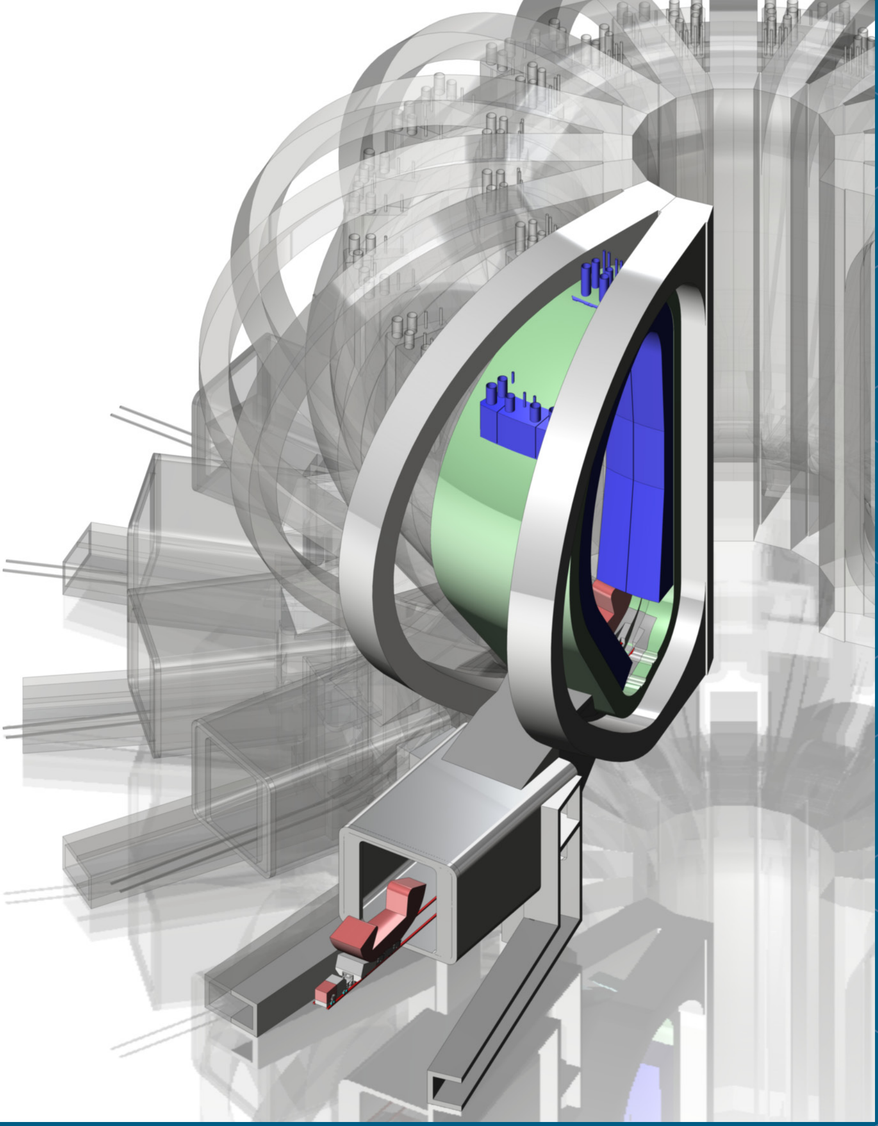


VTT

beyond
the obvious

FinnFusion Yearbook 2018

Jari Likonen | Markus Airila (Eds.) |

VTT TECHNOLOGY 352

VTT TECHNOLOGY 352

FinnFusion Yearbook 2018

Jari Likonen and Markus Airila (Eds.)

VTT Technical Research Centre of Finland Ltd

ISBN 978-951-38-8686-8 (Soft back ed.)
ISBN 978-951-38-8685-1

VTT Technology 352

ISSN-L 2242-1211
ISSN 2242-1211 (Print)
ISSN 2242-122X (Online)
DOI: 10.32040/2242-122X.2019.T352

Copyright © VTT 2019

JULKAISIJA – PUBLISHER

VTT
PL 1000
02044 VTT
Puh. 020 722 111
https://www.vtt.fi

VTT
P.O. Box 1000
FI-02044 VTT, Finland
Tel. +358 20 722 111
https://www.vttresearch.com

PunaMusta Oy, Helsinki 2019

Preface

Acting fast is vital as climate change needs to be battled right now. Energy from fossil fuels must be replaced by CO_2 free energy. There is tremendous and worldwide effort in the development of renewables as wind and solar, in combination with storage in lakes, batteries and chemical fuels. Fusion will most probably not contribute significantly to the CO_2 transition by 2050, but given its inherent advantages (safe, low physical footprint, abundant availability of fuel) it has the potential to deliver an important part of the world's energy need later in time. The new EUROfusion "Fusion Roadmap" has been written with all this in mind; it shows a realistic time path towards a fusion reactor while trying to minimise risks as much as possible by proposing a dedicated research plan.

For the past three years, the ITER project has sustained a vigorous pace and robust performance, with the ITER Organization and Domestic Agencies working as an integrated One-ITER team to meet the project's demanding schedule and the ground-breaking technical requirements of this first-of-a-kind machine. Looking toward the coming Tokamak Building delivery and transition to Machine Assembly phase, all the efforts are pushed to keep the project on track for success.

The Tokamak Concrete Crown civil works were completed on schedule in August 2018 by Fusion for Energy. Three US supplied drain tanks and four Chinese supplied vapour suppression tanks were installed the same month, the first Korean supplied vacuum vessel sector is more than 80% finished. Russia has completed its production of poloidal field conductor for the magnet system. India has nearly completed fabrication of the cryostat lower cylinder and base. The manufacturing of toroidal field coil winding packs, as well as cold testing and insertion of the winding packs into precision fabricated cases, is well advanced in Europe and Japan. Indeed, substantial progress is ongoing for every major ITER component, system and structure.

On the EUROfusion side, recent highlights are Wendelstein 7-X's world record triple product (density times temperature times confinement time characterising the overall performance level towards power plant conditions) ever achieved in stellarator. Another highlight is that a full power year of ITER divertor heat load on the tungsten tiles was mimicked in MAGNUM-PSI. JET is preparing first for 100% tritium campaign and later in 2020, a full DT campaign, for the first time since 1997. However, on the brink of Brexit, the fate of the world's largest tokamak and the only one with DT capability and further the date of the whole DT campaign is endangered. Related to this, I had the pleasure to meet Prince Andrew, Duke of York, who visited JET in March 2018, to tell the Prince about the importance of JET on the European fusion program. A major question mark hangs over the future of JET beyond 2020 and this formed the background of Prince Andrew's visit where the importance of JET to the EU fusion program was described to the Prince.

In June 2018, the FinnFusion annual seminar was organised in Espoo. It was the largest national annual seminar with 60 participants from Finnish research organisations and companies involved in fusion research. The special topic of the seminar was the IFMIF-DONES Material Research Facility currently proposed to be constructed in Granada, Spain. Fortum, University of Helsinki and VTT are actively participating in the research of material neutron damage, safety assessments and licencing of the facility. The second special session was on FinnFusion commercial fusion projects, presented by Comatec, Fortum, Luvata, Suisto Engineering, Tamlink and VTT.

Looking ahead toward the next European Framework Program FP9 in 2021-2027, a recent public hearing organized by the Budgetary Control Committee of the European Parliament has shed light on the significant impact of ITER in terms of economic benefits and job creation. According to Massimo Garribba, Director at EC's Directorate-General for Energy, ITER has produced almost EUR 4.8 billion in gross value added and almost 34,000 "job years" over the period 2008-2017 by awarding over 900 contracts and grants in 24 countries of the EU. European companies report that working for ITER generates a new knowledge base, offers new business opportunities and increases their competitiveness and growth, helping to create additional jobs.

The message from European Parliament hearing is a very important one and should be considered with care also within the Finnish political decision bodies when discussing the funding of the Finnish fusion research. After Tekes ended the programme-type funding in 2017, we have not been able to find a politically agreed way to fund the Finnish fusion program. It would be critically important to restore and enable strategic steering by collecting all parts of fusion research again into a national research programme. Europe is politically strongly committed for the next 40 years to promote economically viable fusion energy. As a member of EU, Finland is also politically expected to be engaged into construction and use of ITER as well as the supporting research. Fusion research is a classical example on research taking place on several multi-disciplinary and novel high-tech areas with international networking being the key for success. Fusion research is such a massive area of research in Europe that Finland simply cannot afford to be vaguely involved or stay outside of it!

Tuomas Tala
Head of Research Unit
FinnFusion Consortium

Contents

Abstract
Tiivistelmä

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)
EAMA	Articulated serial manipulator on EAST tokamak
EAST	Experimental Advanced Superconducting Tokamak
ECRH	Electron cyclotron resonance heating
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
ETS	European transport solver (simulation code)
EUROFER	The European Steel Association (also steel type)

EUROfusion	European consortium implementing the Fusion Roadmap
F4E	Fusion for Energy (the European Domestic Agency of ITER)
FT-2	Tokamak facility
HCD	Heating and current drive
HCPB	Helium Cooled Pebble Bed
HFGC	High-field side gap closure tile in JET vessel
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)
ITG	Ion temperature gradient
ITPA	International Tokamak Physics Activity
JET	Joint European Torus (tokamak facility)
JINTRAC	Set of plasma simulation codes
KSTAR	Korea Superconducting Tokamak Advanced Research (tokamak facility)
LIBS	Laser induced breakdown spectroscopy
LUT	Lappeenranta University of Technology
MAST	Mega Amp Spherical Tokamak (tokamak facility)
MAST-U	MAST Upgrade
MD	Molecular dynamics (simulation method)
MEAE	Ministry of Economic Affairs and Employment (in Finland)
NBI	Neutral beam injection
NJOC	New JET Operating Contract
PCS	Power conversion system
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
ROViR	Remote Operation and Virtual Reality (research facility at VTT)
RU	Research Unit (member of EUROfusion)
Serpent	Monte Carlo reactor physics simulation code developed at VTT
SIMS	Secondary ion mass spectrometry
SOL	Scrape-off layer
SOLPS	Scrape-off Layer Plasma Simulation (fluid plasma simulation code)
TCV	Tokamak à Configuration Variable (tokamak facility)
TDS	Thermal desorption spectrometry
TOF-ERDA	Time-of-flight elastic recoil detection analysis
Tekes	The Finnish Funding Agency for Innovation
TEM	Trapped electron mode
TUMAN-3M	Tokamak facility
UH	University of Helsinki
TUT	Tampere University of Technology
VDE	Vertical displacement event
VTT	VTT Technical Research Centre of Finland Ltd
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.

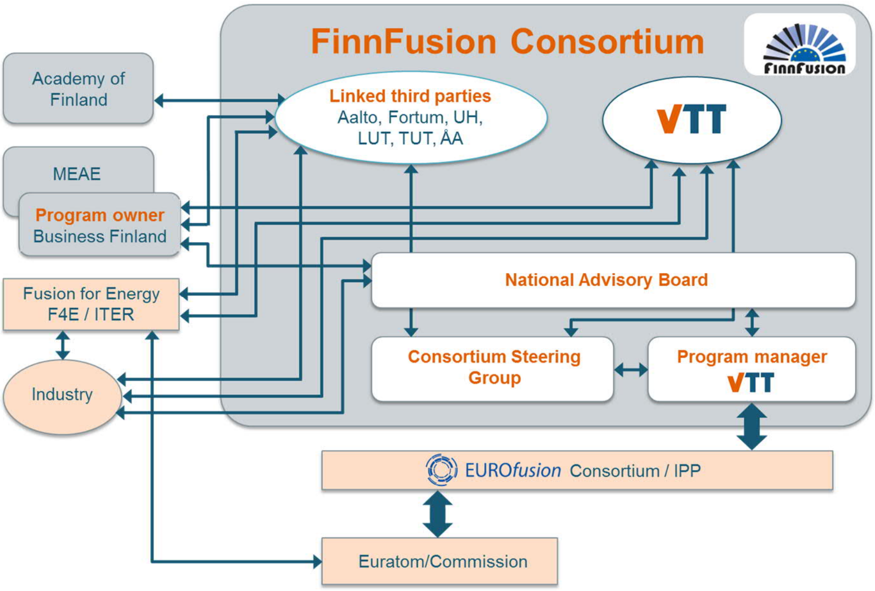


Figure 1.1. Organigram of Finnish Fusion Research Community in 2015–2020.

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 2018:

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: Safety engineering
Members: MSc. Toni Ahonen, MSc. Atte Helminen (Project Manager), Lic.Tech. Ilkka Karanta, MSc Timo Malm Dr. Anna Matala, MSc. Topi Sikanen, MSc. Risto Tuominen, MSc. Tero Tyrväinen, MSc. Pasi Valkokari

Activities: Remote handling, DTP2
Members: MSc. Jarmo Alanen, Dr. William Brace (Project Manager), Tech. Vesa Hämäläinen, MSc. Hannu Martikainen, MSc. Joni Minkkinen Dr. Ali Muhammad, MSc. Harri Mäkinen, MSc. Teemu Mätäsniemi, Dr. Timo Määttä (Project Manager), Dr. Olli Saarela, MSc. Hannu Saarinen, MSc. Karoliina Salminen, Dr. Romain Sibois, Lic.Tech. Mikko Siuko, MSc. Petri Tikka, Dr. Risto Tiusanen, MSc. Outi Venho-Ahonen, MSc. Jarno Videnoja
Student: Olli Rantanen

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

Activities: Physics
Members: Prof. Mathias Groth (Head of Laboratory), Dr. Laurent Chôné, Dr. Juuso Karhunen, Dr. Timo Kiviniemi, M.Sc. Joona Kontula, Dr. Taina Kurki-Suonio, Dr. Susan Leerink, Dr. Bartosz Lomawoski, Dr. Paavo Niskala, Dr. Seppo Sipilä, Dr. Antti Snicker, Dr. Christos Stavrou, MSc. Ivan Paradela Perez, MSc. Konsta Särkimäki, MSc. Vladimir Solokha, MSc Jari Varje, M.Sc. Andreas Holm, Henri Kumpulainen, Patrik Ollus
Students: Emil af Björkesten, Oscar Björklund, Joel Kilpeläinen, Unna Lauranto, Mohammad Hashemi, Vladimir Solokha, Antti Virtanen

Lappeenranta University of Technology (LUT)[1], 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 of Technology (TUT)[2]

Activities: Remote handling, DTP2
Members: MSc. Liisa Aha, MSc. Lionel Hulttinen, Dr. Janne Koivumäki, Prof. Jouni Mattila (Project Manager), MSc. Pauli Mustalahti, MSc. Petri Mäkinen, 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. E. 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

Fortum Power and Heat Ltd.

Activities: Power plant engineering
Members: MSc. Sami Kiviluoto, Dr. Jaakko Ylätalo, MSc. Antti Teräsvirta, MSc. Antti Rantakaulio, Dr. Harri Tuomisto

---

[1] From 2019: LUT University (Lappeenranta-Lahti University of Technology LUT)
[2] From 2019: Tampere University

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
	Herkko Plit, Baltic Connector
	Arto Timperi, Comatec
	Jukka Kolehmainen, Diarc
	Leena Jylhä, Finnuclear
	Kristiina Söderholm, Fortum
	Mika Korhonen, Suisto Engineering
	Olli Pohls, Fluiconnecto
	Ben Karlemo, Luvata
	Liisa Heikinheimo, MEAE
	Arto Kotipelto, TVO
	Jarmo Lehtonen, Tevolokomo
	Pertti Pale, PPF Consulting
	Anna Kalliomäki, Academy of Finland
	Janne Uotila, Sandvik
	Lauri Siivonen, Tamlink
	Veera Sylvius, Space Systems Finland
	Hannu Juuso, Business Finland
	Timo Laurila, Business Finland
	Kari Koskela, Business Finland
	Satu Helynen, VTT
	Johannes Hyrynen, VTT
	Timo Määttä, VTT
	Mathias Groth, Aalto
	Kai Nordlund, UH
	Jouni Mattila, TUT
	Heikki Handroos, LUT
	Jan Westerholm, ÅA
Co-ordinator	Tuomas Tala, VTT
Secretary	Markus Airila, VTT

The FinnFusion advisory board had two meetings in 2018.

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 Science and Technology Advisory Committee (STAC)

- Kai Nordlund, UH

1.5.4 EUROfusion HPC Allocation Committee

- Susan Leerink, AU

1.5.5 EUROfusion ITER Physics Project Boards

- WP JET2: Antti Hakola, VTT
- WP JET4: Mathias Groth, AU / Jari Likonen, VTT
- WP PFC: Jari Likonen, VTT

1.5.6 EUROfusion DEMO Project Board

- Kai Nordlund, UH
- Tuomas Tala, VTT

1.5.7 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

1.5.8 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

1.5.9 Other international duties and Finnish representatives in the following fusion committees and expert groups in 2018

- Markus Airila is the VTT representative in EUROfusion Communications Network (FuseCOM).
- Mathias Groth is a member of EUROfusion expert group for Power Exhaust (PEX).
- Mathias Groth is a member of the programme committee of the Plasma Surface Interaction Conference (PSI) 2013-2020.
- Kalle Heinola is a member of the international committee of the H-Workshop (International Workshop on Hydrogen Isotopes in Fusion Reactor Materials).
- 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 ITPA expert group on energetic particles. Tuomas Tala is a member of the ITPA expert group on transport and confinement.
- 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).
- 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 2018

2.1 WP JET1: Analysis and modelling tasks 2018

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

2.1.1 Overview

JET shutdown planned for year 2017 for the preparation of the upcoming DT campaigns continued over the whole year 2018. 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 earlier JET experiments and using several computer codes in the detailed analysis.

2.1.2 Particle transport and density peaking

Dedicated experiments for investigating electron density peaking have been performed on the JET tokamak. The discharges in the dimensionless collisionality scan, where other dimensionless quantities such as q95, normalized plasma pressure, temperature scale lengths and the normalized ion gyro-radius were held constant, clearly showed that density peaking increases with lower collisionality suggesting that hot burning plasmas might naturally gain peaked density profiles thus increasing fusion yield. However, data analysis and initial modelling of these discharges suggested that a surprisingly large part of this peaking is due to the NBI particle source which in reactors will be much more limited. This finding was in contrast to earlier studies on AUG and JET where collisionality was found to be the dominant factor and NBI fueling playing just a minor role.

