGYK, partly funded by PRACE, we are working in collaboration with CSC to test new particle-in-cell (PIC) algorithms and bring them to the LUMI platform. We have also developed the first structure preserving subcycling algorithm for PIC. The long term collaboration with Ioffe Institute has continued actively e.g. in comparing edge electric field simulations including scrape-off-layer to the probe measurements (see Figure 7.2 and, also, Section 9.3).

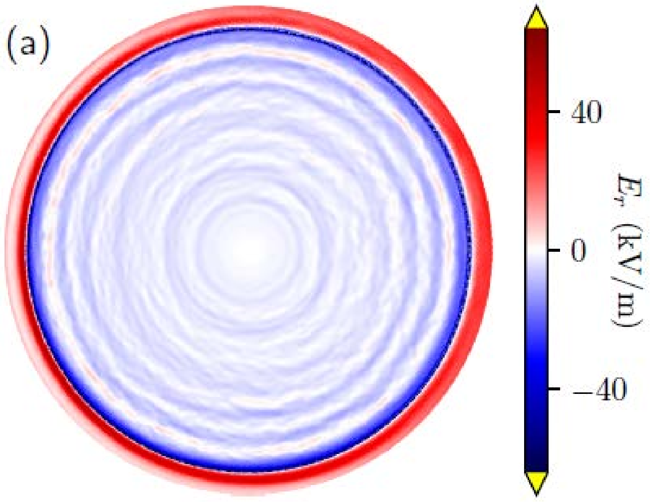


Figure 7.2 a) Poloidal cut of E_r in ELMFIRE simulation. The dashed circle shows the LCFS.

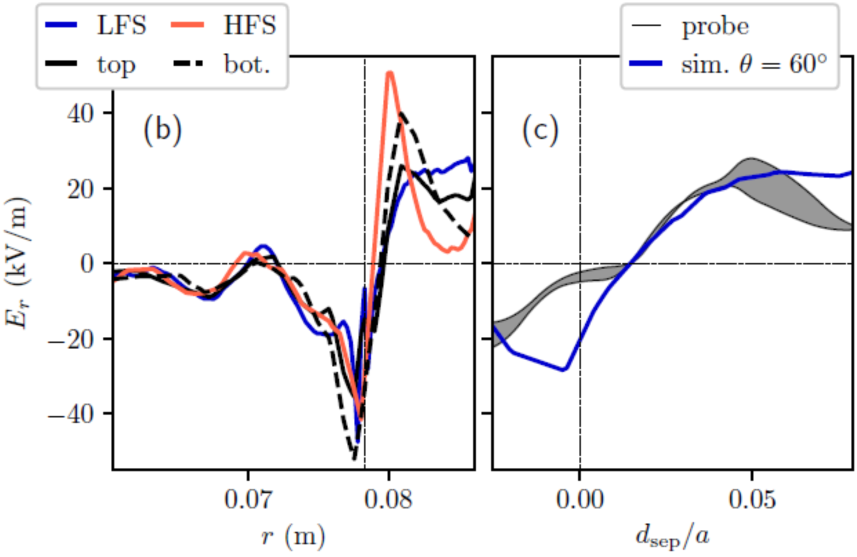


Figure 7.2 b) Radial profiles of E_r at the edge of the simulation for various poloidal positions. c) Comparison between E_r simulated by ELMFIRE (blue line) and FT-2 reciprocating probe measurements (black lines/grey range).

7.3 Molecular Dynamics

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

The molecular dynamics simulations of plasma and neutron effects in fusion reactor materials took a major step forward in 2019, when we developed the first machine-learning interatomic potential for W suitable for radiation effects calculations. This development, funded by a EUROfusion Enabling research project, lead to an interatomic interaction model that can reproduce very accurately all W materials properties relevant for fusion materials studies. The new potential enabled e.g. determining the threshold displacement energy surface in W over all crystal directions, see Figure 7.3. [J. Byggmästar et al, Phys. Rev. B 100, 144105 (2019)]. This quantity determines the minimum energy needed to create a crystal defect in W, and is thus crucial for understanding plasma-material interactions in ITER and DEMO.

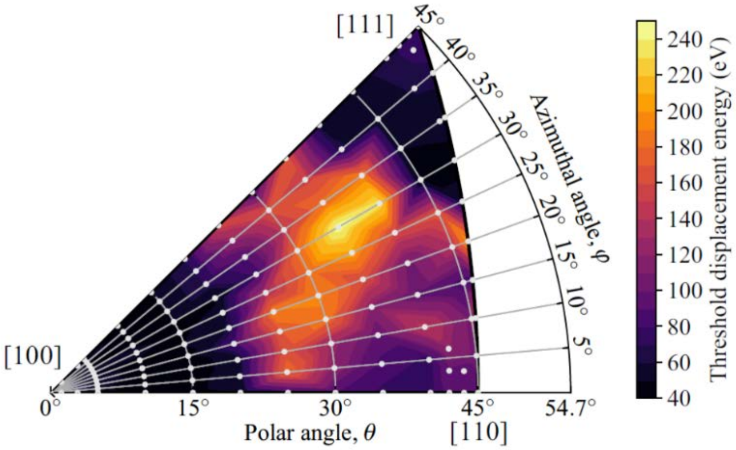


Figure 7.3. Threshold displacement energy surface in W determined by the first machine-learning W interatomic potential.

7.4 Serpent

Research Scientists: T. Kaltiaisenaho, 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 2019 Serpent has been used for simulation of neutron transport and tritium production under PPPT task PMI-7.5 (see chapter 3.3). Main aim was to perform Serpent simulations for WCLL TBM-mockup. Thorough benchmarking against the Serpent simulations will be carried out using existing MCNP model.

8. NJOC and PMU

8.1 Overview

Two FinnFusion scientists were seconded to work in the JET operating contract team (NJOC) in 2019. This section highlights the NJOC projects:

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

8.2 NJOC Viewing and thermal measurements diagnostician

Estimation of 2D distributions of electron density and temperature in the JET divertor from tomographic reconstructions of deuterium Balmer line emission

Research scientist: J. Karhunen, AU

Estimates for the 2D distributions of the electron density (n_e) and temperature (T_e) have been obtained using reflection-corrected tomographic reconstructions of deuterium Balmer line emission in the JET divertor in combination with line-integrated spectroscopic measurements of n_e and T_e. The method improves the localization of the line-integrated measurements by indicating the poloidal and radial extents of the n_e and T_e distributions and improves thus the local comparability between experiments and divertor modelling.