To investigate this in more detail, and to understand where the apparent disagreement originates, extensive modelling activities were launched using best available simulation codes. In this work the particle transport experiments performed on JET have been modelled in detail using the JET integrated transport solver JINTRAC, the gyro-kinetic code GENE and the gyro-fluid code TGLF. We find that the JINTRAC/TGLF is able to reproduce our experimental electron density profiles generally well although there are known cases elsewhere where their accuracy is suboptimal. These and the gyro-kinetic modelling at normalized radii 0.4/0.6 both support our earlier findings where roughly half of the density peaking is due to NBI particle fueling. Looking into the details of the gyro-kinetic modelling and turbulence measurements in accompanying DIII-D experiments we can ascribe the difference between JET and AUG/DIII-D to their different turbulence characteristics. JET discharges in our collisionality scan, and fairly generally also in other NBI heated scenarios, are more deeply ITG dominated while AUG/DIII-D generally lie in the mixed ITG/TEM turbulence regime (due to their ECH heating systems).

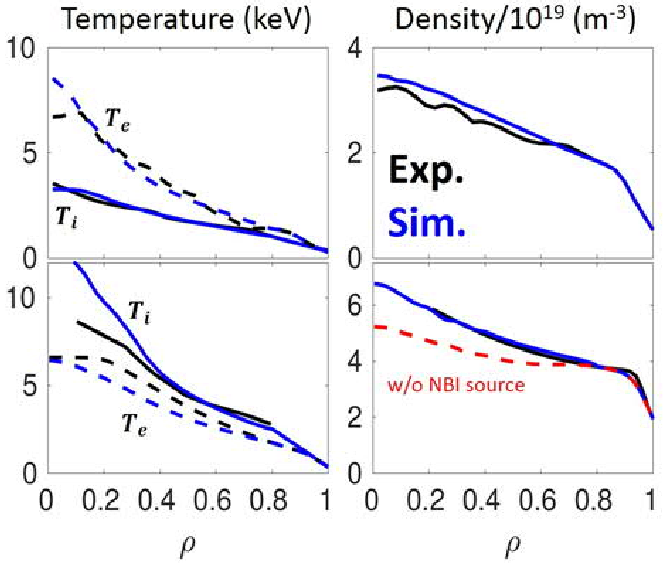


Figure 2.1. Experimental profiles in black and JINTRAC/TGLF simulations in blue. Top row shows data from ICRH only heated H-mode plasma where core particle sources are absent and bottom row shows data from a strongly peaking low collisionality discharge with >20 MW of NBI heating. The dashed red line shows the density prediction when the NBI particle source is discarded thus giving an estimate for the core particle source contribution to the peaking.

We can conclude that turbulence driven density peaking is weaker in ITG dominated plasmas (thus allowing NBI to contribute) while it is strong in mixed ITG/TEM plasmas. This is also seen in Figure 2.1 that shows two JET discharges, one with ICRH only heating ($T_e/T_i>1$, i.e. dominantly electron heating) and one with strong NBI heating ($T_i/T_e<1$, dominantly ion heating). JINTRAC/TGLF can reproduce both of these experiments and it shows that indeed even without NBI core source density can be peaked (top row) when the turbulence is in the mixed ITG/TEM regime and that NBI fueling significantly increases density peaking in plasmas that are deeply ITG dominated (bottom row).

2.2 WP JET2: Plasma-facing components

Research scientists: K. Heinola (Sub-Project Leader), 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, ILW1 (2011-2012), ILW2 (2013-2014) and ILW3 (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 2018 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. SIMS analysis of the divertor tiles exposed in ILW-3 for erosion, deposition and fuel retention studies were completed in 2018. SIMS measurements show that the thickest beryllium (Be) dominated deposition layers are located at the upper part of the inner divertor and are up to ~16 µm thick at the top horizontal part of Tile 1 exposed in 2015–2016. The highest deuterium (D) amounts (~ $7 \cdot 10^{18}$ at./cm^2) were found on the upper part of Tile 1, where the Be deposits are ~10 µm thick and on HFGC tile. D was mainly retained in the near-surface layer of the Be deposits but also deeper in tungsten (W) and molybdenum (Mo) layers of the marker coated tiles, especially at W-Mo layer interfaces. SIMS results for D retention on the divertor tiles have been compared with TDS and Nuclear Reaction Analysis (NRA) in 2018 and there is a good agreement between the results.

Fuel retention, especially the radioactive tritium (T), in the plasma-facing components plays an important role in the safe operation of future fusion devices such as ITER and DEMO. In ITER, the baseline strategy for the removal of retained T is baking of the main wall at 240°C and at 350°C for the divertor. In order to assess the efficiency of baking for T removal, hydrogen retention/release behaviour has been studied using realistic, ITER-Like tokamak samples exposed in 2015–2016 that were annealed by TDS. Figure 2.2 shows a TDS spectrum for a sample from the top horizontal part of Tile 1. It can be observed that at the ITER baking temperature of 350 °C only a minor part of deuterium was released and that main release occurs at much higher temperatures.

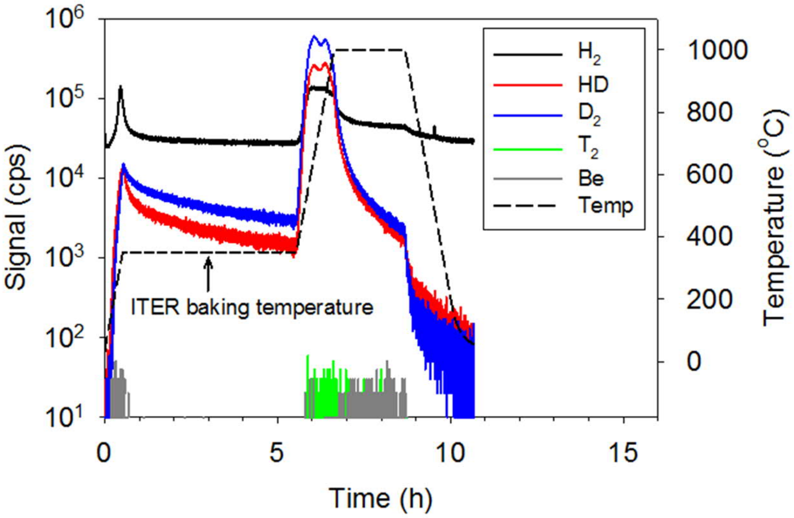


Figure 2.2. TDS spectrum for a sample from the top horizontal part of Tile 1.

2.3 WP JET3: Effect on neutron production with varying plasma parameters

Research scientists: J. Varje, AU
J. Leppänen, P. Sirén, VTT

The neutron activation system in JET is used to accurately measure neutron yields by measuring the activity of samples of materials exposed to the neutrons emitted by the plasma. In the upcoming deuterium-tritium campaign different materials with varying energy thresholds for activation will be used to discriminate between the 2.5 MeV DD and 14.1 MeV DT neutrons. Different heating schemes can produce reactants with energies ranging up to MeV range, which results in correspondingly wider neutron spectra. The ASCOT-AFSI-Serpent calculation chain has been used to model the neutron fluxes due to various realistic plasma sources, including thermonuclear, NBI and ICRH heated plasmas. This has further been used to estimate the effect different heating schemes have on the activation factors of the different materials.

Activation factors were calculated for thermal, NBI and ICRH heated DT plasmas, based on the JET record discharge #92436 with 50-50 DT mixture. While the ICRH heating in particular can produce multi-MeV reactants, the resulting neutron spectra are not broadened as much as in the equivalent DD case. This is due to the DT cross section peaking at around 100 keV, resulting in smaller relative contribution from the high energy ions. This means that the effect of varying the heating scheme in DT is limited, which is also reflected in the calculated activation factors that differ less than 5% between the scenarios for each material.

2.4 WP MST1: Medium-size tokamak campaigns

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

2.4.1 Overview

In 2018, MST1 experiments were run on two devices: ASDEX Upgrade (AUG) and TCV. On AUG, the 2018 plasma operations could only be started in November due to a large number of maintenance work that was required to bring the device back into life after a major steam-water leak in 2017. On TCV, for its part, the summer campaign was successfully completed but in the autumn a multitude of issues with the machine (vacuum leaks, degrading gyrotrons, short in vertical stabilization coils) cut the campaign short by a couple of weeks. The first campaign on the third MST1 device, MAST-U, was deferred into late 2019 due to unforeseen issues with commissioning of the machine. Despite the problems, significant progress was made on the three focus areas of MST1: (i) Demonstrating the compatibility of small, no- or suppressed ELM regimes with ITER and DEMO requirements; (ii) Developing and characterizing conventional and alternative divertor configurations under ITER and DEMO relevant conditions; (iii) Developing and characterizing methods to predict and avoid disruptions as well as control and mitigate runaway electrons. FinnFusion contributed especially to the experimental plasma-wall interaction studies, SOL modelling, intrinsic torque investigations, as well as numerical simulations of fast ions and runaway electron beams.

2.4.2 Assessment of the role of drifts in divertor plasma conditions

A set of AUG L-mode discharges with the toroidal magnetic field in the forward and reversed directions have been used to study the impact of neoclassical drifts on the divertor plasma conditions and detachment (see Figure 2.3). The evolution of the peak heat flux and the total power loads onto both the outer and the inner targets depends significantly on the toroidal field direction: increasing the core plasma density affects mainly the heat loads in the $B_t < 0$ (unfavourable) direction, whereas increasing the plasma current has a larger impact on the heat loads for $B_t > 0$ (favourable). Ion saturation current measurements show similar trends to those of the IR heat flux data. These discrepancies are not only caused by drifts but also by different levels of radiated power in the core, thus the power across the separatrix. Tomographic reconstructions show that the power at the separatrix is not constant within the entire dataset. Finally, at $I_p = 0.8$ MA, a significant reduction of the peak heat flux is observed at both targets for both field directions. On the other hand, at $I_p = 0.6$ MA, a reduction of the peak heat flux is only observed for $B_t < 0$ at the outer target. Additionally, the onset of particle detachment is only observed at the outer target for $B_t < 0$ with $I_p = 0.8$ MA.

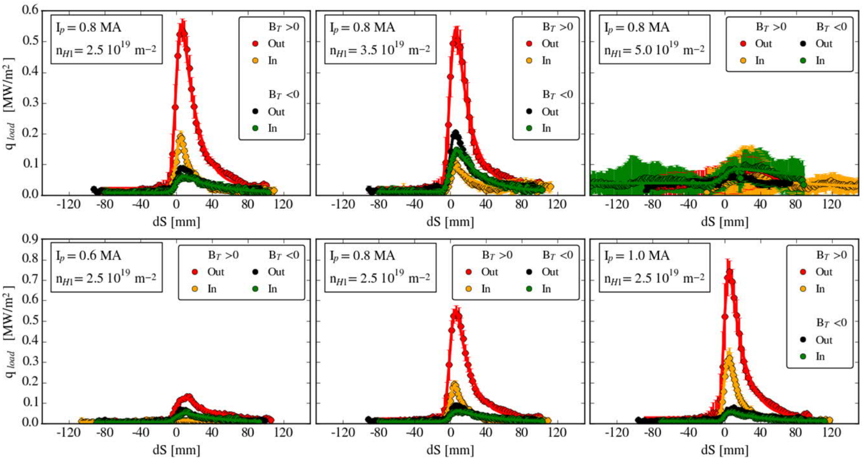


Figure 2.3. Heat flux on the outer and inner targets of AUG for various plasma currents and densities.

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

The ASCOT orbit-following code version 4, interfaced with the radiofrequency heating code package RFOF, has been applied to model ion cyclotron heating of hydrogen in ASDEX Upgrade discharge #33147 at t = 1s in order to simulate the measured fast ion loss detector (FILD) signal.

A two-stage simulation scheme was devised. The first stage consists of applying RFOF's ion cyclotron heating model with parameters matched to those of discharge #33147, to create a hot hydrogen tail distribution from an initially thermal population of hydrogen markers weighted to represent 5% of electron density. A simulation time of 100ms was used to ensure that the resulting tail distribution represented the steady state where wave power absorbed by the markers and collisional dissipation are in balance.

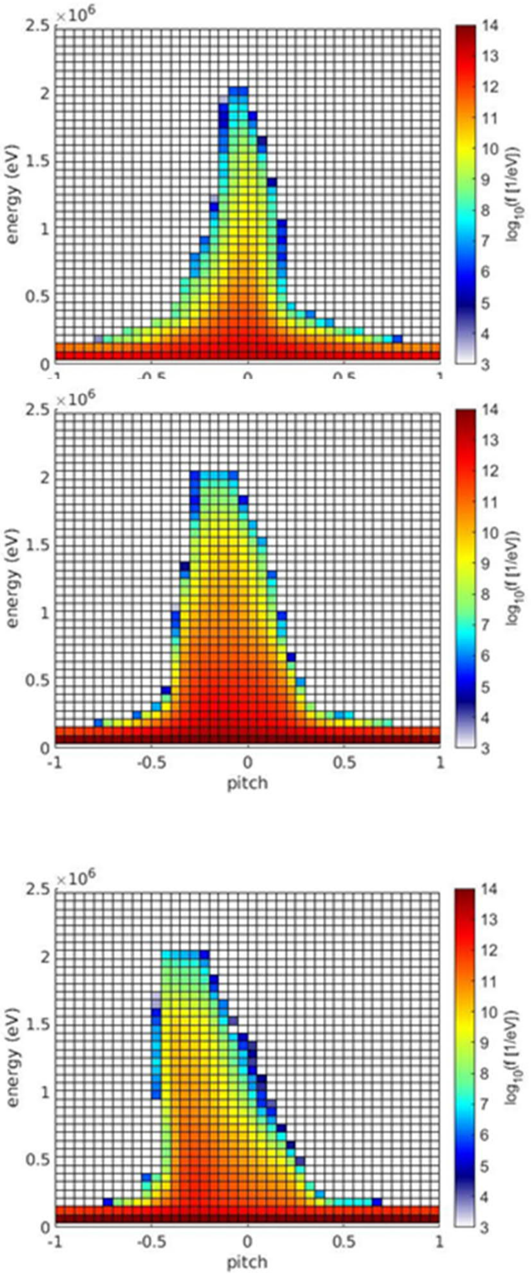


Figure 2.4. Hot hydrogen tail distribution f(*R*,*z*,ξ,*E*) in pitch-energy space, obtained in a 100ms ASCOT-RFOF heating simulation and shown for three radial regions: (a) ρ_{pol} = 0…0.333; (b) ρ_{pol} = 0.333…0.666; (c) ρ_{pol} = 0.666…1.000.

In the second stage, the obtained hot tail distribution f(R,z,ξ,E) was used as a source for sampling hot hydrogen markers (E > 200 keV) at random R and z and following them until a statistically sufficient number of hits on the FILD were recorded. As the heating simulation already contains the effects of neoclassical diffusion and ripple transport, no collisions with the background plasma were applied in this stage, and only a short simulation of 0.1ms was needed to record the wall loads and FILD signal. Taking into account the idealizations assumed in the simulations so far (e.g. simple cylindrical FILD model, no MHD phenomena), a satisfactory agreement with the experimentally observed FILD signal was found.

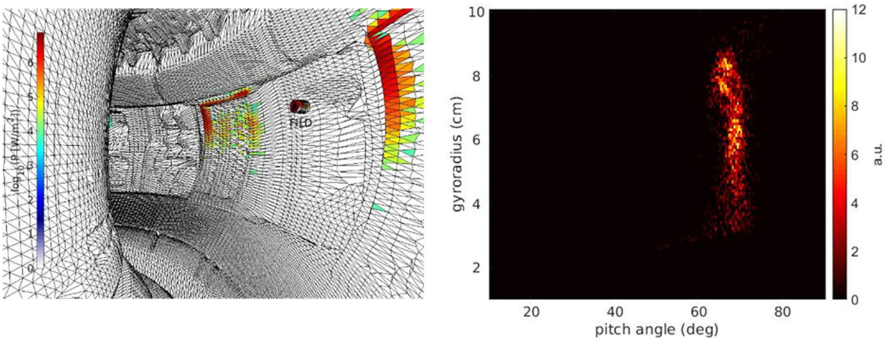


Figure 2.5. Left: IC-heated hydrogen wall loads. Right: FILD signal as a function of pitch angle and gyroradius recorded from the 0.1ms FILD simulation.

2.4.4 Deputy Task Force Leadership activities

In 2018, Antti Hakola continued his activities as a Deputy Task Force Leader (DTFL) of the MST1 Work Package. The DTFL term was extended until the end of 2020 and, as in the past, consisted of coordinating specific experiments on AUG and TCV in 2018 as well as planning, monitoring, and reporting the outcomes of experimental campaigns on the two devices. Programmatically MST1 was structured into 22 High-Level Topics (HLTs) under which all the experiments, data analyses, and modelling were channeled and in all the devices. The responsibility areas of Antti Hakola were controlling core contamination and dilution by tungsten, preparing efficient operation for ITER and DEMO in terms of plasma-facing components (PFCs), and optimising predictive models for the edge and divertor plasma conditions of ITER and DEMO. The results were presented in different review meetings and a number of conference contributions and journal articles were submitted. The main highlights were: (i) 3D effects, introduced by MHD modes, can noticeably alter W transport and especially the turbulent part may result in strong W accumulation or expulsion of W from the core; (ii) Based on simulations with the MEMOS code, the dynamics of molten W on plasma-facing components is primarily governed by the volumetric Lorentz force, thermo-capillary flows due to thermal surface-tension gradients and viscous deceleration; (iii) A consistent picture for the formation of a density shoulder at the edge, resulting from altered transport by plasma filaments, is now available and a large neutral pressure both at the divertor and in the main plasma seems to be a necessary pre-requisite for that.

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

Research scientists: M. Groth, T. Kurki-Suonio, I. Paradela Perez, K. Särkimäki, J. Varje, AU
T. Ahlgren, K. Heinola, A. Lahtinen, K. Nordlund,
K. Mizohata, J. Räisänen, UH
M. Airila, A. Hakola, J. Likonen, VTT

2.5.1 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 2018, the top three objectives were: (i) Perform in situ NRA in Magnum-PSI to quantify local D retention in W-based plasma-facing materials; (ii) Investigate stabilization of defects under simultaneous damaging and hydrogen loading of W; and (iii) Carry out PIC modelling of spatially resolved sheath characteristics and ERO modelling of W re-deposition in such conditions. Under FinnFusion, the focus areas of PFC were surface analyses of tokamak and laboratory samples, modelling of AUG experiments using the ERO and SOLPS codes, and simulating erosion and retention properties of Be and W. Here, we highlight the results from the analyses of laboratory-made Be-containing deposited layers.