A two-dimensional Monte Carlo optimization model, based on intensity ratios between tomographic reconstructions of the Balmer D_α, D_γ and D_ε emission, has been constructed for obtaining n_e and T_e with the help of the ADAS photon emissivity coefficients. Due to the restrictions of the ADAS collisional-radiative model, molecular emission and the potential effects of plasma opacity are not currently considered. The solutions are provided with typical statistical error estimates of 5—15%. The method has been benchmarked with synthetic emission data from a set of EDGE2D-EIRENE simulations, showing reproduction of reference n_e and T_e distributions within 10% and 15%, respectively.

Estimates of n_e during a JET L-mode density ramp pulse show extension and movement of the outer divertor high-n_e region with n_e up to 1.5×10^{21} m^{-3} from the outer strike point towards the X-point within 25% agreement with line-integrated spectroscopic n_e measurements, as the outer divertor proceeds from partial to full detachment (see Figure 8.1). Simultaneously, the divertor T_e is estimated at 0.5-3 eV.

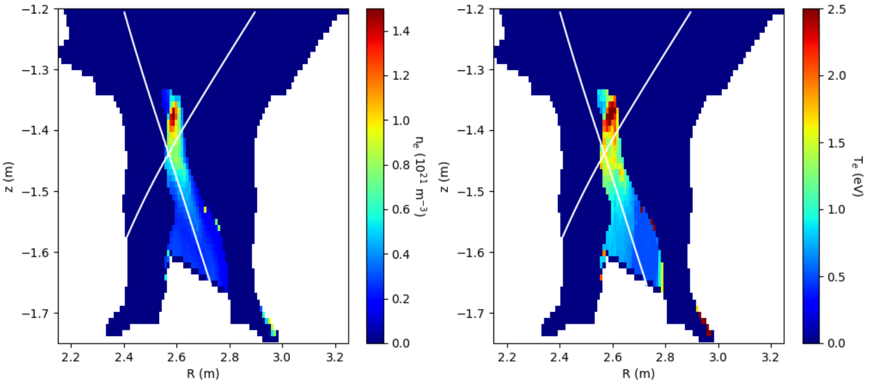


Figure 8.1. 2D distributions of n_e and T_e estimated from tomographic reconstructions of deuterium Balmer line emission in detached outer divertor conditions.

8.3 NJOC ASCOT Code Responsible Officer

JETPEAK-ASCOT: Database-coupled user interface and intershot capability for fast particle analysis and semi-empirical extrapolation to DTE2

Research scientist: P. Siren, VTT

A flexible tool for quick standard fast particle analysis and DT extrapolations has been created by introducing a new interface and coupling between the ASCOT fast particle code and the JETPEAK database. It allows efficient post-processing of large data sets as well as for intershot-analysis during plasma operation with limited time between discharges.

The JETPEAK database is used between plasma pulses for immediate collection and fitting of diagnostics data over user-defined stationary phases of each pulse. The data is automatically read as an input by ASCOT for intershot analysis of, e.g., fast particle density and power deposition, synthetic neutron flux and DT extrapolations of the heating power deposition, fusion power and neutron rate (see Figure 8.2).

The tool has been utilised for DT extrapolations of representative and comprehensive data sets from JET-ILW experiments in baseline and hybrid plasma scenarios. The DT target plasma temperature and density profiles were scaled using the results from regression analysis over large existing JET datasets cumulated during the scenario development experiments over the past 4 years. The tool is flexible and allows different types of extrapolations, including separate scaling of the ion and electron temperature profiles, while retaining typical thermal equipartition between ions and electrons. This is important at high power/low density, when T_i can significantly exceed T_e, substantially boosting to the DT fusion power.

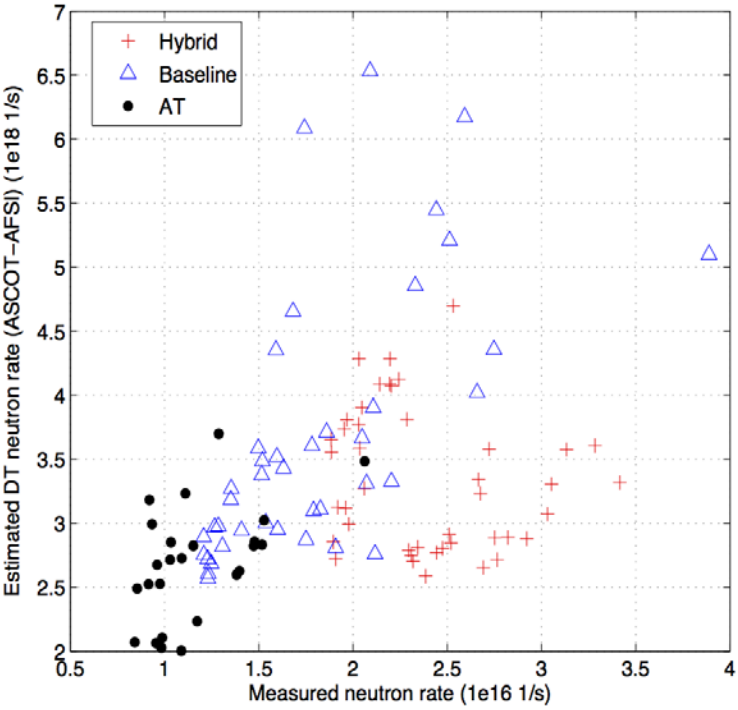


Figure 8.2. Expected neutron rate from DT extrapolation by ASCOT-AFSI for three plasma scenarios.

9. International collaborations

9.1 DIII-D tokamak

Research scientists: M. Groth, 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. 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.

The proposal of a dedicated experiment to measure UV emission at the Lyman-Werner band wavelength range successfully passed the DIII-D Research Opportunity Forum (held February 12–14, 2019) and ensuing experimental planning breakout sessions. The experiment was scheduled for execution in September 2019, then in October 2019, but eventually postponed until 2020 because of delays in the procurement and delivery of the spectrometer.

While awaiting the commissioning of HR-UV, post-processing of EDGE2D-EIRENE simulations for DIII-D and comparison to Divertor Thomson Scattering revealed that the discrepancy between the predictions and the measurements is below the ionisation front in high-recycling and detached divertor conditions (to be presented at PSI 2020). The discrepancy is either driven by overpredicting radial deuteron transport or mispredicting carbon sputtering sources and/or transport. Measurements of the UV emission in JET-ILW in campaign 38 with their available spectrometer systems, and inference of the divertor electron temperature and density using visible spectroscopy is used to resolve the DIII-D carbon complexity. The measurements and EDGE2D-EIRENE predictions for both DIII-D and JET-ILW show that the onset of divertor detachment occurs at around 2 eV, and is related to increased plasma pressure losses due to deuteron-deuterium molecule interaction (to be presented at IAEA-FEC 2020).

9.2 DTU

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

VTT's fusion and optic teams joined forces in a VTT funded project to develop a fibre optic sensor for measuring temperature in fusion relevant conditions. The measurement principle is based on polarisation maintaining (PM) fibre, where in the active part of the sensor, the polarisation changes in response to temperature. The benefit of this scheme over some others is that all the measurement equipment except the active sensor (quartz) can be remote thus avoiding neutron and radiation interference and damage. Also, the melting temperature of quartz is high allowing up to 1000 °C temperatures that might happen e.g. near the surface of the divertor tiles.

Wide band light sources covering 1350-1750 nm range and spectrometers were used in the measurement setup (see Figure 9.1). Mathematical models were developed and compared against the full spectrum measurements in order to eventually replace the light sources with a limited number of cheap lasers allowing both faster time response and economics.

Three different commercially available PM fibres were tested and annealed cyclically to remove hysteresis and stabilise their performance. Various sensors were made in house by fusing 2-20 cm sections of the PM fibre in 45-degree angles w.r.t polarisation axis and tested both in high temperature ovens and at the North tokamak in collaboration with the Technical University of Denmark (DTU). Encouraging results were obtained in up to ~900 °C temperatures showing that the concept is viable and could be integrated in e.g. plasma facing components for practical use.

Figure 9.1. Measurement setup for testing the sensor at the North tokamak, DTU, Copenhagen.

9.3 Ioffe Institute

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

Comparison of FT-2 plasma measurements to gyrokinetic ELMFIRE modelling was carried out in co-operation with FT-2 group located in Ioffe Institute, St. Petersburg, Russia and financed by Academy of Finland. The gyrokinetic simulation results obtained in the limiter vicinity were compared to the probe measurements. Electron density, temperature and plasma potential measured at different poloidal angles was compared but toroidal resolution of ELMFIRE was not high enough which required extrapolation. Comprehensive benchmarking of ELMFIRE against the

Doppler reflectometry data including GAMs was carried out. A very close agreement of the gyrokinetic modeling and FT-2 Doppler reflectometry experiment was demonstrated. Doppler frequency shifts provided by real and fast synthetic O-mode Doppler reflectometry diagnostics seem to be in qualitative agreement. The poloidal velocity of fluctuations deduced from them appears to be a factor of 2 – 4 different from the value obtained directly from the density fluctuations provided by ELMFIRE. Computations for the ETG mode are in progress. The anomalous energy flux associated with the ETG-mode seems to be negligible. The enhanced scattering frequency spectra obtained at the probing in the equatorial plane are used for radial velocity fluctuations determination. The results are shown to be close to the values extracted from the gyrokinetic computations.

9.4 JT-60SA

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

Research scientists: J. Varje, T. Kurki-Suonio, AU

With its combination of low-energy perpendicular and high-energy tangential beams, JT-60SA is featuring a high-energy ion population quite different from JET. Consequently, lessons learned from JET are not necessarily directly applicable. Predictive simulations play an important role, but it is crucial that, once the beams are turned on, the ways to diagnose the fast ion population are in place. While there are reliable methods for observing fast ions lost from the plasma, diagnosing ions confined in the hot plasma is more difficult. Neutrons can provide the key fast ion diagnostic in JT-60SA since neutron sources are dominated by reactions with NBI ions.

The neutron sources in JT-60SA are dramatically different from those at JET mainly due to the very high 500 keV reactant energy, leading to significantly higher DD cross section. Consequently, 3-5 times higher DD neutron fluxes are expected.

Using the ASCOT-AFSI simulation chain, the production of both 2.45 MeV and 14.1 MeV neutrons, from DD and DT reactions, respectively, was assessed as illustrated in Figure 9.2. The beam-thermal fusion is found to dominate in all cases, 60-85 % of the neutrons come from beam-thermal reactions, of which up to 50-70 % are due to the 500 keV beams. It is worth noting that while the overall production of neutrons varies by more than a factor of two between the different scenarios, the differences in the beam-thermal fusion rates are smaller.

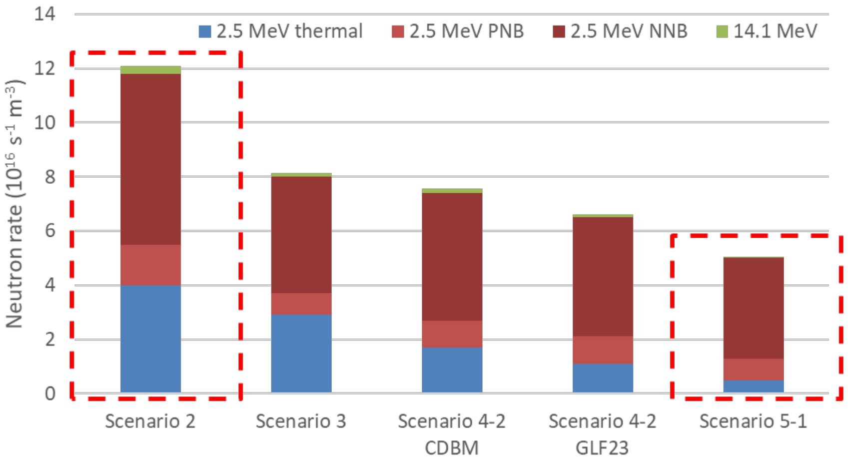


Figure 9.2. Production of 2.45 MeV and 14.1 MeV neutrons in the different JT-60SA scenarios.