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

Post-exposure analyses of wall tiles from JET-ILW have revealed thick, Be-rich and C- and O-containing co-deposited layers being formed on the high-field-side divertor surfaces. Within PFC, a project was launched back in 2014 to produce laboratory proxies for these deposits such that their properties and fuel-retention characteristics could be studied in detail and conclusions could be drawn for ITER. VTT has been the main coordinator of the activities and in 2018 reported the status of the work in the PSI 2018 conference. The studied samples exhibit various compositions, D contents, thicknesses, and surface structures and, moreover, their surface temperature was varied from room temperature to 600°C to cover the conditions that may occur in JET-ILW or ITER. The performed surface analyses show that the thicker the sample, the larger will be the amount of D retained. The largest D levels have been observed for Be-C-O-D samples and they can be controlled by adjusting the amount of C in the deposits (see Figure 2.6). Defects and various traps as well as strong C-D and O-D bonds are largely responsible for the measured D inventory. On the other hand, the higher the surface temperature is, the smaller will be the amount of D retained (see Figure 2.6). Simultaneously, the amount of C, N, and O impurities increases. Compared to the JET-ILW samples, the Be-C-O-D layers deposited under optimized conditions are quite close in their composition but more work is needed to fully match also the film structure. This will be addressed in 2019 by producing samples under conditions that mimic a series of typical plasma discharges in JET-ILW or ITER.

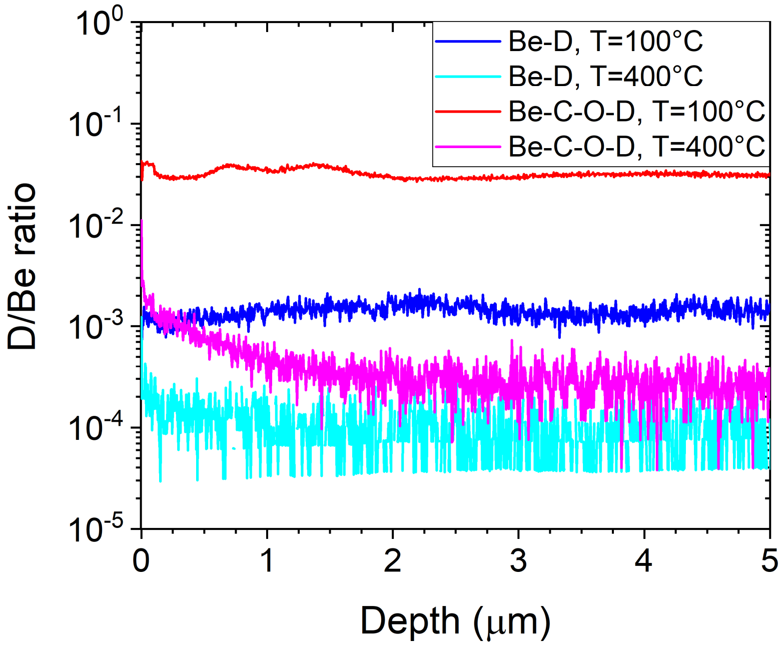


Figure 2.6. D/Be ratio extracted from measured elemental SIMS (Secondary Ion Mass Spectrometry) depth profiles for selected Be-D and Be-C-O-D samples produced at different surface temperatures.

2.5.3 ASCOT simulations of molybdenum global transport in TEXTOR

ITER will use tungsten as the divertor material from day#1, and W-based high heat flux components will suffer from erosion and melting. It is the high-Z impurities eroded from plasma-facing components (PFC) that will determine the energy production efficiency in fusion power plants and the lifetime of PFCs. Therefore it is essential to understand the global migration of high-Z impurities.

The last days of the now-decommisioned TEXTOR tokamak were well utilized by carrying experiments with tracer element technique. As a result, global deposition maps on molybdenium, tungsten and some medium-Z metals were obtained, when 140 tiles across the device were removed and analyzed (A. Weckmann's PhD work). In order to unravel the dominant processes in the migration of molybdenium, ASCOT was used to simulate the experiments. ASCOT is a first-principles test particle code so, unlike in fluid codes, all neoclassical and classical processes are inherently included. Also radial electric field and plasma flows can be included. Furthermore, the simulation region comprises both the core and the SOL plasmas, and the first wall includes important components such as ports as limiters.

Even though the project was challenged by significant deficits in the plasma kinetic profiles, the relative importance of various physical processes could be identified: the radial electric field in the SOL prevents molybdenium from entering the upper hemisphere, while the core toroidal flow had negligible effect even though from the energy and charge number distributions it was clear that the markers had traversed the core. Comparing the simulated and measured deposition maps indicated that while some measured structures were missing, some additional features appeared in the simulations. The suspects for these deviations are expected to be deposition/re-erosion and/or SOL flows, neither one of which could be included in the simulations at this stage.

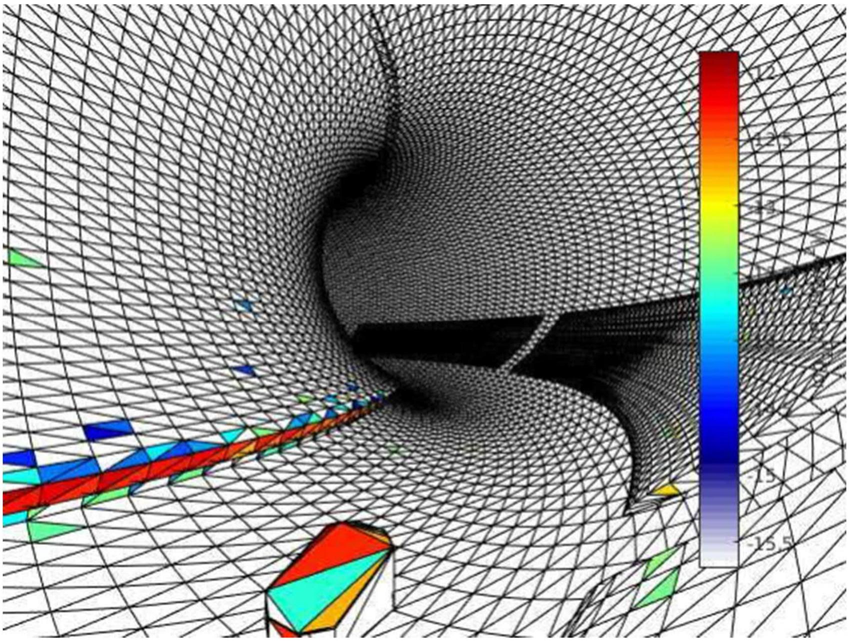


Figure 2.7. A view of TEXTOR interior as seen by ASCOT. The injection valve is visible at the bottom of the device. The colored triangles indicate regions of molybdenium deposition.

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

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

The year 2018 was especially interesting for ASCOT simulations in W7-X, since the neutral beam injection system was commissioned during the OP1.2b campaign. The use of experimentally obtained plasma profiles from the Wendelstein 7-X operating phase OP1.2a for ASCOT simulations was started in 2018. A parameter scan from different shot profiles showed that the NBI wall loads were often significant and sometimes highly localized, exceeding the safe limits of operation even for short NBI pulses. Based on the ASCOT simulations, additional protective shielding was installed in W7-X to allow for safe operation during longer NBI pulses. This shielding was found to be both necessary and effective during the operational campaign.

The process of validating the ASCOT code against experimental results was also started in 2018. Qualitative agreement was achieved, with a quantitative match when comparing beam injection into an empty torus. The first ASCOT estimations of the effect of charge exchange reactions on NBI ion confinement in W7-X were also made. The CX reactions were found to significantly increase the total NBI power load to the W7-X wall.

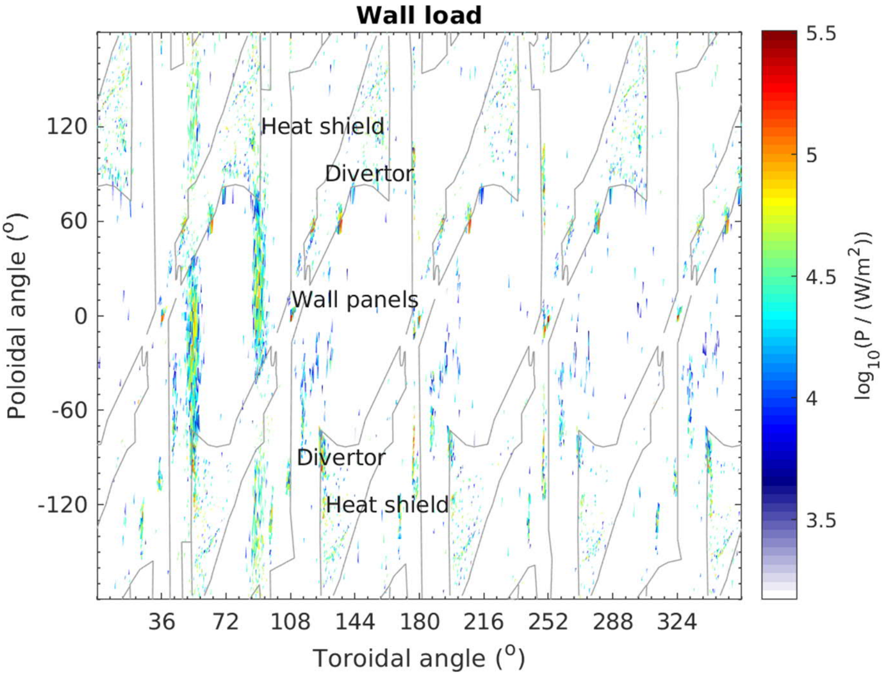


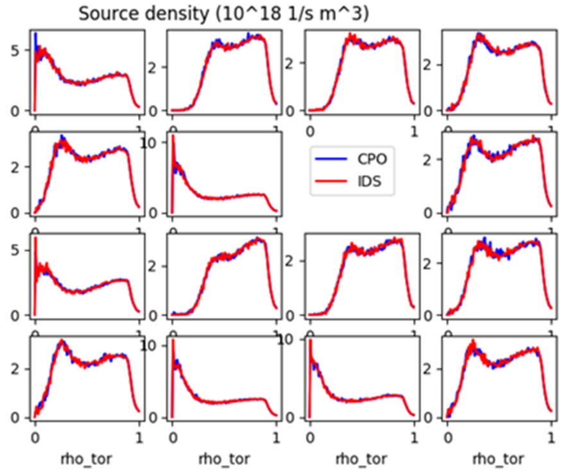
Figure 2.8. NBI power load to the W7-X wall with CX reactions. The power load to the wall panels is increased compared to simulations without CX reactions.

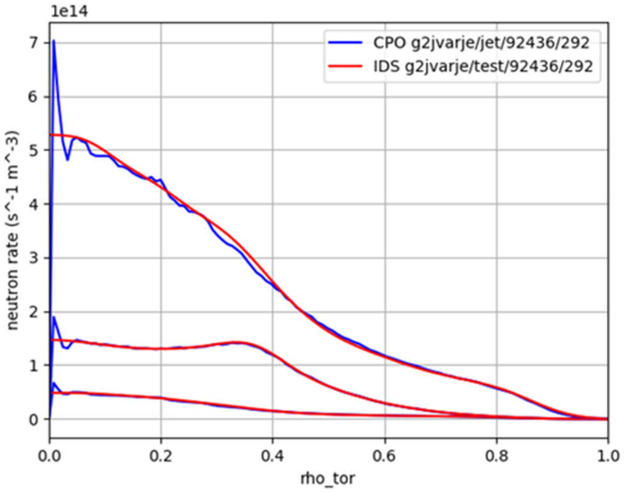
2.7 WP CD: Code development for integrated modelling

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

During 2018, maintenance and user support was provided for the CPO versions of BBNBI, ASCOT and AFSI actors. Significant new developments include addition of plasma rotation in all actors, TT fusion in AFSI and development of NBI source definition in BBNBI in support of NBI-ICRH actors.

IMAS adaptation of the BBNBI, ASCOT and AFSI actors was completed in 2018, and they were integrated into the workflow and verified to reproduce results from the CPO versions (Fig. 2.9). The actors have been released for use in HCD workflows.





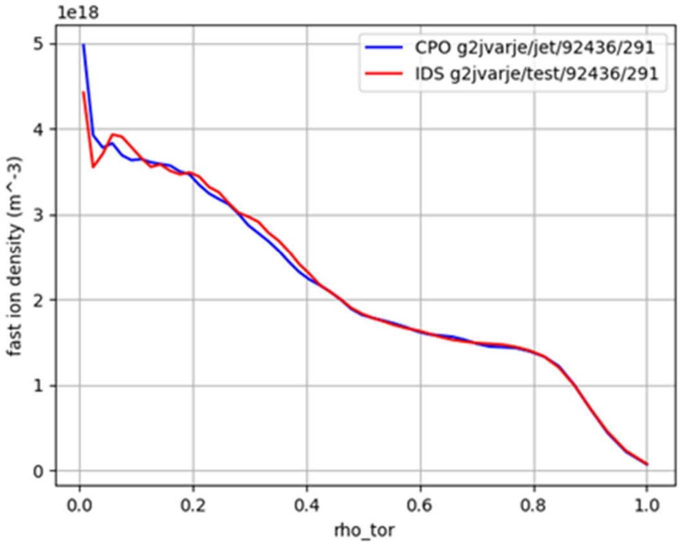


Figure 2.9 Comparison of the source rate, fast ion density and neutron rates for the CPO and IDS versions.

2.8 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 divertor. With state-of-the-art edge codes we model dependencies of radiation and detachment on the magnetic and structural geometry of the divertor.

VTT participated in these activities in 2018 by simulating the exhaust processes in the reference single-null, X-divertor and Super-X divertor configurations. The parametric scans, consisting of hundreds of SOLPS simulations with and without impurities, serve as a starting point for more detailed simulations of the exhaust processes in 2019. The scans revealed significant differences in the detachment and power sharing properties between the various configurations, which need to be understood and verified in the future.

3. Power Plant Physics & Technology Work Programme 2018

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

Research scientists:	T. Kurki-Suonio, K. Särkimäki, J. Varje, AU
	S. Kiviluoto, A. Teräsvirta, J. Ylätalo, Fortum
	E. Dorval, S. Norrman, VTT

3.1.1 Introduction

FinnFusion activities within WP PMI cover modelling tasks on DEMO Decay Heat Removal System and Direct Coupling PCS. In this Yearbook, we report the progress of the task HCPB BB DEMO without IHTS+ESS (small ESS option).

3.1.2 Apros transient analysis of the DEMO HCPB direct coupling concept with a solid energy storage system

In 2018, Fortum was tasked as part of the work package PMI to perform a transient analysis of a new concept for storing energy in the DEMO concept plant. The cyclical operation of the tokamak reactor type introduces great challenges to conventional power plant processes. The DEMO plant is predicted to operate during burn period approximately 2 hours at full thermal power of 2100 MW in the Helium Cooled Pebble Bed (HCPB) configuration. After that a dwell period of 10-30 minutes is initiated where thermal power drops to one percent of the of the burn period power. Previously the compensation of the power drop was handled with an Intermediate Heat Transfer System (IHTS) with molten salt storages and an auxiliary boiler. However, more economic, small and integral designs are desired. The integral solid and steam accumulator concept was devised to meet this goal (see Fig. 3.1). The goal was to operate at 50% turbine power during a ten minute dwell. It was determined that the required mass of the solid storages would be very large, 2100 m^3. Alongside that, a steam accumulator of 400 m^3 was necessary. The unloading and loading of the solid storages was also very slow, although a distributed mass concept was introduced in the plant. In conclusion, the solid energy storage system is a working solution in theory but economically and size-wise probably not feasible.

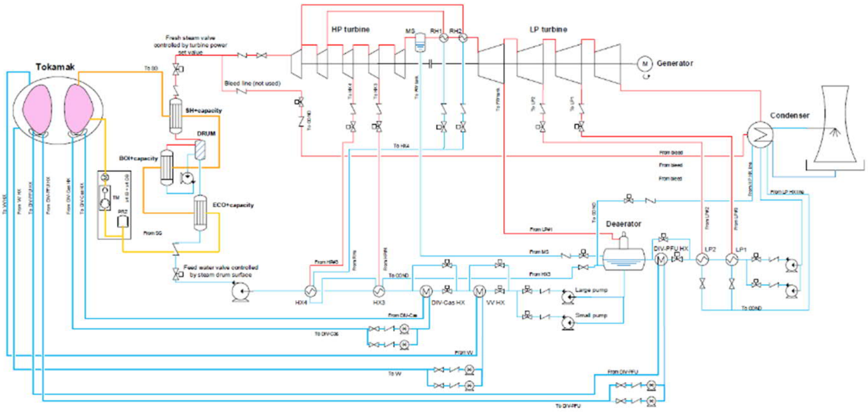


Figure 3.1 Process diagram of the HCPB Direct Coupling DEMO plant with solid thermal and steam accumulators

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

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

Two concepts of the helium cooled pebble bed (HCPB) DEMO design are still under evaluation within WP BOP. The traditional concept includes an intermediate heat transfer system (IHTS) with an energy storage system (ESS) between the primary heat transfer system (PHTS) and the power conversion system (PCS). This concept is referred to as IHTS+ESS, with Hitec (molten salt) as the coolant and energy storage media. The other concept is without an intermediate loop, but with an auxiliary boiler producing steam during dwell time instead (ESS concept). The models of both HCPB concepts have developed during the year based on a continuously maturing design data. For conventional systems, like the PCS, the configuration and data is proposed by industrial partners. For the in-vessel design, a major modification is a change from a 18 sector breeding blanket design to a 16 sector design, which also implies a change in the number of PHTS loops. Normal plant operation including transitions from pulse to dwell and back is still the main area of interest for the system analysis performed with Apros. The IHTS+ESS concept shows a fairly stable process behaviour. Two variants of the latter concept have been analysed with a steam production from the auxiliary boiler comparable to about 50 % of the total fusion power during dwell. Mechanical and thermal constraints on the turbine means that unloading and uploading of the turbine must be done with gradients far longer that the pulse/dwell transition and this enforces many difficulties for controlling the complete system in a way to minimize thermal stresses and pressure variations. The concept is not seen feasible.

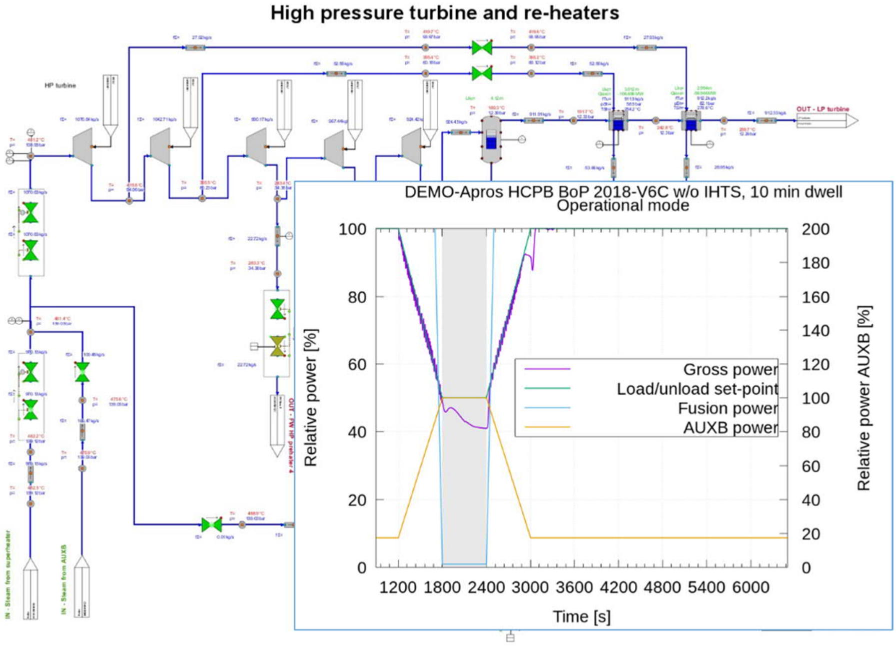


Figure 3.2. PCS high pressure turbine sections and operational mode of un- and uploading of turbine and power sources in -ESS concept.