9.5 KSTAR tokamak

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

Tuomas Tala and Antti Salmi visited NFRI and KSTAR tokamak in November 2019. The following three mission goals to perform ITPA experiment on KSTAR were set: 1) Establish and optimize the small frequency NBI modulation technique to study intrinsic torque on KSTAR, 2) ρ* scaling of intrinsic torque in KSTAR with respect to JET/DIII-D/AUG and 3) identity point with JET/AUG/DIII-D. KSTAR has long pulse capability (>20s) which is very helpful in measuring accurately the rotation perturbations with reduced noise level. Unfortunately, the KSTAR experimental campaign was prematurely terminated 2 days before the journey due to a serious fault in the NBI system and therefore, the experiment did not take place. The visit was, however, very useful as now the experiment is fully prepared and ready to be run, including all the documentation and discussions with the session leader and key local scientific team. Also now, the diagnostics and plasma control systems are much more familiar after having discussed those issues with the responsible officers during the visit. This experiment is now scheduled for 2020 campaign.

9.6 LHD stellarator collaboration

Research scientists: T.Tala, VTT

T. Tala visited LHD in February with the following two main goals in this visit: 1) exchange the various ways to extract particle transport coefficients from the gas puff modulation data (both from the radial profiles and line integrated profiles) and 2) compare particle transport between tokamak (JET) and stellarator (LHD). JET has put a lot of effort in particle transport experiments and analyses in recent years and a multi-machine activity is on-going within the ITPA framework under the TC-15 joint experiment. One of the emphasis in JET has been on isotope effect and LHD can provide additional information on isotope dependence of particle transport coefficients between D and H. Half of a day was devoted to this experiment on LHD, to complete the isotope scan between deuterium and hydrogen. The experiment was successful, with a fairly good match with the earlier hydrogen experiment with respect to dimensionless match. The diagnostics of density modulation data is different from JET and therefore, the analysis method is also different. A good exchange of ideas and data took place during the visit and the results published in an invited talk in the EPS 2019 conference. Kenji Tanaka, the local host, agreed to visit JET later in 2019.

10. Fusion for Energy activities

10.1 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 diagnostic components. The main function of this system is to route the electrical sensor signals from the divertor area up to the tokamak vacuum boundary. The RHC system operates in high vacuum, high irradiation and high temperature conditions. The system is connected in a limited space via remote handling during the installation of the diagnostic divertor cassettes. There are 16 diagnostic cassettes out of 54 divertor cassettes with five different RHC configurations.

VTT has been working on the Preliminary Design of Remote Handling Connector and Ancillary Components. This continues the work done under the conceptual design phase of the system, where the architecture of the RHC system and the outboard and inboard configurations were decided (see Figure 10.1). The preliminary design is highly impacted by finding an appropriate balance between the external and internal space limitations and system requirements. The design of the system has been an iterative process including mechanical design, thermal, magnetic and structural load analysis, risk analysis, and remote handling assessment. The design alternatives were verified by manufacturing and testing mock-ups. Test environments included Divertor Test Platform 2 (DTP2) and Remote Handling Connector Platform (RHCP) at VTT heavy laboratory.

Development of the system followed the official ITER and F4E PDR processes. PDR review meeting was organized at the end of 2019. The current focus of the project is in the closure of the PDR phase by resolving chits raised during the review meeting. The scope of the PDR phase is to provide the baseline for the final design of the RHC system.

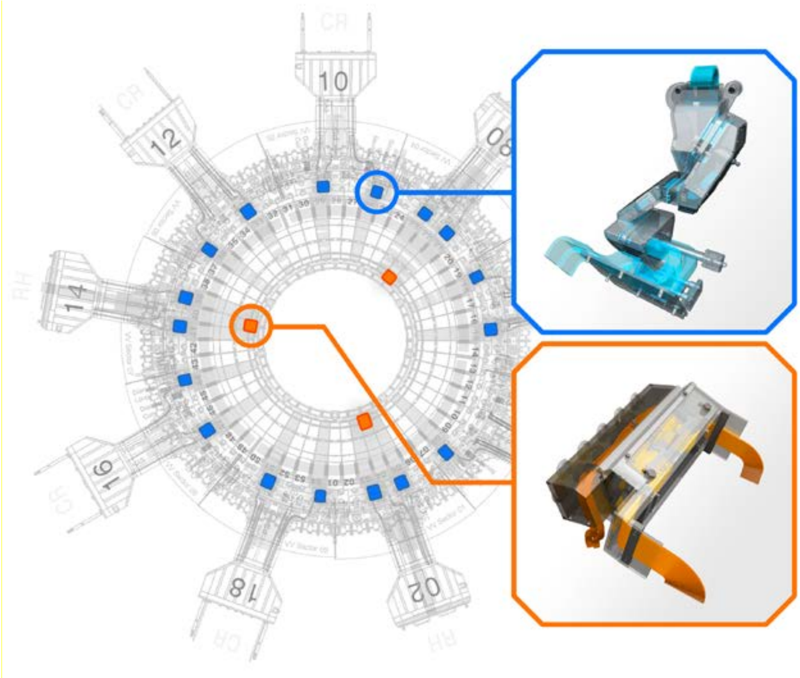


Figure 10.1. RHC inboard and outboard configurations in ITER tokamak.

10.2 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 at the end of 2019. The C&C is the operator user interface application to control the movement of the RH robots. During 2019, the C&C was specified by F4E and VTT to be implemented by GTD, a Spanish system and software engineering company. The VR is used to monitor the movements of the robot in real time, especially where camera views are not possible. In 2019, the requirements for the VR were captured, and a study was carried out to select a commercial-off-the-shelf VR software to be tailored for the ITER RHS.

A development of another RHCS subsystem, Computer Assisted Teleoperation, is coordinated by Tampere University. Purpose of this task is 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 current study aims to recognize the RH Equipment with high accuracy (< 3mm). Also a study on the usage of radiation tolerant markers is included in the task. At the end of 2019, this task was completed and the promising results presented in a workshop to the F4E, ITER Organization and other relevant stakeholders. Tampere University and F4E plan to extend this task to develop the 3D Node system into a real product for ITER usage.

Figure 10.2. A view of the Remote Handling System control room of the Divertor Test Platform (DTP2) at VTT.

11. Other activities

11.1 Missions and secondments

Antti Hakola to IPP Garching, Garching, Germany, 17–23 January 2019 (WP MST1).