3.3 WP RM: Remote maintenance systems

Research scientists: W. Brace, R. Sibois, M. Siuko, J. Videnoja, VTT
C. Li, M. Li, S. Moradkhani, H. Wu, LUT

3.3.1 DEMO Divertor remote maintenance system development

The Demo divertor remote maintenance (DRM) system development work package for 2018-2019 comprises of the final engineering design work of a proof of principle conceptual design for a transport system to operate in the lower-ports of the DEMO reactor. The development work includes the design of the various elements of the transport system and the synergistic integration of the system modules: - radial mover, end-effector, and lifting device.

The radial mover is used for pushing and pulling the end-effector carrying the divertor cassette in and out of the vacuum vessel, and for the transportation and fixing of larger loads in the lower port. The radial mover has been coupled to the end-effector so that it can be easily decoupled. The end-effector carries the cassettes, and the lifting device is used for the toroidal movement and fixation of the left and right divertor cassettes.

Several concepts have been developed and analyzed, and a final concept under development comprise the use of SERAPID chain mechanism. The chain is attached to the radial mover for the push-pull movement. The chain is also inserted into the end-effector for the toroidal movement of the lifting device. The lifting device is embedded into the end-effector, and in place of a hydraulic powered lift, there is the consideration of a mechanical wedge contraction and screw jack power lift for lifting the divertor cassettes. The concept together with the SERAPID chain technology eliminates the use of hydraulics from the DRM ensuring availability creating a particular reliable solution.

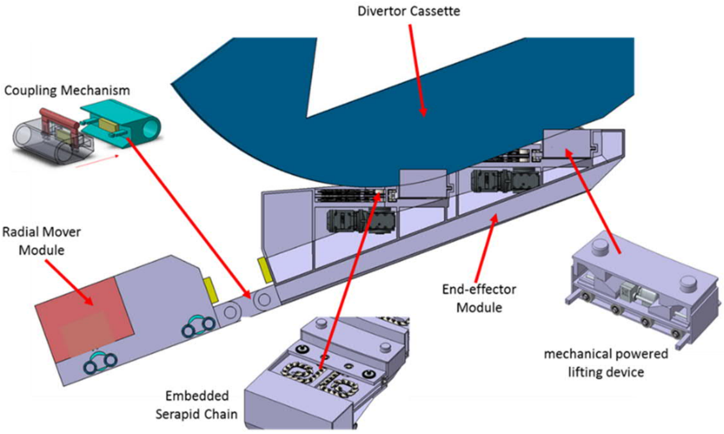


Figure 3.3. Divertor cassette transport system.

3.4 WP MAT: 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 fusion devices, both in current and proposed ones. The defect production and evolution will affect their properties, and can render them unusable for different applications. Previous years, studies on the defect production in these materials have been carried out. Both the defects produced in single cascades and the effect of prolonged irradiation have been thoroughly studied. Last year, we studied the evolution of certain defects when hit by a recoil, and it was observed that dislocation loops can and will change their Burgers vector. This year we thoroughly studied the defect production in the vicinity of previous cascade debris.

We investigated several defect structures, sizes, temperatures, interatomic potentials and recoil energies, and found that all of these affected the defect production. Both elemental Fe and elemental W were investigated, and both materials showed similar trends for interstitial-type defects. It was found that if the cascade overlaps fully with the pre-existing defect cluster, almost zero new point defects were formed. The larger the separation distance between the defect and the cascade centre, the higher the defect production. When no cascade overlap was observed, the defect production was not affected by the nearby pre-existing defect. We developed an analytical model to describe the defect production as a function of the distance between the cascade and the pre-existing defect, presented in Fig. 3.4 for iron. These results can be used in larger-scale models, like Monte Carlo simulations, to account for cascade overlap effects in irradiation simulations over longer time scales. In addition to the suppressed defect production in the vicinity of pre-existing defects, we obtained the probabilities for change in Burgers vector for both the 1/2<111> and the <100> dislocation loops.

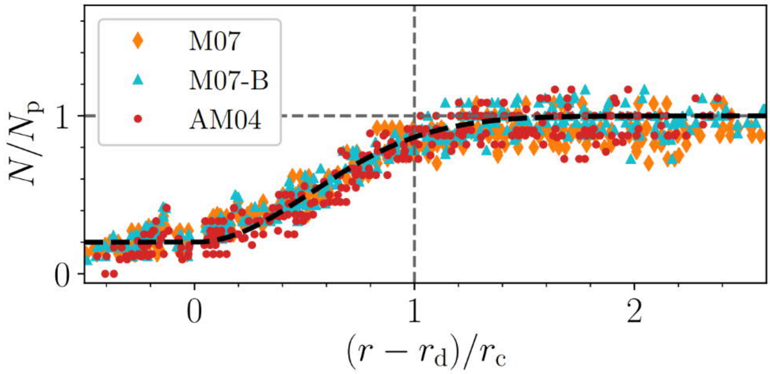


Figure 3.4. Normalised defect production in Fe in various interatomic potentials as a function of the separation distance between the cascade and the pre-existing cluster. The black dotted line is the analytical model.

3.5 WP ENS: Early Neutron Source definition and design

Research scientists: A. Helminen, I. Karanta, T. Sikanen, T. Tyrväinen, VTT
A. Rantakaulio, Fortum

3.5.1 Overview

The structural materials of fusion device DEMO are validated against fusion characteristic neutron spectrum in International Fusion Materials Irradiation Facility - DEMO Oriented Neutron Source (IFMIF-DONES). IFMIF-DONES is designed in the EUROfusion Work Package Early Neutron Source (WPENS) project.

From Finland, VTT and Fortum participated in WPENS project in 2018. VTT involvement concentrated mainly on the safety analysis and Fortum on the requirement management related tasks.

3.5.2 Safety analysis

In one task, failure modes and effects analysis (FMEA) was carried out for the electrical power and fire protection systems of IFMIF-DONES. FMEA is a systematic method to identify critical failures in systems important to safety. Information from the critical failure modes and causes are used, for example, for the identification of initiating events and for the modelling of system fault trees. In addition to the failure identification, FMEA provides important information on the functional dependencies, which is beneficial in the fault and event tree modelling.

In a second task, a comparison was made between the reference accident scenarios and the initial event trees. The updated event trees can be used in the risk quantification of accident scenarios in the following years of WPENS project.

3.5.3 Requirement management

A study investigating the traceability of IFMIF-DONES safety requirements using the electrical power system as an example was conducted. The focus of study was on the licencing aspects. Improvements were proposed on the requirements management process for better requirement hierarchy, linking, and transparency (see Figure 3.5). An efficient and transparent requirements management process is a key factor to the smooth licensing of IFMIF-DONES.

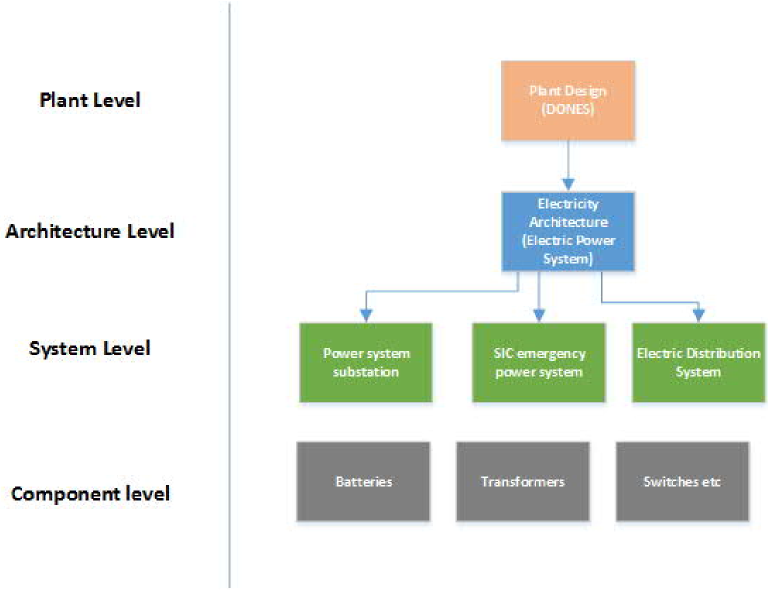


Figure 3.5. Requirement hierarchy of electrical power system.

3.6 PPPT Industry task (DEMO RH systems technology support)

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

This industry task consists of six separate technology cases for the DEMO power plant. Comatec performs the work entirely at its own premises and 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.
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 will be finalized in the spring of 2019. Comatec creates separate project reports for each of the tasks.

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 showed that the partnership works very well.

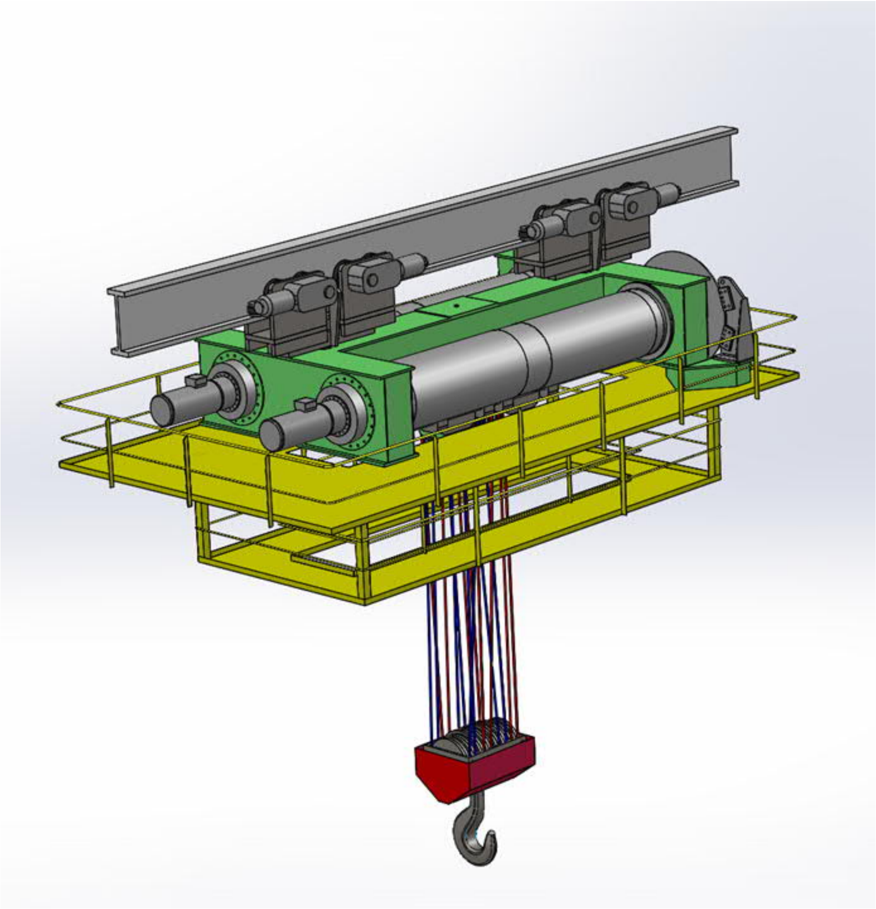


Figure 3.6. High payload and redundant ceiling mounted track trolley.

4. Communications

VTT organized the FinnFusion Annual Seminar in Espoo on 4 June 2018. Invited speakers were Liisa heikinheimo, Ministry of Economic Affairs and the Employment, and Francisco Martin-Fuertes, CIEMAT, Spain. The number of participants was 60. The Annual Report, *FinnFusion Yearbook 2017,* VTT Science **179** (2018) 75 p., was published for the Annual Seminar.

During 2018, Finnish and international media published several articles and interviews on the fusion research activities in Finland:

- Tuomas Tala, Magnetismi: Maailman suurimmat magneetit kootaan fuusioenergian tutkimushankkeeseen ITERiin Ranskaan (Magnetism: World's largest magnets are assembled fot ITER fusion research project in France), radio interview with Tiedeykkönen Extra, YLE, 20 December 2018 (https://areena.yle.fi/1-50029318).
- Tuomas Tala, Ihmiskunnan pelastusrengas (The life buoy of mankind), interview on ITER in Helsingin Sanomat, 24 December 2018 (https://dynamic.hs.fi/2018/iter/index.html).

Lecture courses at Aalto University, School of Science:

- *Fusion Energy Technology (Mathias Groth, spring 2018).*
- *Fundamentals of Plasma Physics for Space and Fusion Applications (S. Leerink, T., Kurki-Suonio, spring 2018).*
- *Energialukutaito (Energy literacy) (T. Kurki-Suonio, J. Ala-Heikkilä, fall 2018) Education and training.*

Other communications and outreach activities included:

- Tuomas Tala represented EUROfusion scientists in a meeting with Prince Andrew at JET. See VTT news on 23 March 2018 (https://www.vtt.fi/medialle/uutiset/vtt-n-johtava-tutkija-tuomas-tala-keskusteli-prinssi-andrewn-kanssa-brexitin-vaikutuksesta-eu-n-jet-fuusiotutkimuslaitoksen).
- Markus Airila, Paula Bergqvist, Seppo Karttunen, Rainer Salomaa and Tuomas Tala, interview with the pioneers of the Finnish fusion programme to prepare video clips for Fusion Expo, 28 August 2018.

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 2018, six doctoral dissertations and one Master's thesis were completed (see Section 11.5.4).

5.1.2 Doctoral students

Student: Paavo Niskala (AU)
Supervisor: Mathias Groth (AU)
Instructor: Timo Kiviniemi (AU)
Topic: *Isotope effect in transport and flows of fusion plasmas*
Report: The interplay of flows and turbulence in Ohmic FT-2 tokamak plasmas is analysed with the flux-driven gyrokinetic ELMFIRE code. The global full-f modeling agrees well with the analytical estimates in a neoclassical setting, while including kinetic electrons and impurities has a small impact. Turbulence modifies ExB flow through relaxation of profiles, non-adiabatic response of passing electrons around rational surfaces, and turbulent flow drive. In the simulations, the non-linear energy transfer from the turbulence to the flows through the Reynolds force is balanced by the collisional flow dissipation. Temporal relationship between the oscillating flow, Reynolds force, and turbulent particle flux is consistent with the idea of geodesic acoustic mode modulating turbulent transport on the time scale of the mode.

Student: Vladimir Solokha (AU)
Supervisor: Mathias Groth (AU)
Instructors: Mathias Groth (AU)
Topic: *Isotope effect on the JET divertor plasmas*
Report: The performance of ITER during DT operation depends on the effectiveness of the energy exhaust. The ITER divertor should be able to dissipate about 100MW during a discharge. The existing operational scenario assumes that most of this power will be dissi-

pated by the neutral atoms and molecules.The experimental modeling of these processes was performed in the JET tokamak with ohmic discharges which showed that detachment onset (a.k.a rollover) density and density limit are higher in hydrogen than in deuterium. Further investigation of the isotope effect on the divertor physics was made with the help of the EDGE2D-EIRENE code. Numerical simulations of the scrape-off layer plasma and neutral particles showed that increase of the isotope mass reduces pumping plenum conductance in molecular flow regime. Consequently, this phenomena leads to approximately 30% higher neutral density in the vacuum vessel in deuterium discharges than in hydrogen at the same upstream density.

Student: Konsta Särkimäki (AU)
Supervisor: Mathias Groth (AU)
Instructor: Taina Kurki-Suonio (AU)
Topic: *Stochastic processes and particle transport in tokamaks*
Report: Thesis work has so far resulted in three publications. It was shown that runaway electron transport in perturbed field can be described with an advection-diffusion model. A novel Monte Carlo collision operator for relativistic patricles that uses adaptive time-step was developed. Mechanics behind RMP-induced fast ion losses were examined and a possible new transport mechanism was found. Current work has focused on the development of ASCOT5 code and collaborating with the users on various projects.

Student: Shayan Moradkhani (LUT)
Supervisor: Huapeng Wu (LUT)
Instructor: Huapeng Wu (LUT)
Topic: *Development of haptic teleoperation technology for the maintenance of DEMO*
Report: A parallel manipulator has been designed for the assembly of the Vacuum Vessel of a fusion reactor. This assembly process comprises of material handling, machining and welding process. In order to ensure the reliability and safety of the automated process, the aim is to develop a condition-monitoring algorithm implementing a real-time simulation environment that is running with a robot controller in parallel with the actual robot motion. Condition monitoring is used in case of a sensor malfunction to prevent collision, tool wear and over cutting. The results are also validated with laboratory experiments.

Student: Changyang Li (LUT)
Supervisor: Huapeng Wu (LUT)
Instructor: Huapeng Wu (LUT)
Topic: *Design and implementation of a mobile parallel robot for assembling and machining the fusion reactor vacuum vessel*
Report: The objective of the research is to build a mobile robot machine for Fusion Engineering Test Reactor. The design of the mobile robot machine is done and now in manufacturing stage. The task of the robot is to carry out assembling process inside the vacuum vessel of the fusion reactor, the assembling process is consisting of scanning, machining, welding and nondestructive testing. To better meet reactor configurations, the structure and the kinematics of the mobile parallel robot have been optimized for the reactor access. The design phase mainly includes mechanism design, components selection, FE analysis and kinematic analysis. The new designed robot machine is more reliable and realizable, and it is also suitable for ITER and EU fusion DEMO assembly. In the future, the research direction will focus on the multi-objective structural optimization design considering workspace, accuracy, payload ability, cost and stiffness.

Student: Longchuan Niu (TUT)
Supervisor: Jouni Mattila (TUT)
Instructor: Jouni Mattila (TUT)
Topic: *Computer Aided Teleoperation utilizing 3D scene construction by stereo camera*
Report: Remote handling of Divertor Cassette Locking System in harsh ITER conditions is performed using teleoperated manipulators. Integration of stereoscopic cameras into manipulation enables a new means of Computer Aided Teleoperation of remote handling by precisely tracking of both tools and target objects. This improves usability and safety. Existence of several constraints in high dose of radiation environment such as noises, limited resolution of radiation-tolerant camera sensors are typical design challenges. To maximize the precision of tracking, a novel 3D template matching method, similar to Iterative Closest Point (ICP) algorithm, is being used. A prototyped eye-in-hand 3D vision system is implemented together with the robot's control system. The prototype implementation result verifies efficacy of the proposed method.

Student: Pauli Mustalahti (TUT)
Supervisor: Jouni Mattila (TUT)
Instructor: Jouni Mattila (TUT)
Topic: *Bilateral force reflecting master-slave control system development for heavy-duty RH manipulators subject to high-gear ratios and static nonlinearities*
Report: In ITER Remote Handling (RH) manipulator operations in vacuum vessel are subject to heavy loads in a limited space. These operations require RH devices with high mechanical gear ratios and a high-precision force/motion control. However, the dynamic behaviour of manipulators with nonlinearities of 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: Petri Mäkinen (TUT)
Supervisor: Jouni Mattila (TUT)
Instructor: Jouni Mattila (TUT)
Topic: *Stability guaranteed control of flexible link RH manipulators*
Report: In ITER Remote Handling robotic devices, the cassette multifunctional mover (CMM) is required to lift heavy loads in a space limited vacuum vessel. The heavy loads cause the links of the manipulator to bend. These structural flexibilities mean that rigid body assumptions, typically applied in robotics, do not hold. This study focuses on developing novel control methodologies for such flexible-link manipulators using a nonlinear model-based approach. Additional key areas of the studies are stability-guaranteed controller structure and the estimation of the end-point position, required for feedback control, of flexible-link manipulators.

Student: Jesper Byggmästar (UH)
Supervisor: Kai Nordlund (UH)
Instructor: Kai Nordlund (UH)
Topic: *Multiscale modelling of radiation effects in fusion reactor materials*
Report: We have continued our previous work on molecular dynamics simulations of collision cascades overlapping with pre-existing damage in iron and tungsten. This year, we finalised a comprehensive and systematic study on the effects of cascades overlapping with interstitial and vacancy-type dislocation loops and other defect clusters. The main observed cascade-overlap effects include a significantly reduced defect production and frequent transformations of the Burgers vector of dislocation loops. The results were combined into

simple analytical models. These models can be transferred to kinetic Monte Carlo simulations to, for the first time, take cascade overlap into account when modelling irradiation over longer time scales.

Student: Aki Lahtinen (UH)
Supervisor: Jyrki Räisänen (UH)
Instructors: Antti Hakola (VTT), Jari Likonen (VTT)
Topic: *Plasma-wall interactions in fusion devices*
Report: In 2018, the work focused on the analysis of the divertor tiles of JET ITER-like wall (ILW). Studied tiles were exposed during the third JET-ILW campaign in 2015-16 (ILW-3). ILW-3 campaign was longer (23.4h) than the 2011-12 (19h) and 2013-14 (19.4h) campaigns, and it ended with high-power deuterium plasma discharges. Divertor tiles were studied with Secondary Ion Mass Spectrometry (SIMS). Measurements showed that beryllium deposition on ILW-3 divertor tiles was quite similar to the earlier campaigns but retained deuterium amounts were lower. Nickel, molybdenum and tungsten signals had peaks at the surface of the deposits, which indicates that their deposition on the divertor tiles was increased during the high-power plasma phase at the end of the campaign. Probable reason for the reduction in the fuel retention is higher surface temperature of the tiles during the high-power plasma operation.

Student: Emil Levo (UH)
Supervisor: Kai Nordlund (UH)
Instructors: Fredric Granberg (UH)
Topic: *Radiation stability of nanocrystalline single-phase multicomponent alloys*
Report: Irradiation simulations were performed with molecular dynamics to study the stability of several nanocrystalline Ni-based multi-component alloys. Three nanocrystalline cells were created for each material, with grains consisting of FCC lattices oriented in random crystallographic directions. They were irradiated with subsequent 5 keV recoils, until the nanocrystallinity of the system disappeared. An increase in stability was observed when adding elements to the composition and comparing to Ni. When comparing the alloys with each other, it was obvious that the addition of elements did not guarantee a higher stability. The combination of element types, and concentration played a huge role. The different cells of the same composition lost their nanocrystallinity at different doses, indicating that initial grain geometry also had an effect.

Student:	Paula Sirén (VTT)
Supervisor:	Jaakko Leppänen (VTT)
Instructors:	Filip Tuomisto (AU)
Topic:	*Radiation stability of nanocrystalline single-phase multicomponent alloys*
Report:	It is essential for the research of reactor relevant plasmas to understand how heat transfer is affected by the properties of and phenomena in the plasma fuel. The major part of heat is transferred out via energetic neutrons. The neutrons must be taken into account as a heat source as well as from the perspective of material activation and induced reactions. In simulations the calculation chain from the reactants to products, heat transfer and material effects requires the coupling methods in plasma physics, reactor analysis and thermohydraulics calculation. This thesis focuses on reactor relevant plasmas. The first part discusses plasma operational scenarios concentrating especially on advanced tokamak scenarios. The second and third parts consider fusion products and their characterisation. In the fourth part, the calculation chain from the modelling of plasma fuel to the balance-of plant modelling is described with the focus on the coupling of plasma physics and neutronics. As a demonstration case, the predictions ITER plasma data and a CAD model have been used.

5.2 WP TRA – EUROfusion Engineering Grant

Design of control systems for remote handling of large components

Research scientist: M. Li, LUT

Taking TARM as a specific study object, the deformation model of its subcomponent has been investigated in detail. The hybrid deformation modeling, which integrates the joint kinematics and artificial neural network for subcomponent deformation, has been validated to be competent for the deformation computation of geometric-complex assemblies by simulation. The research suggests that a two-hidden-layers neural network is sufficient to model the deformation physics of a joint assembly. The neural network generalization can be achieved through early-stop and Bayesian regulation training. In the study of a joint assembly, 30 neurons have been used in each hidden layer, and the network contains 1173 weights in total. Through Bayesian regulation, it has been found that about 273 weights were effectively working; this provides a meaningful insight into developing proper size of neural networks for manipulators that contain multiple joints.

The code for analysing the TARM CAD in Solidworks COSMOS has been developed, and 1300 sets of deformation data have been obtained from the TARM CAD in different kinematics which took 27 days of continuous computation. Hybrid deformation model has been developed based on the entire TARM CAD model and obtained data.

Nevertheless the following facts, which exist in the deformation of realistic large DEMO manipulators, need to be further addressed and included in the hybrid modeling process:

a) deformation behaviour contributed by different materials in the structure
b) deformation behaviour contributed by the transmission systems in driving joints
c) contact deformation contributed by the pins, bearings, bolts etc. in each joints and subcomponents connections
d) the modulus change of the structure due to the yield process, the thermal effect etc.

To evaluate all the effects of challenges mentioned above, the on-site loading experiments on TARM are necessary, in order to collect the realistic training data for the hybrid modeling and further verification. Fig. 5.1 shows the method of hybrid deformation modeling.

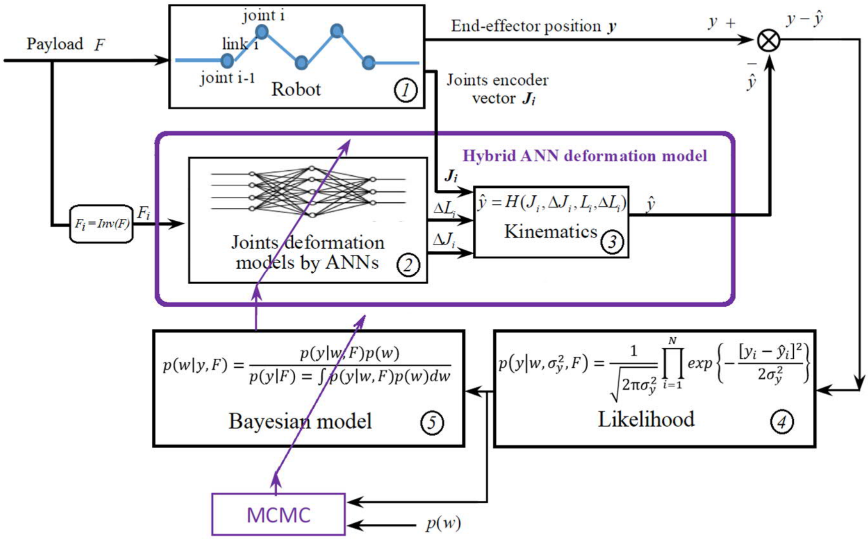


Figure 5.1. Hybrid deformation modeling of manipulator.

5.3 WP TRA – EUROfusion Researcher Grant

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

Research scientist: A. Snicker, AU

The work within 2018 can be summarized with three main achievements. First, the comparison of the guiding center and gyromotion orbit-following schemes in the presence of TAEs was finished. The conclusion of the work was that the differences between the gyromotion and guiding center orbit-following schemes are marginal in terms of alpha particle transport in ITER in the presence of TAE modes. Hence, it is a sufficient approach to use guiding center orbit-following for such studies. However, the TAE spectra used in this study composed of just one toroidal mode, the story can be different when full spectrum of toroidal modes are used.

The second part was to carry out simulations for the interplay of NTMs and RMPs on the fast ion transport in ASDEX Upgrade and in ITER (see Fig. 5.2). The experimental validation study carried out in ASDEX Upgrade was not fully finished in 2018, and the work will be continued in 2019. The predictive ITER simulations show that there is a synergy between the NTMs and RMPs, inclusion of NTMs can more than double the alpha particle losses caused by RMP coils.

Third part of the work was to carry out neutral beam ion shine-through calculations for ITER reduced field operation regimes (see Fig. 5.3). This work was strongly requested by ITER Organization. The results of this work has already been used for various meetings, including the invited talk at the EPS meeting and a contributed poster in the IAEA meeting. The results will be submitted for publication in Nuclear Fusion early 2019, as will other work done in 2018.

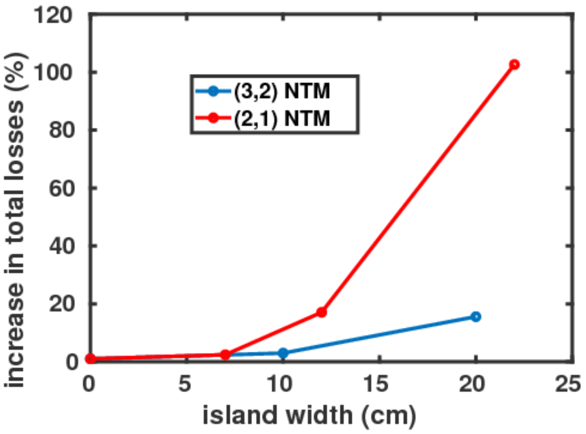


Figure 5.2 Increase in the alpha particle power load as a function of the NTM island width in ITER baseline H-mode.

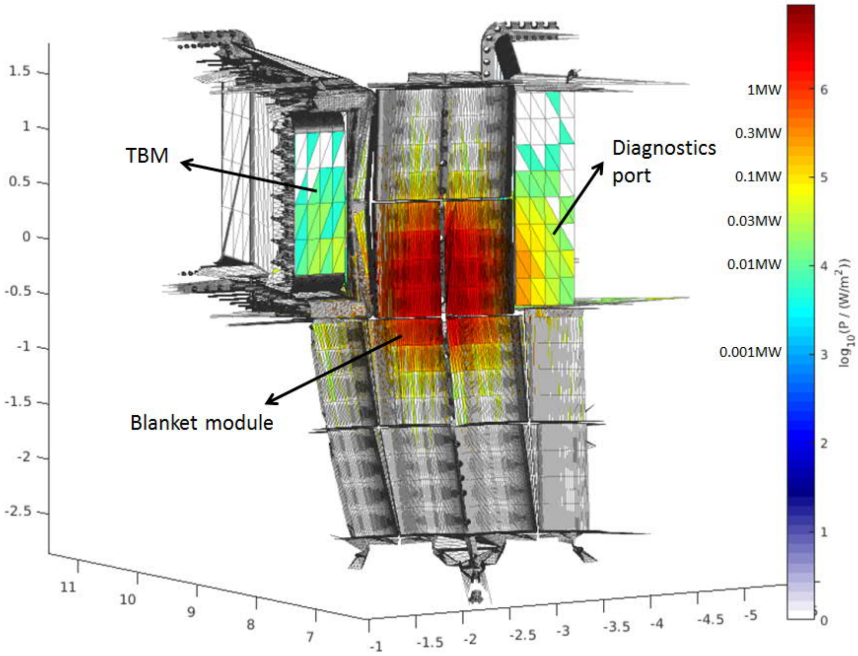


Figure 5.3. Shine-through caused by the neutral beam ion system in the reduced field operation scenarios of ITER.

5.4 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

The objective of this project is to investigate with classical molecular dynamics (MD) the sputtering and reflection processes of beryllium-oxygen mixed materials irradiated by deuterium ions.

To run MD simulations, inter-atomic potentials are needed. At the beginning of the project, only the O-H part in the ternary potential Be-O-H was missing. Thus, the project started with the parametrization of the O-H part which has been fitted to reproduce the energetics and geometry of O-H dimer calculated by density functional theory (DFT) calculations. The obtained potential has been further tested to investigate the energetics and geometry of interstitial H in BeO wurtzite crystal: according to recent DFT calculations, the most stable position of interstitial H is H_2 which is well reproduced by the Be-O-H potential.

After parametrizing the Be-O-H potential, cumulative irradiations of BeO with 3000 impacts of 10 – 200 eV D ions have been performed. Due to MD time and space limitation, the irradiated surface is 24x25 Å and each impact lasts 7000 ps which represents an incident flux of about 10^{28} $m^{-2}s^{-1}$. After about 500 impacts, exfoliation of a few-Å-thick BeO layer is observed which is due to the too large flux leading to non-realistic sputtering after the saturation of the D concentration. In order to estimate more accurately the sputtering yields, non-cumulative irradiations have been run with different D concentrations. The cells with different concentrations (0, 0.12 atomic fraction and 0.3 atomic fraction) are taken from the cumulative irradiations. The concentration of 0.12 atomic fraction is the saturation concentration observed experimentally.

The non-cumulative irradiations show that the sputtering yields increase as the concentration of D increases in the material. This increase is partly due to the presence of D but also and mainly due to the damage accumulated during the cumulative irradiations. The sputtering yields obtained from the MD simulation with 0.12 at.fr. of D are in good agreement with the experimental measurements which can be seen in Fig. 5.4. The sputtering of molecules has also been analysed and the simulations show that below 50 eV, the sputtering is dominated by O sputtering in OH type molecules created by swift chemical sputtering mechanisms. Between 50 eV and 80 eV, the sputtering is dominated by Be sputtering (mainly physical) while at higher energy, the production of Be_xO_y molecules rises up.

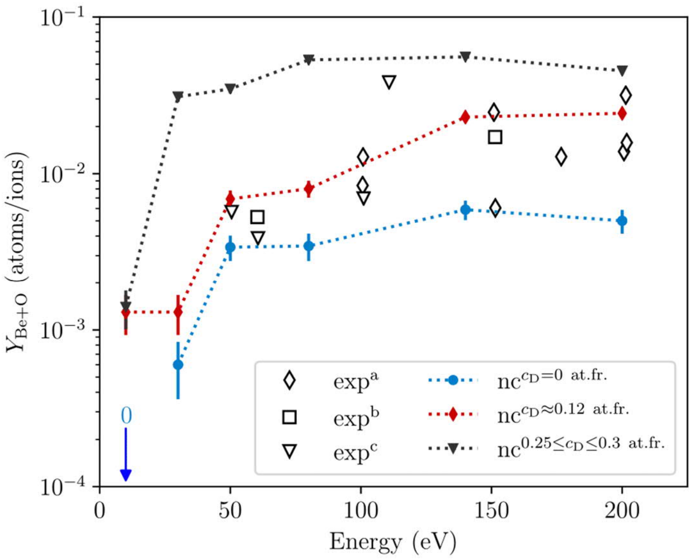


Figure 5.4. Total MD sputtering yields (Be+O) at 300 K for the non-cumulative irradiations (nc) with three different D concentrations. The MD data are compared with experimental data.

6. Enabling Research

Research scientists: T. Kurki-Suonio, K. Särkimäki, A. Snicker AU
K. Heinola, UH
J. Likonen, VTT

FinnFusion participated in two Enabling Research projects in 2018:

- AWP15-ENR-01/CCFE-08: Tritium and deuterium retention in metals with variable radiation-induced microstructure (TriCEM)
- AWP-17-ENR-MFE-CIEMAT-03: Phase-space dynamics of energetic ions in the presence of Alfvén eigenmodes, edge localized modes and externally applied magnetic perturbations

In this report, we highlight the ENR project coordinated by CIEMAT.

6.1 Phase-space dynamics of energetic ions in the presence of Alfvén eigenmodes, edge localized modes and externally applied magnetic perturbations

To model the behavior of fast-ions in the presence of ELMs, a time-dependent electromagnetic field is necessary. In the ASCOT code, such a model existed but only for the magnetic field. Hence, work was carried out to implement the electric field part. During 2018, this model was finished and the testing was started. The work was carried out in close collaboration with the University of Sevilla fast-ion group. The model is currently being used to model the acceleration of neutral beam ions in the presence of ELMs, to verify that the experimentally observed acceleration is caused by the electric field of the ELMs.

In addition, numerical ASCOT simulations have been carried out to understand the interaction of fast-ions with the static external magnetic perturbations. In ASDEX Upgrade tokamak, the magnetic perturbation is caused by two rows of in-vessel coils, causing a resonant magnetic perturbation (RMP). This perturbation can be used to mitigate or even suppress ELMs, but on the other hand the effect of these perturbations on the neutral beam ions is not fully understood. In the work, it was found out that an edge resonant transport layer (ERTL) is formed in the vicinity of the plasma edge leading to resonant transport of beam ions. The nature of the transport is dependent on the phase difference between the currents flowing in the two rows of coils, or on the poloidal spectrum of the perturbation. Favorable and unfavorable configurations were identified based on the numerical simulations, and experiments were carried out to verify that indeed the fast-ion losses can be minimized or maximized using the found configurations.

7. Code development

7.1 ASCOT

Research Scientists: J. Kontula, T. Kurki-Suonio, P. Ollus, S. Sipilä, A. Snicker, K. Särkimäki, J. Varje, AU

Development of ASCOT5 has been an ongoing process. Neoclassical physics were implemented and verified that the code produces numerically the well-known analytical results for neoclassical transport and slowing-down distribution. The code supports both tokamak and stellarator geometry.