Tuomas Tala to JET facilities, Culham, United Kingdom, 21–25 January 2019 (WPJET1).

Mathias Groth IPP Garching, Garching, Germany 22–25 January 2019 (WP MST1).

Antti Hakola to IPP Garching, Garching, Germany, 28 January–8 February 2019 (WP MST1).

Aki Lahtinen to IPP Garching, Garching, Germany, 28 January–1 February 2019 (WP MST1).

Tuomas Tala to NIFS, Toki, Japan, 2–8 February 2019 (International Collaborations).

Jari Likonen to NILPRP, Bucharest, Romania, 4–6 February 2019 (WP JET2).

Mathias Groth to DIII-D/General Atomics, San Diego, California, USA, 7–22 February 2019 (International Collaborations).

Antti Hakola to CCFE, Abingdon, United Kingdom, 11–13 February 2019 (WP MST1).

Jari Likonen to IPP Garching, Garching, Germany, 17–27 February 2019 (WP MST1).

Antti Hakola to IPP Garching, Garching, Germany, 17–28 February 2019 (WP MST1).

Aki Lahtinen to IPP Garching, Garching, Germany, 18 February–8 March 2019 (WP MST1).

Tuomas Tala to JET facilities, Culham, United Kingdom, 4–13 March 2019 (WPJET1).

Jari Varje to JET facilities, United Kingdom, 4–15 March 2019 (WP JET1).

Mathias Groth and Henri Kumpulainen to JET facilities, United Kingdom, 11–15 March 2019 (WP JET1).

Antti Hakola to IPP Garching, Garching, Germany, 18–21 March 2019 (WP MST1).

Jari Likonen to JET facilities, United Kingdom, 25–29 March 2019 (WP JET2).

Antti Hakola to IPP Garching, Garching, Germany, 7–16 April 2019 (WP MST1).

Jari Likonen to IPP Garching, Garching, Germany, 26 April 2019 (WP MST1).

Aki Lahtinen to IPP Garching, Garching, Germany, 6–10 May 2019 (WP MST1).

Antti Hakola to IPP Garching, Garching, Germany, 6–16 May 2019 (WP MST1).

Tuomas Tala to IPP Garching, Garching, Germany, 20–24 May 2019 (WP MST1).

Antti Hakola to IPP Garching, Garching, Germany, 4–6 June 2019 (WP MST1).

Jari Likonen to IPP Garching, Garching, Germany, 4–20 June 2019 (WP MST1).

Jari Varje to JET facilities, United Kingdom, 10 June–23 August 2019 (WP JET1).

Aki Lahtinen to IPP Garching, Garching, Germany, 11–14 June 2019 (WP MST1).

Antti Hakola to IPP Garching, Garching, Germany, 12–20 June 2019 (WP MST1).

Tuomas Tala to JET facilities, Culham, United Kingdom, 14–25 June 2019 (WPJET1).

Patrik Ollus to CCFE, Abingdon, United Kingdom, 24 June–4 July 2019.

Antti Hakola to IPP Garching, Garching, Germany, 1–5 July 2019 (WP MST1).

Antti Hakola to IPP Garching, Garching, Germany, 14–19 July 2019 (WP MST1).

Tuomas Tala to JET facilities, Culham, United Kingdom, 15–16 July 2019 (WPJET1).

Aki Lahtinen to IPP Garching, Garching, Germany, 15–19 July 2019 (WP MST1).

Mathias Groth and Henri Kumpulainen to JET facilities, United Kingdom, 22–27 July 2019 (WP JET1).

Tuomas Tala to IPP Garching, Garching, Germany, 19–23 August 2019 (WP MST1).

Tuomas Tala to JET facilities, Culham, United Kingdom, 2–5 September 2019 (WPJET1).

Seppo Sipilä to IPP Garching, Garching, Germany, 2–6 September 2019 (WP MST1).

Henri Kumpulainen to JET facilities, United Kingdom, 2–13 September 2019 (WP JET1).

Antti Hakola to EPFL, Lausanne, Switzerland, 3–11 September 2019 (WP MST1).

Tuomas Tala to JET facilities, Culham, United Kingdom, 9–10 September 2019 (WPJET1).

Jari Varje to JET facilities, United Kingdom, 9 September–18 October 2019 (WP JET1).

Tuomas Tala to JET facilities, Culham, United Kingdom, 16–19 September 2019 (WPJET1).

Antti Hakola to CEA, Cadarache, France, 23–26 September 2019 (WP MST1).

Tuomas Tala to JET facilities, Culham, United Kingdom, 30 September–2 October 2019 (WPJET1).

Antti Hakola to EPFL, Lausanne, Switzerland, 30 September–3 October 2019 (WP MST1).

Antti Hakola to EPFL, Lausanne, Switzerland, 6–11 October 2019 (WP MST1).

Jari Likonen to JET facilities, United Kingdom, 13–19 October 2019 (WP JET2).

Jari Varje to IPP Garching, Germany, 21–25 October 2019 (WP MST1).

Antti Hakola to IPP Garching, Garching, Germany, 22–24 October 2019 (WP MST1).

Antti Hakola to IPP Garching, Garching, Germany, 28–31 October 2019 (WP MST1).

Jari Varje to JET facilities, United Kingdom, 4–22 November 2019 (WP JET1).

Antti Hakola to EPFL, Lausanne, Switzerland, 7–13 November 2019 (WP MST1).

Tuomas Tala to JET facilities, Culham, United Kingdom, 11–15 November 2019 (WPJET1).

Tuomas Tala to NFRI/KSTAR, Toki, Japan, 16–22 November 2019 (International Collaborations).

Henri Kumpulainen to JET facilities, United Kingdom, 18–29 November 2019 (WP JET1).

Antti Hakola to IPP Garching, Garching, Germany, 25–27 November 2019 (WP MST1).

Tuomas Tala to JET facilities, Culham, United Kingdom, 25–28 November 2019 (WPJET1).

Aki Lahtinen to IPP Garching, Garching, Germany, 2–6 December 2019 (WP MST1).

Seppo Sipilä to IPP Garching, Garching, Germany, 2–12 December 2019 (WP MST1).

Patrik Ollus to MAST-U facilities, Abingdon, United Kingdom, 2–13 December 2019.