Work was initiated to include also time-dependent electromagnetic field, MHD wave-particle interactions, and the capability to use ELMFIRE data as an input for ASCOT5 simulations. Future work involves implementing charge-exchange reactions.

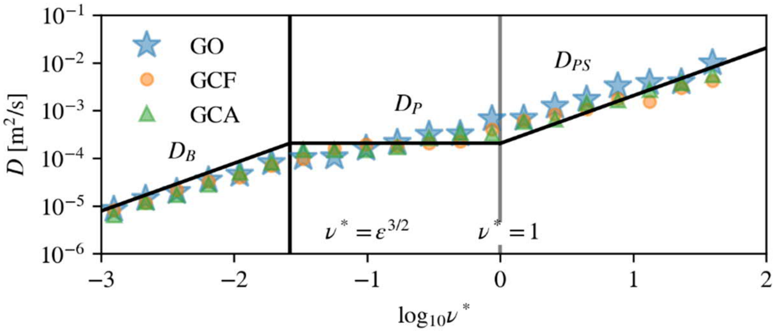


Figure 7.1. Neoclassical particle diffusion coefficient as calculated by ASCOT5 for ITER-like tokamak and compared to known analytical results. Colors correspond to different simulation modes: Gyro Orbit, Guiding Center Fixed time step, Guiding Center Adaptive time step.

7.2 Full-f gyrokinetic turbulence code ELMFIRE

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

The behaviour of flows and turbulence has been investigated using ELMFIRE code in co-operation with FT-2 and TUMAN-3M groups both located in Ioffe Institute, St. Petersburg, Russia. The new version of the code spanning from the magnetic axis to scrape-off-layer (SOL) uses the logical boundary condition, which allows for improved stability and flexibility in terms of geometry. FT-2 plasma, with two poloidal limiters defining SOL, is simulated. We recover expected results in the SOL and find an improvement in our capacity to model the experimental particle and energy sinks in the SOL. The group is included in the EUROfusion Enabling research project “Numerical Methods for the Kinetic Equations of Plasma Physics” which ends 2018.

The fast linear (Born approximation) version of the X-mode Doppler reflectometry (DR) synthetic diagnostics is developed in the framework of the ELMFIRE modeling of the FT-2. The DR signal frequency spectra and the dependence of their frequency shift and shape on the probing antenna position are computed and shown to be similar to those measured in the high magnetic field side probing DR experiment at the FT-2 tokamak.

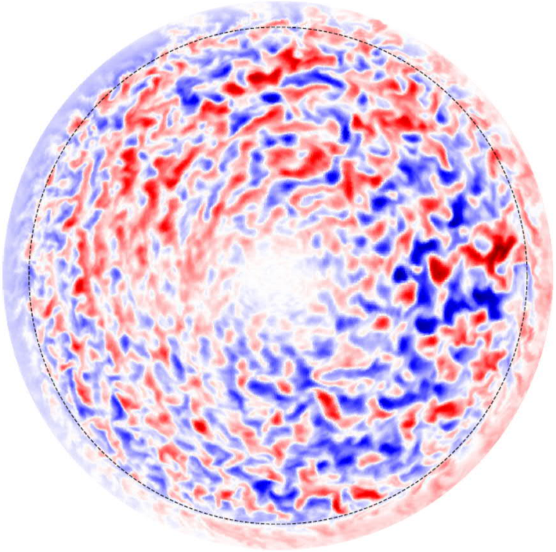


Figure 7.2. Turbulence stuctures in poloidal cross-section of FT-2 tokamak from ELMFIRE modelling including scrape-off-layer.

7.3 Molecular Dynamics

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

The University of Helsinki uses mainly the parallel cascade molecular dynamics code PARCAS, a code especially designed for simulating radiation effects due to ion and neutron irradiation. The code implements all the special features needed to model irradiation effects correctly and efficiently, namely realistic repulsive potentials, electronic stopping power, an adaptive time step, and boundary-layer temperature control. It is fully parallel with a 2D domain decomposition, and has been tested to scale well up to 89 000 computing cores. It has been used for about 500 publications on radiation effects in materials.

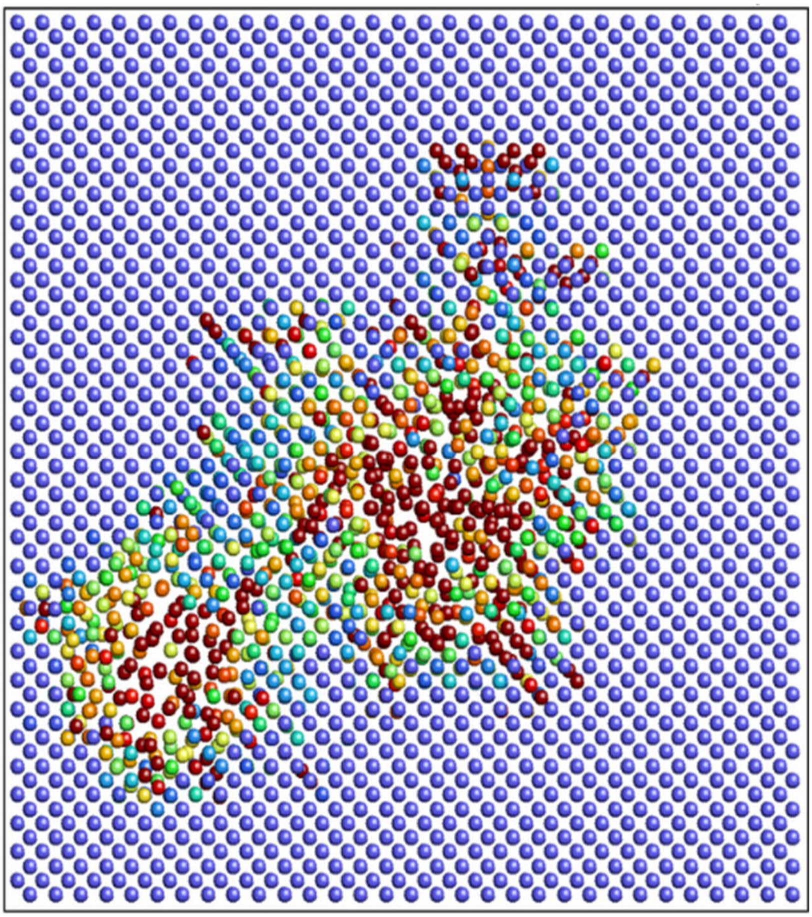


Figure 7.3. Collision cascade induced by a 10 keV recoil in Fe.

7.4 Serpent

Research Scientists: J. Leppänen, T. Kaltiaisenaho, 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 42 countries. The total number of users is around 900.

The resources allocated for Serpent development in 2018 were somewhat limited. The work covered mostly the implementation of a fusion gamma source routine for the purpose of synthetic gamma diagnostics as part of the JET1 Work Package.

8. NJOC and PMU

8.1 Overview

Two FinnFusion scientists were seconded to work in the JET operating contract team (NJOC) in 2018. 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

Research scientist: J. Karhunen, AU

Enhanced spatial accuracy and significant reduction of background artefacts have been observed in experimentally resolved 2D line emission distributions in the JET divertor by considering reflections from metallic wall surfaces in generation of tomographic reconstructions of tangentially viewing visible-range spectroscopic divertor cameras. Using ray tracing and a model for surface reflectivity and roughness, contributions of divertor and main chamber light sources to divertor camera images via reflections are integrated in the geometry definition of the tomography process. Consequently, comparability between experiments and divertor modelling and localization of line-integrated divertor spectroscopy measurements are improved.

Comparisons between tomographic reconstructions with reflections considered and neglected indicate that reflections intensify the recorded emission by 10—30% in the brightest emission regions extending from the strike points into the divertor volume towards the X-point. Mimicking divertor spectroscopy measurements by integrating the tomographic reconstructions along vertical lines-of-sight implies that similar amplification due to reflections is estimated to be inherently present in spectroscopic measurements. In the regions between these main emission clouds and the reflecting surfaces, reflections are found to account for up to 60% of the recorded emission. This implies that neglecting reflections in the reconstruction process overestimates the emission intensity and expands its spatial distribution towards the wall surfaces in the private-flux region or SOL in horizontal and vertical target configurations, respectively, as the reflected light is falsely interpreted as plasma emission.

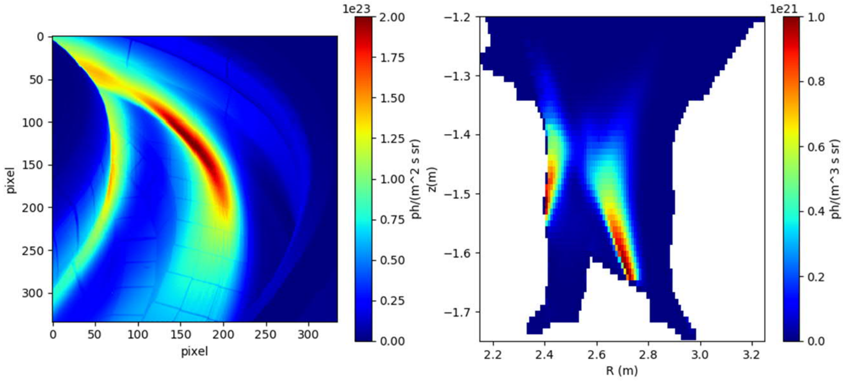


Figure 8.1. Tomography enables deriving 2D emission distributions (right) from divertor camera images (left).

8.3 NJOC ASCOT Code Responsible Officer

Role of the JETPEAK database in validation of ASCOT-AFSI fast particle and fusion product calculation chain in JET

Research scientist: P. Siren, VTT

JETPEAK is a growing structured multipurpose database which consists of time-averaged JET data samples from stationary phases from several thousand JET discharges in a wide range of experiments and plasma conditions. JETPEAK has been used for different physics studies, such as particle, momentum and energy transport and for systematic comparisons of the measured and calculated neutron rates.

JETPEAK currently includes an estimated 1000 variables, scalar, 1D (profiles) and 2D. JETPEAK supports comprehensive modelling directly from rich data in the database. ASCOT is the first major modelling code to benefit from integration with JETPEAK. This is achieved by an automated chain of analysis that creates inputs from JETPEAK, executes the ASCOT-AFSI and writes the main results back to JETPEAK for further use. Based on these, AFSI calculates synthetic neutron and gamma diagnostics signals, enabling future detailed comparisons with fusion product diagnostics, especially in view of the planned JET DT experiments.

The figure below shows a comparison of DD neutron rates calculated in first automatic ASCOT-AFSI runs for JETPEAK with the experimental neutron rates in JET-ILW plasmas. Measured ion temperature profiles not being available for the majority of cases, calculations were performed assuming T_i=T_e and T_i=T_{ieq20} where the latter is obtained from T_e by assuming, as frequently observed with dominant ion heating, that the ion-electron equipartition power represents ~20% of the ion heat deposition. Calculated neutron camera profiles are ready for comparison with experimental measurements corrected for scattered neutrons as soon as they will be provided and may yield clues as to the nature of this neutron deficit.

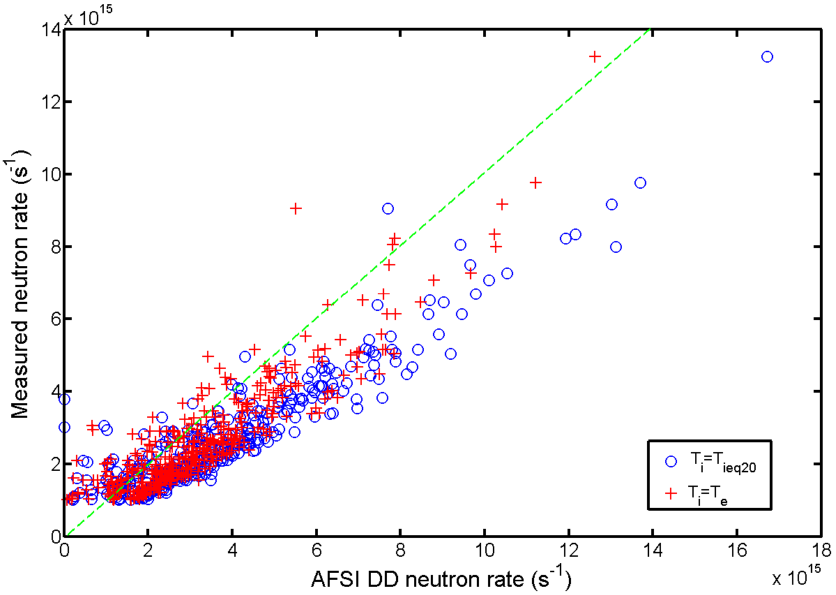


Figure 8.2. A comparison of DD neutron rates calculated in first automatic ASCOT-AFSI runs for JETPEAK with the experimental neutron rates in JET-ILW plasmas.

9. International collaborations

9.1 DIII-D tokamak

Research scientists:	M. Groth, AU A. Salmi, T. Tala, VTT

9.1.1 Plasma detachment studies

The EUV emission in DIII-D high-recycling Ohmic plasmas is measured to be dominated by Ly-alpha emission, and emission from low-to-medium carbon charge states (consistent with 1990s results). The EUV molecular bands (Lyman-Werner bands) are spectrally unresolved with the present DivSPRED spectrometer, but show a broad feature at the wavelength range of the Lyman-Werner bands that contributes up 20% to total EUV emission. In contrast, in the visible wavelength range, the measured molecular band emission is three orders of magnitude lower than D-alpha emission. EDGE2D-EIRENE simulations of the plasmas predict molecular emissions 50-100x lower than atomic lines. Based on these results, and until the resolution of the broad-feature issue, we conclude that emission from D_2 molecules is negligibly smaller than atomic emission (Ly-alpha).

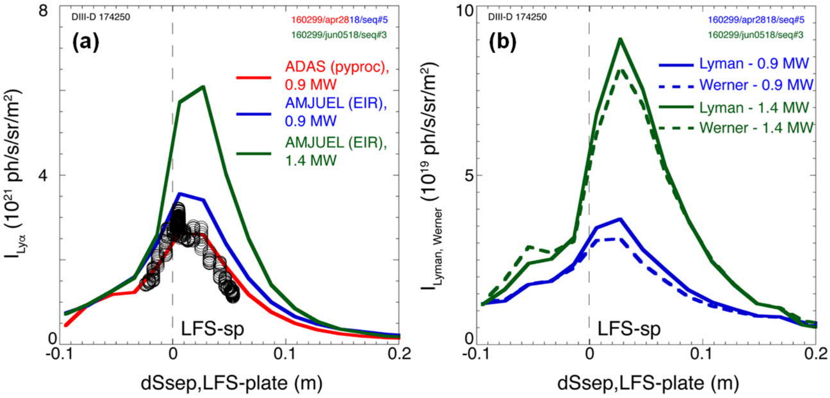


Figure 9.1. (a) Radial profiles of the measured Lyman-alpha emission in DIII-D shot 174350 (black symbols), and EDGE2D-EIRENE predictions of using the ADAS (red line) and post-processed standalone EIRENE predictions using the AMJUEL (blue line) databases. The green line denotes a separate standalone EIRENE prediction at elevated input power (1.4 MW versus 0.9 MW). (b) Standalone EIRENE predictions of the Lyman (solid lines) and Werner (dashed lines) molecular band intensities for a low-power (0.9 MW, blue) and high-power (1.4 MW, green) EDGE2D-EIRENE run.

9.1.2 Plasma fueling and pedestal opacity (ITPA TC-27)

T. Tala and A. Salmi visited General Atomics (San Diego, USA) to participate in the DIII-D part of the ITPA TC-27 experiment led by Dr Mordjick to study plasma fueling by means of gas puffing. The experimental recipe followed to those used on the JET tokamak: in NBI and ECH heated H-mode plasmas we scanned the amount of steady state Deuterium gas fueling from 0 to 300 torrl/s (maximum) while maintaining a periodically modulated (3 Hz) gas fueling to probe how SOL and pedestal opacity varies within the scan. It was found that there is a clear qualitative difference in the behavior of the perturbed gas penetration when going from low fueled (attached) to high fueled (detached) divertor conditions suggesting that the divertor conditions play an important role in the fueling process. Modelling of these is very challenging and is still ongoing to gain further understanding and to validate the simulation tools against the rich set of measurements.

9.2 Ioffe Institute

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

Financed by the Academy of Finland a collaboration between the fusion groups at AU and Ioffe Institute in St. Petersburg has started already in 1992 recently focusing on transport phenomena and flows in the FT-2 and TUMAN-3M tokamaks. The FT-2 tokamak is equipped with a sophisticated diagnostic setup including e.g. Doppler reflectometry (DR). The measured cross-correlation function of high field side radial correlation X-mode DR in FT-2 is shown to disagree with the fast linear version of synthetic diagnostic even though the computed and measured DR signal frequency spectra are similar. A modest phase modulation of the probing and backscattering waves by the long-scale turbulent density fluctuations is shown, both experimentally and in computation, to be responsible for the observed effect.

Nonlinear simulations of pellet injection in TUMAN-3M tokamak show a clear decrease in transport due to the pellet injection similarly as in experiments. In contradiction with neoclassical theory, simulations do not show steep flow profile in the edge plasma due to pellet and only a modest effect of the pellet on the E× B shearing rate. Instead, the suppression of transport is caused by pellet induced changes in the plasma profiles and especially collisionality. The substantial impact of collisionality on linear growth rates is clearly observed in linear gyrokinetic simulations.

9.3 JT-60SA

Research scientists: K. Särkimäki, T. Kurki-Suonio, AU

ASCOT4, and more recently ASCOT5, is being used to assess beam ion losses due to TF-ripple and error field correction coils (EFFCs) in JT60-SA. Särkimäki participated in WPSA workshop in Barcelona.

The work was advanced on two fronts. On one front ASCOT5 was adopted due to it being computationally superior to ASCOT4. On the other front, magnetic field was computed from the coil geometry using the code BioSaw. First simulations estimating fast ion losses have been completed.

Future work involves predicting fast ion loss detector signal for different configurations and estimating losses due to EFFCs when plasma response is accounted for.