William Brace to CCFE, Abingdon, United Kingdom, 15–20 December 2019.

Joona Kontula to MPG-Greifswald - Greifswald, Germany, 15–21 December 2019.

Antti Hakola to IPP Garching, Garching, Germany, 16–19 December 2019 (WP MST1).

Jari Likonen to IPP Garching, Garching, Germany, 16 December 2019 (WP MST1).

Jari Likonen to JET facilities, United Kingdom, 17–19 December 2019 (WP JET2).

11.2 Conferences, seminars, workshops and meetings

Johannes Hyrynen and Mikko Siuko participated in the ISFRHT 2019 meeting, CCFE, Abingdon, United Kingdom, 18–21 February 2019.

Huapeng Wu participated in the seminar on RM in RACE, CCFE, Abingdon, United Kingdom, 18–23 February 2019.

William Brace participated in the meeting of experts in the divertor integration, IPP Garching, Garching, Germany, 19–22 February 2019.

Jari Varje participated in WPCD annual planning meeting, CINECA, Bologna, Italy, 26 February–1 March 2019 (WP CD).

Leena Aho-Mantila, Markus Airila, William Brace, Taina Kurki-Suonio, Antti Salmi, Andrea Sand and Tuomas Tala participated in 1st EUROfusion DEMO Workshop, Espoo, Finland, 27–28 February 2019.

Fredrik Granberg and Antti Hakola participated in the Physics Days 2019, Helsinki, Finland, 5–7 March 2019.

Jari Varje participated in WPSA project planning meeting, US, Sevilla, Spain, 18–22 March 2019 (WP CD).

Tuomas Tala participated in the TC ITPA meeting, Austin, United States, 24–28 March 2019.

Atte Helminen and Tero Tyrväinen participated in WPENS technical meeting #7, CIEMAT, Granada, Spain, 25–30 March 2019.

Jari Varje and Seppo Sipilä participated in ITER IMAS code camp, CEA, Cadarache, France, 1–5 April 2019 (WPCD).

Joona Kontula, Taina Kurki-Suonio, Patrik Ollus, Seppo Sipilä, Antti Snicker, Konsta Särkimäki and Jari Varje participated in ITPA Energetic Particle meeting, Rovaniemi, Finland, 8–11 April 2019.

Fredrik Granberg and Kai Nordlund participated in Atomistic Simulations of Carbon-Based Materials workshop, Helsinki, Finland, 10–12 April.

Tuomas Tala participated in the EUROfusion General Assembly meeting, Fracati, Italy, 16–17 April 2019.

Taina Kurki-Suonio participated in the JEFF and Kick-off meetings for tasks PMI-7.4 and PMI-7.5, Boulogne-Billancourt, France, 24–25 April 2019.

Juuso Karhunen, Paula Sirén and Jari Varje participated in the 3rd European Conference on Plasma Diagnostics, Lisbon, Portugal, 6–9 May 2019.

Henri Kumpulainen participated in Joint ICTP-IAEA School for Atomic and Molecular Spectroscopy in Plasmas, Trieste, Italy 6–10 May 2019.

Marton Szogradi participated in 1st WPBOP Design Progress Review Meeting, IPP Garching, Garching, Germany, 7–8 May 2019.

Tuomas Tala participated in the JET General Planning Meeting, CCFE, Abingdon, United Kingdom, 12–15 May 2019.

William Brace and Mikko Siuko participated in 1st Design Review WPRM meeting, IPP Garching, Garching, Germany, 13–16 May 2019.

Antti Hakola and Etienne Hodille participated in 17th International Conference on Plasma-Facing Materials and Components for Fusion Applications (PFMC-17), Eindhoven, Netherlands, 20–24 May 2019.

Fredric Granberg and Andrea Sand participated in ENR-PRD-IREMEV monitoring meeting, KTH, Stockholm, Sweden, 2–5 June 2019.

William Brace, Jesper Byggmästar, Antti Hakola, Etienne Hodille, Ari Hokkanen, Lionel Hulttinen, Changyang Li, Henri Kumpulainen, Taina Kurki-Suonio, Shayan Moradkhani, Pauli Mustalahti, Longchuan Niu, Andrea Sand, Antti Snicker, Vladimir Solokha, Konsta Särkimäki and Tuomas Tala participated in 3rd Joint Nordic Fusion Energy Seminar, Copenhagen, Denmark, 11–12 June 2019.

Tommy Ahlgren participated in 4th International Workshop on Models and Data for Plasma-Material Interaction in Fusion Devices, NIFS, Gifu, Japan, 15–21 June 2019.

Fredrik Granberg participated in 10th International Workshop on Nanoscale Pattern Formation at Surfaces, Guildford, United Kingdom, 7–10 July 2019.

Henri Kumpulainen and Taina Kurki-Suonio participated in 46th European Physical Society Conference on Plasma Physics, Milan, Italy, 8–12 July 2019.

Tuomas Tala participated in the EUROfusion General Assembly meeting, Riga, Latvia, 17–18 July 2019.

Aslak Fellman and Andrea Sand participated in AtomCRaD meeting, University of Manchester, Manchester, United Kingdom, 22–26 July 2019.

Tuomas Tala participated in the NORTH-tokamak opening ceremony at DTU, Copenhagen, Denmark, 22–23 August 2019.

Antti Snicker participated in 23rd ITPA-EPP meeting, Naga, Japan, 9–11 September 2019.

William Brace, Olli Rantanen, Janne Saukkoriipi and Mikko Siuko participated in collaboration meeting between RACE and VTT, CCFE, Abingdon, United Kingdom, 15–21 September 2019.

Antti Salmi participated in ITPA T&C meeting, Hefei, China, 13–18 October 2019.

Eero Hirvijoki participated NUMKIN2019 meeting in IPP Garhing, Germany, 14–18 October 2019.

Antti Hakola participated in the ASDEX Upgrade Programme Seminar, Ringberg, Germany, 4–6 November 2019.

Leena Aho-Mantila participated in Third IAEA Technical Meeting on Divertor Concepts, IAEA Headquarters, Vienna, Austria, 4–7 November 2019.

Niels Horsten participated in interview for EUROfusion researcher grant, IPP Garching, Garching, Germany, 29–31 October 2019.

Antti Salmi and Tuomas Tala participated in in the ITPA TC-17 experiment, NFRI, Daejeon, Korea, 16–22 November 2019 (International Collaborations).