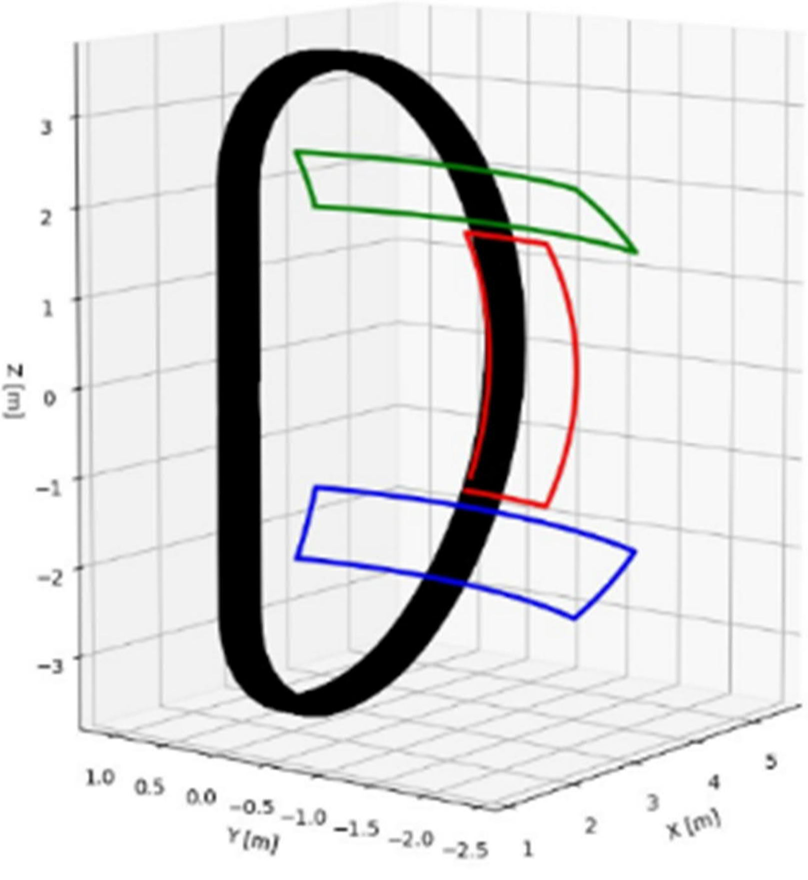


Figure 9.2. Illustration of error field correction coils and TF coil geometry.

9.4 KSTAR tokamak

Research scientists: T.Tala, VTT

Tuomas Tala visited Prof. Na and his group at SNU in Seoul to finalise the experimental plan and discuss the pulse plan into the fine details of the ITPA TC-17 experiment (ρ^* scaling of momentum particle and heat transport) planned for 2018 campaign. The main goal of this experiment is to compare the momentum transport and intrinsic torque between JET, AUG and KSTAR, with the possibility to achieve the identity conditions, and then scale ρ^* up. KSTAR has long pulse capability (>20s) which is very helpful in measuring accurately the rotation perturbations with reduced noise level. Recently also the NBI power level of KSTAR has increased significantly, improving the success of this experiment. However, the KSTAR campaign ended prematurely and this experiment was not executed. This experiment will be scheduled during the next KSTAR experimental campaign in 2019.

9.5 MIT collaboration

Research scientists: T.Tala, VTT

Tuomas Tala visited MIT to finalise the analysis of the C-Mod experiment on particle transport within the ITPA framework. The purpose of the experiment was to study the dependence of density peaking on collisionality υ^* in I-mode on C-Mod. The C-Mod discharges do not have NBI fuelling and therefore gives relevant information on the role of NBI fuelling and a valuable comparison to corresponding JET and DIII-D υ^* scans. Moreover, I-mode has special characteristics for edge particle transport with respect to H-mode as the edge particle transport barrier is absent. The steady-state density data indicated no dependence on υ^* in I-mode. This is similar to JET and DIII-D L-mode dependence on υ^*. This result indicates that particle transport characteristics are more analogous to those of L-mode than H-mode and similar to L-mode ones observed in JET and DIII-D. Gas puff modulation was also applied on C-Mod, but the modulated density data is too noisy to able to extract the particle transport coefficients.

10. Fusion for Energy activities

10.1 Preparatory and Preliminary Design of Remote Handling Connector and Ancillary Components

F4E grant: F4E-OPE-0829

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

The focus of the Preparatory and Preliminary Design of Remote Handling Connector and Ancillary Components as a Remote Handling Connector System (RHCS) has been on developing the RHC concept to more detailed and analysed solutions. The development started with the analysis of the concept, which was created in the earlier phase of the RHC design. The contract included RHC Platform design and manufacturing, enhancing the outboard connector solution with new Bridging Link (BL) design, analysing the loads and calculating the stresses, including the electromagnetic, thermal and seismic loads in the most severe events. The design included also the looms with cables and clamps on the Divertor Body and the clamps inside the BL. The pin and socket lay-out were developed according to the most demanding Divertor Cassette with over 200 pins and over 100 cables in different sizes and types of mineral insulated cables. The Cassette Connector solution needed flexibility for the plugging of the RHC and a flexible cable concept was developed. For the Central Cassette Connector a new design was created. The design was based on the concept which needs no special remote handling processes or tools. This RHC will be plugged with the Divertor Cassette movement.

Several mock-ups were designed, tested and demonstrated on the RHC Platform. In addition mock-ups for the irradiation tests were designed and manufactured. For the Preliminary Design Review (PDR) process, over 30 Design and analysis reports were prepared. The aim of the development was to create solutions that can be finalised with the next design phase i.e. the Final Design, which will be followed by the Manufacturing phase in 2021-2022.

10.2 Remote Diagnostics Application Software for RH Equipment

F4E grant: F4E-GRT-0901

Research scientists: J. Alanen, J. Minkkinen, H. Saarinen, VTT
L. Aha, TUT

The RHCS development consist of tasks to develop and integrate the RHCS subsystems, Remote Diagnostics System (RDS), Command & Control (C&C) and Virtual Reality (VR) to be incorporated into the ITER Remote Handling (RH) control room. These tasks are 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 C&C is the operator user interface application to control the movement of the RH robots. The VR is used to monitor the movements of the robot in real time, especially where camera views are not possible. 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 stereo 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 and single camera system is included in the task. In year 2018, the marker study and an automatic stereo-camera calibration procedure were completed.

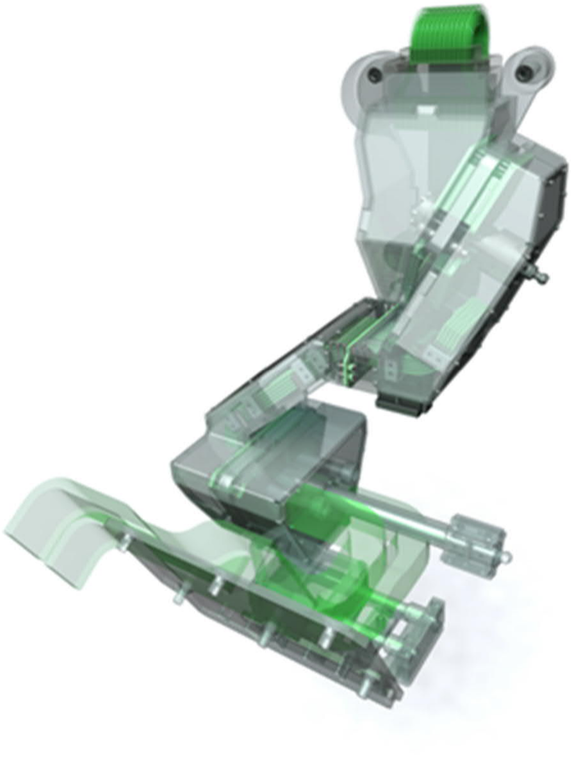


Figure 10.1. An enhanced Bridging Link Concept RHC.

11. Other activities

11.1 Missions and secondments

Mathias Groth and Bartosz Lomanowski to FZ Juelich, Germany, 9–12 January 2018.

Heikki Handroos, Huapeng Wu, Ming Li and Mikko Siuko to CASHIPS, Hefei, China, 20–26 January 2018.

Joona Kontula to IPP Greifswald, Greifswald, Germany, 21 January–3 February 2018.

Jari Likonen to JET facilities, United Kingdom, 22–26 January 2018 (WP JET2).

Tuomas Tala and Antti Salmi to DIII-D/General Atomics, San Diego, California, USA, 22 January–2 February 2018 (International Collaborations).

Mathias Groth to DIII-D/General Atomics, San Diego, California, USA, 5–17 February 2018 (International Collaborations).

Kalle Heinola to IST, Lissabon, Portugal, 11–16 February 2018 (WPJET2).

Antti Hakola to IPP Garching, Garching, Germany, 20–23 February 2018 (WP MST1).

Jari Likonen to JET facilities, United Kingdom, 22–28 February 2018 (WP JET2).

Bartosz Lomanowski to FZ Juelich, Germany, 1–2 March 2018.

Andrea Sand to JET facilities, United Kingdom, 3–11 March 2018.

Jari Varje to JET facilities, United Kingdom, 5–9 March 2018 (WP JET1).

Antti Salmi to JET facilities, United Kingdom, 5–16 March 2018 (WP JET1).

Paula Siren to JET facilities, United Kingdom, 5–23 March 2018 (WP JET1).

Kalle Heinola to IST, Lissabon, Portugal, 12–16 March 2018 (WP JET2).

Laurent Chôné and Tuomas Tala to JET facilities, United Kingdom, 12–21 March 2018 (WP JET1).

Antti Hakola to IPP Garching, Garching, Germany, 12–16 March 2018 (WP MST1).

Markus Airila and Tuomas Tala to JET facilities, United Kingdom, 12–21 March 2018 (WP JET1).

Toni Kaltiaisenaho to JET facilities, United Kingdom, 12–23 March 2018 (WP JET1).

Jari Likonen to JET facilities, United Kingdom, 19–23 March 2018 (WP JET2).

Susan Leerink to JET facilities, United Kingdom, 20–21 March 2018 (WP JET1).

Antti Hakola to IPP Garching, Garching, Germany, 22–28 March 2018 (WP MST1).

Tuomas Tala to JET facilities, United Kingdom, 23–25 April 2018 (WP JET1).

Antti Hakola to IPP Garching, Garching, Germany, 24–27 April 2018 (WP MST1).

Susan Leerink to JET facilities, United Kingdom, 29 April – 4 May 2018 (WP JET1).

Antti Snicker to CIEMAT, Sevilla, Spain, 2–22 May 2018.

Tuomas Tala to EPFL, Lausanne, Switzerland, 7–9 May 2018 (WP MST1).

Susan Leerink to JET facilities, United Kingdom, 13–17 May 2018 (WP JET1).

Toni Kaltiaisenaho, Antti Salmi and Tuomas Tala to JET facilities, United Kingdom, 14–18 May 2018 (WP JET1).

Paula Siren, Jari Varje and Leonid Zakharov to JET facilities, United Kingdom, 14–25 May 2018 (WP JET1).

Antti Hakola to IPP Garching, Garching, Germany, 21–24 May 2018 (WP MST1).

Antti Hakola to EPFL, Lausanne, Switzerland, 27 May – 1 June 2018 (WP MST1).

Antti Hakola to EPFL, Lausanne, Switzerland, 5–13 June 2018 (WP MST1).

Antti Hakola to IPP Garching, Garching, Germany, 26 June – 4 July 2018 (WP MST1).

Jari Likonen to JET facilities, United Kingdom, 2–13 July 2018 (WP JET2).

Antti Hakola to IPP Garching, Garching, Germany and GA meeting, Lausanne, Switzerland, 8–13 July 2018 (WP MST1).

Susan Leerink to JET facilities, United Kingdom, 8 July – 2 August 2018 (WP JET1).

Paula Siren and Jari Varje to JET facilities, United Kingdom, 9 July – 3 August 2018 (WP JET1).

Antti Salmi to JET facilities, United Kingdom, 15–26 July 2018 (WP JET1).

Mathias Groth to JET facilities, United Kingdom, 16–20 July 2018 (WP JET1).

Antti Hakola to IPP Garching, Garching, Germany, 16–25 July 2018 (WP MST1).

Mathias Groth to JET facilities, United Kingdom, 30 July – 3 August 2018 (WP JET1).

Paula Siren to JET facilities, United Kingdom, 22–31 August 2018 (WP JET1).

Antti Hakola to IPP Garching, Garching, Germany, 4–7 September 2018 (WP MST1).

Antti Hakola to EPFL, Lausanne, Switzerland, 10–21 Sepember 2018 (WP MST1).

Antti Hakola to EPFL, Lausanne, Switzerland, 25–28 Sepember 2018 (WP MST1).

Tuomas Tala to EPFL, Lausanne, Switzerland, 1–2 October 2018 (WP MST1).

Antti Hakola to IPP Garching, Garching, Germany, 9–16 October 2018 (WP MST1).

Jari Likonen to JET facilities, United Kingdom, 15–19 October 2018 (WP JET2).

Antti Hakola to IPP Greifswald, Greifswald, Germany, 16–19 October 2018 (WP S1).

Antti Hakola to IPP Garching, Garching, Germany, 23–31 October 2018 (WP MST1).

Antti Hakola to IPP Garching, Garching, Germany, 5–9 November 2018 (WP MST1).

Jari Varje to JET facilities, United Kingdom, 5–16 November (WP JET1).

Antti Hakola to IPP Garching, Garching, Germany, 11–16 November 2018 (WP MST1).

Markus Airila to JET facilities, United Kingdom, 12–16 November (WP JET1).

Antti Snicker to IPP Garching, Garching, Germany, 25 November – 7 December 2018 (WP MST1).

Antti Salmi and Tuomas Tala to JET facilities, United Kingdom, 26–30 November 2018 (WP JET1).

Antti Hakola to IPP Garching, Garching, Germany, 27–30 November 2018 (WP MST1).

Antti Hakola to IPP Garching, Garching, Germany, 4–14 December 2018 (WP MST1).

11.2 Conferences, seminars, workshops and meetings

Iván Paradela Pérez participated in German Physical Society conference (plasma section), Erlangen, Germany, 5–9 March 2018.

Jari Varje participated in Code Camp at ITER, Cadarache, France, 12–23 March 2018 (WP CD).

Seppo Sipilä participated in Code Camp at ITER, Cadarache, France, 18–24 March 2018 (WP CD).

Antti Hakola participated in 2nd WEST Experiment Planning Meeting, CEA, Cadarache, France, 19–22 March 2018 (WP PFC).

Jari Varje participated in WPCD code camp, PSNC, Poznan, Poland, 3–11 April 2018 (WP CD).

Mikko Siuko participated in meeting with Eurofusion on KDI, CCFE, Abingdon, United Kingdom, 10–12 April 2018.

Atte Helminen and Antti Rantakaulio participated in the WPENS technical meeting #5, CEA, Saclay, France, 10–13 April 2018.

Tuomas Tala participated in the 21st EUROfusion General Assembly Meeting, Sofia, Bulgaria, 11–12 April 2018.

Jari Likonen and Kenichiro Mizohata participated in Meeting on IBA analysis of JET ILW PFCs, IST, Lissabon, Portugal, 16–19 April 2018 (WP JET2).

Bartosz Lomanowski, Antti Hakola, Etienne Hodille, Taina Kurki-Suonio, Ivan Paradel Perez and Elnaz Safi participated in Joint SOL/PWI modelling meeting, AMU, Marseille, France, 16–20 April 2018.

Tuomas Tala, Juuso Karhunen and Paula Siren participated in the Control Room Roles Refresher Course, Culham, CCFE, United Kingdom, 23–25 April 2018.

Antti Snicker participated in ITPA energetic particle meeting, ITER, Cadarache, France, 23–25 May 2018 (International Collaborations).

Andrea Sand participated in Functional Materials and EDDI meetings, CEIT, San Sebastian, Spain, 4–8 June 2018 (WP MAT).

Fredric Granberg IREMEV monitoring meeting CEIT, San Sebastian, Spain, 5–7 June 2018 (WP MAT).

Antti Hakola, Mathias Groth, Andreas Holm, Juuso Karhunen, Jari Likonen, Bartosz Lomanowski, Ivan Paradela Perez and Tomi Vuoriheimo participated in 23rd Internat ional Conference on Plasma Surface Interactions in Controlled Fusion Devices (PSI-23), Princeton, United States, 17–22 June 2018.

Jesper Byggmästar and Fredric Granberg participated in COSIRES 2018 conference, Shanghai, China 18–22 June 2018.

Antti Snicker participated in EPS plasma physics conference, Prague, Czech Republic, 1–6 July 2018.

Markus Airila participated in the 41st Fusion for Energy Governing Board meeting, Barcelona, Spain, 5–6 July 2018.

Antti Hakola participated in the 22nd EUROfusion General Assembly Meeting, Lausanne, Switzerland, 9–10 July 2018.

Tuomas Tala participated in Analysis of the ITPA TC-15 experiment on C-Mod meeting, MIT, Cambridge, USA, 21–28 July 2018 (International Collaborations).

Antti Snicker participated in ITPA EP meeting, IST, Lissabon, Portugal, 2–5 September 2018 (International Collaborations).

Iván Paradela Pérez participated in 13th Carolus Magnus Summer School, Weert, The Netherlands, 3-14 September 2018.

Tuomas Tala participated in the the 23rd joint EU-US Transport Task Force meeting, University of Seville, Spain, 11–14 September, 2018.

Tuomas Tala participated in the ITPA TC meeting, ITER, Cadarache, France, 17–20 September, 2018.

Aki Lahtinen, Paula Siren and Jari Varje participated in 30th Symposium on Fusion Technology (SOFT-2018), Giardini Naxos, Italy, 16–21 September 2018.

Jari Varje participated in the WPCD code camp, UL, Ljubljana, Slovenia, 24 September – 5 October 2018 (WP CD).

Atte Helminen and Antti Rantakaulio participated in the WPENS technical meeting #6, Krakow, Poland, 16–20 October 2018.

Tuomas Tala participated in the 23rd EUROfusion General Assembly Meeting, Zagreb, Croatia, 17–18 October 2018.

Taina Kurki-Suonio, Antti Snicker and Tuomas Tala participated in IAEA fusion conference, Gandhinagar, India, 20–28 October 2018.

Jesper Byggmästar and Fredric Granberg participated in 9th Multiscale Materials Modeling conference, Osaka, Japan 28 October – 2 November 2018.

Mathias Groth participated in the APS Divsion of Plasma Physics Conference, Portland, Oregon, USA, 5–9 November 2018.

Jari Likonen participated in MST1 GPM meeting, IPP Garching, Garching, Germany, 5–9 November 2018 (WP MST1).

Tuomas Tala participated in in the ITPA TC-17 experiment, NFRI, Daejeon, Korea, 7–15 November 2018 (International Collaborations).

Fredric Granberg participated in Monitoring meeting, CIEMAT, Madrid, Spain, 19 November 2018 (WP MAT).

William Brace participated in DEMO RM pre-Feasibility Review meeting, CCFE, Culham, United Kingdom, 18–21 November 2018.

Andrea Sand participated in IREMEV meeting, CIEMAT, Madrid, Spain, 19–20 November 2018 (WP MAT).

Antti Hakola participated in JET2-PFC Annual Meeting, RBI, Zagreb, Croatia, 19–22 November 2018 (WP PFC).