Antti Hakola participated in WPJET2-WPPFC Annual Meeting, CU, Bratislava, Slovakia, 18–21 November 2019.

Taina Kurki-Suonio, Antti Snicker and Konsta Särkimäki organized EUROfusion-coordinated ASCOT training sesssion, Aalto University, Espoo, Finland, 25–29 November 2019.

Jari Likonen participated in MST1 core transport, H&CD and integrated scenario modelling working session, IPP Garching, Garching, Germany, 25–29 November 2019.

Atte Helminen and Olli Suurnäkki participated in WPENS technical meeting #8, ENEA, Frascati, Italy, 18–21 November 2019.

Fredric Granberg participated in IREMEV Monitoring meeting, NCSRD, Athens, Greece, 27–29 November 2019.

Antti Hakola participated in EFPW meeting, Moulin de Vernègues, France, 2–5 December 2019.

Tuomas Tala participated in the F4E Governing Board meeting, Barcelona, Spain, 9–10 December 2019.

Tuomas Tala participated in the EUROfusion General Assembly meeting, Riga, Latvia, 16–17 December 2019.

11.3 Visitors

Prof. Yuji Hatano and Sun Eui Lee from Toyama University visited VTT, 28 January–1 February 2019.

Elizabeth Tolman from MIT visited Aalto University, 28 January–8 February 2019.

Leonid Askinazi, Alexey Gurchenko, Evgeniy Gusako, Mikael Irzak, Denis Kouprienko, Sergey Lashkul and Anton Sidorov from Ioffe Institute visited Aalto University, 4–8 February 2019.

Salomon Janhunen from University of Texas visited Aalto University, 4–18 February 2019.

Juuso Karhunen from CCFE, Alicia Marín-Roldán and Pavel Veis from Comenius University, and Peeter Paris from Tartu University visited VTT, 24–28 June 2019.

Leon Kos from University of Ljubljana, was a visiting researcher at Aalto University, 6 May–29 June 2019.

Alain Brizard from St. Michael's college Vermont visited Aalto University 8–19 July 2019.

Giorgos Anastassiou from National Technical University of Athens, Nikolay Bakharev from Ioffe Institute, Marcelo Baquero from EPFL, Klara Bogar from IPP-CR, Kenneth Cage from University of Irvine, Sam Lazerson from IPP-Greifswald, Clive Michael from CCFE, Sadig Mulam from CIEMAT, Enrico Panontin from University of Milano-Bicocca, Juan F. Rivero from CIEMAT, Andrea Sperduti from Uppsala University, Lorenzo Stipani from EPFL and Pietro Vincenzi from Consortio RFX participated in ASCOT training session, Aalto University, 25–29 November 2019.

Minh-Tran from EPFL, visited Aalto University for Konsta Särkimäki’s PhD thesis, 26–27 November 2019.

Leonid Askinazi, Alexander Belokurov, Alexey Gurchenko, Evgeniy Gusakov, Oksana Kaledina, Denis Kouprienko and Sergey Lashkul from Ioffe Institute visited Aalto University, 16–20 December 2019.

Salomon Janhunen from University of Texas visited Aalto University, 16–20 December 2019.

Publications 2019

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

11.4 Publications

11.4.1 Refereed journal articles

1. H. Roozbahani and H. Handroos, A novel haptic interface and universal control strategy for International Thermonuclear Experimental Reactor (ITER) welding/machining assembly robot, Robotics and Computer-Integrated Manufacturing **57** (2019) 255.
2. J. Byggmästar, A. Hamedani, K. Nordlund and F. Djurabekova, Machine-learning interatomic potential for radiation damage and defects in tungsten, Physical Review B **100** (2019) 144105.
3. E.A. Hodille, S. Markelj, T. Schwarz-Selinger, A. Zaloznik, M. Pecovnik, M. Kelemen and C. Grisolia, Stabilization of defects by the presence of hydrogen in tungsten: simultaneous W-ion damaging and D-atom exposure, Nuclear Fusion **59** (2019) 16011.
4. T. Ahlgren, P. Jalkanen, K. Mizohata, V. Tuboltsev, J. Räisänen, K. Heinola and P.O. Tikkanen, Hydrogen isotope exchange in tungsten during annealing in hydrogen atmosphere, Nuclear Fusion **59** (2019) 26016.
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7. O.L. Krutkin, A.B. Altukhov, A.D. Gurchenko, E.Z. Gusakov, M.A. Irzak, L.A. Esipov, A.V. Sidorov, L. Chôné, T.P. Kiviniemi, S. Leerink, P. Niskala, C. Lechte, S. Heuraux and G. Zadvitskiy, Validation of full-f global gyrokinetic modeling results against the FT-2 tokamak Doppler reflectometry data using synthetic diagnostics, Nuclear Fusion **59** **(**2019) 96017.
8. M. Ajmalghan, Z.A Piazza, E. A. Hodille and Y. Ferro, Surface coverage dependent mechanisms for the absorption and desorption of hydrogen from the W(110) and W(100) surfaces: a density functional theory investigation, Nuclear Fusion **59** (2019) 106022.
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10. E. Joffrin, S. Abduallev, M. Abhangi, P. Abreu, V. Afanasev, M. Afzal, K.M. Aggarwal, T. Ahlgren, L. Aho-Mantila, N. Aiba, M. Airila, O. Asunta, M. Groth, A. Hakola, K. Heinola, J. Karhunen, S. Leerink, J. Likonen, A. Salmi, M.I.K. Santala, J. Simpson, S.K. Sipilä, P. Sirén, T. Tala and J. Varje, Overview of the JET preparation for deuterium–tritium operation with the ITER like-wall, Nuclear Fusion **59** **(**2019) 112021.

11. S. Coda, M. Agostini, R. Albanese, S. Alberti, E. Alessi, S. Allan, J. Allcock, R. Ambrosino, H. Anand, Y. Andrèbe and T. Tala, Physics research on the TCV tokamak facility: from conventional to alternative scenarios and beyond, Nuclear Fusion **59** (2019) 112023.

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13. T. Tala, H. Nordman, A. Salmi, C. Bourdelle, J. Citrin, A. Czarnecka, F. Eriksson, E. Fransson, C. Giroud, J. Hillesheim, C. Maggi, P. Mantica, A. Mariani, M. Maslov, L. Meneses, S. Menmuir, S. Mordijck, V. Naulin, M. Oberparleiter and G. Sips, Density Peaking in JET - Driven by Fuelling or Transport? Nuclear Fusion **59** (2019) 126030.

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18. J. Byggmästar, M. Nagel, K. Albe, K. O. E. Henriksson and K. Nordlund, Analytical interatomic bond-order potential for simulations of oxygen defects in iron, Journal of Physics: Condensed Matter **31** (2019) 215401.

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31. M.Groth, E.M.Hollmann, A.E.Järvinen, A.W.Leonard, A.G.McLean, C.M.Samuell, D.Reiter, S.L.Allen, P.Boerner, S.Brezinsek, I.Bykov, G.Corrigan, M.E.Fenstermacher, D.Harting, C.J.Lasnier, B.Lomanowski, M.A.Makowski, M.W.Shaferg and R.S.Wilcoxg, EDGE2D-EIRENE predictions of molecular emission in DIII-D high-recycling divertor plasmas, Nuclear Materials and Energy **19** (2019) 211.

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46. H. Ji, J. Wu, H. Wu, Z. Liu, J. Ma and X. Fan, Analysis of welding deformation on CFETR 1/32 vacuum vessel mockup, Fusion Engineering and Design **144** (2019) 160.
47. A. Litnovsky, J. Peng, A. Kreter, M. Rasinski, K. Nordlund, F. Granberg, J. Jussila, U. Breuer and Ch. Linsmeier, Optimization of single crystal mirrors for ITER diagnostics, Fusion Engineering and Design **146** (2019) 1450.
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63. D. S. Meluzova, P.Y. Babenko, A.P., Shergin, K. Nordlund and A.N. Zinoviev, Reflection of hydrogen and deuterium atoms from the beryllium, carbon, tungsten surfaces, Nuclear Instruments & Methods in Physics Research. Section B: Beam Interactions with Materials and Atoms **460** (2019) 4.

64. T. Zhang, Y. Song, H. Wu, H. Handroos, Y. Cheng and X. Zhang, Deformation modeling of remote handling EAMA robot by recurrent neural networks, Industrial Robot: An International Journal **46** (2019) 300.

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11.4.2 Conference presentations

70. A. Hakola, K. Heinola, K. Mizohata, J. Likonen, C. Lungu, C. Porosnicu, E. Alves, R. Mateus, I. Bogdanovic Radovic, Z. Siketic, V. Nemanic, C. Pardanaud and EUROfusion WP PFC Contributors, Production of ITER-relevant deposited layers for fuel-retention investigations, Physics Days 2019, Helsinki, Finland, 5–7 March 2019, paper A141.

71. K. Krieger, M. Balden, B. Böswirth, P. de Marne, R. Dux, H. Greuner, V. Rohde, B. Sieglin, J.W. Coenen, B. Göths, Th. Löwenhoff, A. Hakola, A. Lahtinen, J. Likonen, G. de Temmerman and the ASDEX Upgrade Team, Impact of H-mode plasma operation on pre-damaged tungsten divertor tiles in ASDEX Upgrade, 17th International Conference on Plasma-Facing Materials and Components for Fusion Applications, Eindhoven, Netherlands, 20–24 May 2019, paper O-3.

72. A. Hakola, K. Heinola, K. Mizohata, J. Likonen, C. Lungu, C. Porosnicu, E. Alves, R. Mateus, I. Bogdanovic Radovic, Z. Siketic, V. Nemanic, C. Pardanaud and EUROfusion WP PFC Contributors, Effect of surface temperature on fuel retention and structure of Be-containing co-deposited layers, 17th International Conference on Plasma-Facing Materials and Components for Fusion Applications, Eindhoven, Netherlands, 20–24 May 2019, paper O-4.

73. M. Kelemen, P. Pelicon, S. Markelj, E. Vassallo, D. Dellasega, M. Passoni ,T. Schwarz-Selinger and A. Hakola, Angular dependence of W and Mo erosion yield studied on

textured surfaces with keV D ions, 17th International Conference on Plasma-Facing Materials and Components for Fusion Applications, Eindhoven, Netherlands, 20–24 May 2019, paper PA013.

74. M. Kumar, C. Pardanaud, C. Martin, P. Roubin, Y. Ferro, C. P. Lungu, C Porosnicu, V. Nemanic and A. Hakola, Detection of D2 molecules, C-D and Be-O-D bonds in beryllium co-deposits mimicking JET tile 1 deposits by means of Raman microspectrometry, 17th International Conference on Plasma-Facing Materials and Components for Fusion Applications, Eindhoven, Netherlands, 20–24 May 2019, paper PB015.

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11.4.3 Research reports

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Title	**FinnFusion Yearbook 2019**
Author(s)	Jari Likonen (Ed.)
Abstract	This Yearbook summarises the 2019 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 2019 focused on system level design for ITER Remote Handling Connector and on the development of the High Level Control System subsystems for ITER Remote Handling System. EUROfusion supports post-graduate training through the Education work package that allowed FinnFusion to partly fund 13 PhD students in FinnFusion member organizations. In addition, two EUROfusion post-doctoral research and engineering fellowships were running in 2019. In 2019, FinnFusion organized two major fusion events in Finland: the first DEMO workshop together with EUROfusion at VTT in Espoo and an ITPA meeting on energetic particles in Rovaniemi.
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Nimeke	**FinnFusion Yearbook 2019**
Tekijä(t)	Jari Likonen (toim.)
Tiivistelmä	Tähän vuosikirjaan on koottu FinnFusion-konsortion vuoden 2019 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) ja ohjelmistokehitykseen. EUROfusion tukee jatko-opiskelua omalla rahoitusinstrumentillaan, jonka turvin FinnFusion rahoitti osittain 13 jatko-opiskelijan työtä jäsenorganisaatioissaan. Lisäksi vuoden 2019 aikana oli käynnissä kaksi EUROfusionin rahoittamaa tutkijatohtorin projektia. FinnFusion järjesti kaksi merkittävää kokousta Suomessa v. 2019: DEMO kokouksen yhdessä EUROfusionin kanssa VTT:llä Espoossa ja energeettisten partikkelien ITPA-kokouksen Rovaniemellä.
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