Konsta Särkimäki participated in WPSA modelling working session in IST, Lisbon, Portugal, 19–23 November 2018 (WP SA).

Fredric Granberg and Antti Snicker participated in EFPW, KIT, Bad Dürkheim, Germany, 21–23 November 2018.

Jari Varje participated in the JET3 Annual General Meeting, CCFE, Culham, United Kingdom, 3–5 December 2018 (WP JET3).

Jari Likonen participated in MST1 Topic 10 meeting, IPP Garching, Garching, Germany, 4–5 December 2018 (WP MST1).

Jesper Byggmästar participated in the Helsinki Winter School in Theoretical Chemistry, Helsinki, Finland, 10–13 December 2018.

Jari Varje participated in the WPCD code camp, TU Wien, Innsbruck, Austria, 10–21 December 2018 (WP CD).

Tuomas Tala participated in the 42st Fusion for Energy Governing Board meeting, Barcelona, Spain, 11–12 December 2018.

Mathias Groth participated in ITPA Divertor and SOL meeting, Madison, Wisconsin, USA, 11–14 December 2018.

Tuomas Tala participated in the 24th EUROfusion General Assembly Meeting, Gothenburg, Sweden 17–18 December 2018.

11.3 Other visits

Tuomas Tala visited HUST, Wuhan, China, 29–31 May, 2018.

Antti Snicker participated in PhD panel at University of Sevilla, Spain, 17 December 2018.

11.4 Visitors

Sven Wiesen visited Aalto University, 12–16 March 2018.

Guy Matthews, visited Aalto University for Juuso Karhunen’s PhD thesis, 24–25 May 2018.

Evgeniy Gusakov, Alexander Belokurov, Alexey Gurchenko, Alexei Altukhov, Denis Kouprienko and Anton Sidorov from Ioffe Institute visited Aalto University, 18–22 June 2018.

Alain Brizard from St. Michael's college Vermont visited Aalto University 5–11 August 2018.

Salomon Janhunen from University of Texas visited Aalto University 23 September – 5 October 2018.

Nicolas Legouy visited Aalto University 27–28 September 2018.

Carlos Hidalgo visited Aalto University for Paavo Niskala’s PhD thesis, 4–5 October 2018.

Filippo Zonta visited Aalto University 18–19 October 2018.

Evangelos Matzoukas visited Aalto University 13–14 November 2018.

Riccardo Iorio visited Aalto University 13–14 December 2018.

Publications 2018

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

11.5 Publications

11.5.1 Refereed journal articles

1. K. Nordlund, S.J. Zinkle, A.E. Sand, F. Granberg, R.S. Averback, R.E. Stoller, T. Suzudo, L. Malerba, F. Banhart, W.J. Weber, F. Willaime, S.L. Dudarev and D. Simeone, Improving atomic displacement and replacement calculations with physically realistic damage models, Nature Communications **9** (2018) 1084.
2. A.E. Järvinen, S.L. Allen, D. Eldon, M.E. Fenstermacher, M. Groth, D.N. Hill, A.W. Leonard, A.G. McLean, G.D. Porter, T.D. Rognlien, C.M. Samuell and H. Wang, E × B Flux Driven Detachment Bifurcation in the DIII-D Tokamak, Physical Review Letters **121 (**2018) 75001.
3. A.A. Leino, G.D. Samolyuk, R. Sachan, F. Granberg, W.J. Weber, H. Bei, J. Liu, P. Zhai and Y. Zhang, GeV ion irradiation of NiFe and NiCo: Insights from MD simulations and experiments, Acta Materialia **151** (2018) 191.
4. D.R. Mason, A.E. Sand, X. Yi and S.L. Dudarev, Direct observation of the spatial distribution of primary cascade damage in tungsten, Acta Materialia **144** (2018) 905.
5. A. Lehtinen, L. Laurson, F. Granberg, K. Nordlund and M.J. Alava, Effects of precipitates and dislocation loops on the yield stress of irradiated iron, Scientific Reports **8** (2018) 6914.
6. A. Lasa, D. Borodin, J. M. Canik, C. C. Klepper, M. Groth, A. Kirschner, M. I. Airila, I. Borodkina and R. Ding, ERO modeling and sensitivity analysis of locally enhanced beryllium erosion by magnetically connected antennas, Nuclear Fusion **58** (2018) 16046.
7. K. Heinola, F. Djurabekova and T. Ahlgren, On the stability and mobility of di-vacancies in tungsten, Nuclear Fusion **58** (2018) 26004.
8. P. Batistoni, S. Popovichev, A. Cufar, Z. Ghani, L. Giacomelli, S. Jednorog, A. Klix, S. Lilley, E. Laszynska, S. Loreti, L. Packer, A. Peacock, M. Pillon, R. Price, M. Rebai, D. Rigamonti, N. Roberts, M. Tardocchi, D. Thomas, L. Aho-Mantila, M. Airila, A. Hakola, H. Kim, S. Koivuranta, A. Lahtinen, J. Likonen, Y. Liu, T. Makkonen, H. Nordman, A. Salmi, P. Siren, T. Tala, 14 MeV calibration of JET neutron detectors-phase 1: Calibration and characterization of the neutron source, Nuclear Fusion **58** (2018) 26012.
9. C. Guillemaut, C. Metzger, D. Moulton, K. Heinola, M. O'Mullane, I. Balboa, J. Boom, G.F. Matthews, S. Silburn, E.R. Solano and JET contributors, Experimental validation of an analytical kinetic model for edge-localized modes in JET-ITER-like wall, Nuclear Fusion **58** (2018) 66006.
10. K. Särkimaki, J. Varje, M. Becoulet, Y. Liu and T. Kurki-Suonio, Mechanics of ELM control coil induced fast particle transport in ITER, Nuclear Fusion **58** (2018) 76021.
11. M. Maslov, D. B. King, E. Viezzer, D. L. Keeling, C. Giroud, Tuomas Tala, Antti Salmi, M. Marin, J. Citrin, C. Bourdelle, E. R. Solano and JET Contributors, Observation of enhanced ion particle transport in mixed H/D isotope plasmas on JET, Nuclear fusion **58 (**2018) 76022.

12. S. Äkäslompolo, M. Drevlak, Y. Turkin, S. Bozhenkov, T. Jesche, J. Kontula, T. Kurki-Suonio and R. Wolf, Modelling of NBI ion wall loads in the W7-X stellarator, Nuclear Fusion **58 (**2018) 82010.

13. M. Salewski, M. Nocente, B. Madsen, I. Abramovic, M. Fitzgerald, G. Gorini, P.C. Hansen, W.W. Heidbrink, A.S. Jacobsen, T. Jensen, V.G. Kiptily, E.B. Klinkby, S.B. Korsholm, T. Kurki-Suonio, A.W. Larsen, F. Leipold, D. Moseev, S.K. Nielsen, S.D. Pinches, J. Rasmussen, M. Rebai, M. Schneider, A. Shevelev, S. Sipila, M. Stejner and M. Tardocchi, Alpha-particle velocity-space diagnostic in ITER, Nuclear Fusion **58** (2018) 96019.

14. P. Niskala, A.D. Gurchenko, E.Z. Gusakov, A.B. Altukhov, L.A. Esipov, L. Chôné, T.P. Kiviniemi and S.Leerink, Neoclassical and turbulent e × B flows in flux-driven gyrokinetic simulations of Ohmic tokamak plasmas, Nuclear Fusion **58** (2018) 112006.

15. A.A. Belokurov, L.G. Askinazi, L. Chone, E.Z. Gusakov, T.P. Kiviniemi, V.A. Kornev, T. Korpilo, S.V. Krikunov, S.V. Lebedev, S. Leerink, P. Niskala, R. Rochford, A.I. Smirnov, A.S. Tukachinsky and N.A. Zhubr, Dynamics of the LH-transition in TUMAN-3M tokamak in the scenarios with cryogenic pellet injection, Nuclear Fusion **58** (2018) 112007.

16. S.L. Dudarev, D.R. Mason, E. Tarleton, P.W. Ma and A.E. Sand, A multi-scale model for stresses, strains and swelling of reactor components under irradiation, Nuclear Fusion **58 (**2018) 126002.

17. J.S. Park, M. Groth, R.P. Pitts, J.G. Bak, S.G. Thatipamula, J.W. Juhn, S.H. Hong and W. Choe, Atomic processes leading to asymmetric divertor detachment in KSTAR L-mode plasmas, Nuclear Fusion **58** (2018) 126033.

18. P. Sirén, J. Varje, S. Äkäslompolo, O. Asunta, C. Giroud, T. Kurki-Suonio, H. Weisen and JET Contributors, Versatile fusion source integrator AFSI for fast ion and neutron studies in fusion devices, Nuclear Fusion **58 (**2018) 016023.

19. F. Subba, L. Aho-Mantila, D. Coster, G. Maddaluno, G.F. Nallo, B. Sieglin, R. Wenninger, R. Zanino, Modelling of mitigation of the power divertor loading for the EU DEMO through Ar injection, Plasma Physics and Controlled Fusion **60** (2018) 35013.

20. T.P. Kiviniemi, P. Niskala, L.G. Askinazi, A.A. Belokurov, L. Chone, A.D. Gurchenko, E.Z. Gusakov, T. Korpilo, S.V. Lebedev, S. Leerink, R. Rochford and A.S. Tukachinsky, Gyrokinetic simulation of transport reduction by pellet injection in TUMAN-3M tokamak, Plasma Physics and Controlled Fusion **60** (2018) 85010.

21. R. Mateus, D. Dellasega, M. Passoni, Z. Siketić, I. Bogdanović Radović, A. Hakola, E. Alves, Helium load on W-O coatings grown by pulsed laser deposition, Surface and Coatings Technology **355** (2018) 215.

22. J. Byggmastar, E.A. Hodille, Y. Ferro and K. Nordlund, Analytical bond order potential for simulations of BeO 1D and 2D nanostructures and plasma-surface interactions, Journal of Physics: Condensed Matter **30** (2018) 135001.

23. N. Castin, G. Bonny, A. Bakaev, C.J. Ortiz, A.E. Sand and D. Terentyev, Object kinetic Monte Carlo model for neutron and ion irradiation in tungsten: Impact of transmutation and carbon impurities, Journal of Nuclear Materials **500** (2018) 15.

24. J. Byggmästar, F. Granberg and K. Nordlund, Effects of the short-range repulsive potential on cascade damage in iron, Journal of Nuclear Materials **508** (2018) 530.

25. A.E. Sand, J. Byggmastar, A. Zitting and K. Nordlund, Defect structures and statistics in overlapping cascade damage in fusion-relevant bcc metals, Journal of Nuclear Materials **511** (2018) 64.

26. K. Nordlund, S.J. Zinkle, A.E. Sand, F. Granberg, R.S. Averback, R.E. Stoller, T. Suzudo, L. Malerba, F. Banhart, W.J. Weber, F. Willaime, S.L. Dudarev and D. Simeone, Primary radiation damage: A review of current understanding and models, Journal of Nuclear Materials **512** (2018) 450.

27. A.B. Altukhov, A.D. Gurchenko, E.Z. Gusakov, M.A. Irzak, P. Niskala, L.A. Esipov, T.P. Kiviniemi and S. Leerink, Fast synthetic X-mode Doppler reflectometry diagnostics for the full-f global gyrokinetic modeling of the FT-2 tokamak, Physics of Plasmas **25** (2018) 82305.

28. A.B. Altukhov, A.D. Gurchenko, E.Z. Gusakov, M.A. Irzak, P. Niskala, L.A. Esipov, T.P. Kiviniemi, O.L. Krutkin, and S. Leerink, Influence of the probing wave phase modulation on the X-mode radial correlation Doppler reflectometry performance in the FT-2 tokamak, Physics of Plasmas **25** (2018) 112503.

29. T. Kurki-Suonio, K. Sarkimaki, J. Varje, S. Äkäslompolo, J. Kontula, P. Ollus, M. Becoulet, L. Chone, Y. Liu and P. Vincenzi, Clearing the road for high-fidelity fast ion simulations in full three dimensions, Journal of Plasma Physics **84** (2018) 745840603.

30. Y. Oya, S. Masuzaki, M. Tokitani, K. Azuma, M. Oyaidzu, K. Isobe, N. Asakura, A.M. Widdowson, K. Heinola, S. Jachmich, M. Rubel and JET contributors, Correlation of surface chemical states with hydrogen isotope retention in divertor tiles of JET with ITER-Like Wall, Fusion Engineering and Design **132** (2018) 24.

31. A. Baron-Wiechec, K. Heinola, J. Likonen, E. Alves, N. Catarino, J. P. Coad, V. Corregidor, I. Jepu, G. F. Matthews, A. Widdowson and JET contributors. Thermal desorption spectrometry of beryllium plasma facing tiles exposed in the JET tokamak, Fusion Engineering and Design **133** (2018) 135.

32. M. Tokitani, M. Miyamoto, S. Masuzaki, R. Sakamoto, Y. Oya, Y. Hatano, T. Otsuka, M. Oyaidzu, H. Kurotaki, T. Suzuki, D. Hamaguchi, K. Isobe, N. Asakura, A. Widdowson, K. Heinola, M. Rubel and JET contributors, Plasma-wall interaction on the divertor tiles of JET ITER-like wall from the viewpoint of micro/nanoscopic observations, Fusion Engineering and Design **136** (2018) 199.

33. R. Burrows, A. Baron-Wiechec, C. Harrington, S. Moore, D. Chaney, T. L. Martin, J. Likonen, R. Springell, E. Surrey, The possible effect of high magnetic fields on the aqueous corrosion behaviour of Eurofer, Fusion Engineering and Design **136** (2018) 1000.

34. D. Rigamonti, L. Giacomelli, G. Gorini, M. Nocente, M. Rebai, M. Tardocchi, M. Angelone, P. Batistoni, A. Cufar, Z. Ghani, L. Aho-Mantila, M. Airila, A. Hakola, H. Kim, S. Koivuranta, A. Lahtinen, J. Likonen, Y. Liu, T. Makkonen, H. Nordman, A. Salmi, P. Siren, T. Tala and JET Contributors, Neutron spectroscopy measurements of 14 MeV neutrons at unprecedented energy resolution and implications for deuterium-tritium fusion plasma diagnostics, Measurement Science and Technology **29** (2018) 45502.

35. L. Chôné, T.P. Kiviniemi, S. Leerink, P. Niskala and R. Rochford, Improved boundary condition for full-f gyrokinetic simulations of circular-limited tokamak plasmas in ELMFIRE, Contributions to Plasma Physics **58** (2018) 534.

36. A. Holm, M. Groth and T.D. Rognlien, Assessing ion-electron thermal equilibration in the scrape-off layer of tokamaks using UEDGE, Contributions to Plasma Physics **58** (2018) 547.

37. M. Li, H. Wu, H. Handroos, R. Skilton, J. Keep, A. Loving, Comparison of deformation models of flexible manipulator joints for use in DEMO, IEEE Transactions on Plasma Science **46** (2018) 1198.

38. M. Salewski, M. Nocente, A.S. Jacobsen, F. Binda, C. Cazzaniga, J. Eriksson, B. Geiger, G. Gorini, C. Hellesen, V.G. Kiptily, T. Koskela, S.B. Korsholm, T. Kurki-Suonio, F. Leipold, D. Moseev, S.K. Nielsen, J., Rasmussen, P.A. Schneider, S.E. Sharapov, M. Stejner , M. Tardocchi, JET Contributors, ASDEX Upgrade Team & EUROfusion MST1 Team, Bayesian Integrated Data Analysis of Fast-Ion Measurements by Velocity-Space Tomography, Fusion Science and Technology **74** (2018) 23.

39. A. Weckmann, P. Petersson, M. Rubel, P. Ström, T. Kurki-Suonio, K. Särkimäki, A. Kirschner, A. Kreter, S. Brezinsek, J. Romazanov, P. Wienhold, A. Pospieszczyk, A. Hakola and M. Airila, Review on global migration, fuel retention and modelling after TEXTOR decommission, Nuclear Materials and Energy **17** (2018) 83.

40. J. Jussila, F. Granberg and K. Nordlund, Effect of random surface orientation on W sputtering yields, Nuclear Materials and Energy **17** (2018) 113.

41. S.Wiesen, S.Brezinsek, X.Bonnin, E.Delabie, L.Frassinetti , M.Groth, C.Guillemaut, J.Harrison, D.Harting, S.Henderson, A.Huber, U.Kruezi, R.A.Pitts, M.Wischmeier and JET contributors, On the role of finite grid extent in SOLPS-ITER edge plasma simulations for JET H-mode discharges with metallic wall, Nuclear Materials and Energy **17** (2018) 174.

42. R. Mateus, C. Porosnicu, C. Lungu, C. Cruz, Z. Siketić, I. Bogdanović Radović, A. Hakola, E. Alves and WP PFC contributors, Analysis of retained deuterium on Be-based films: Ion implantation vs. in-situ loading, Nuclear Materials and Energy **17** (2018) 242.

43. P. Vincenzi, J. Varje, P. Agostinetti, J.F. Artaud, T. Boltzonella, T. Kurki-Suonio, M. Mattei, P. Sonato and M. Vallar, Estimate of 3D wall heat loads due to Neutral Beam Injection in EU DEMO ramp-up phase, Nuclear Materials and Energy **18** (2018) 182.

44. L. Sanchis, M. Garcia-Munoz, A. Snicker, D.A. Ryan, D. Zarzoso, L. Chen, J. Galdon-Quiroga, M. Nocente, J.F. Rivero-Rodriguez, M. Rodriguez-Ramos, W. Suttrop, M.A. Van Zeeland, E. Viezzer, M. Willensdorfer and F. Zonca, Characterisation of the fast-ion edgeresonant transport layer induced by 3Dperturbativefields in the ASDEX Upgradetokamak through full orbit simulations, Plasma Physics and Controlled Fusion, accepted, 2018.

45. T. Zhang , Y. Song and H. Wu, Deformation modeling of remote handling EAMA robot by recurrent neural networks, Industrial Robot: An International Journal, accepted, 2018.

46. D.R. Mason, X. Yi, A.E. Sand and S.L. Dudarev, Experimental observation of the number of visible defects produced in individual primary damage cascades in irradiated tungsten, Europhysics Letters **122** (2018) 66001.

47. C. Ruset, E. Grigore, M. Rasinski, E. Fortuna, J. Grzonka, M. Gherendi, C. Luculescu, N.P. Barradas, E. Alves and A. Hakola, Nano-porous coatings for gas retention studies, Romanian Reports in Physics, accepted, 2018.

48. P. Paris, J.Butikova, M. Laan, A. Hakola, I. Jõgi, J. Likonen, E. Grigore and C. Ruset, Comparison of LIBS results on ITER-relevant samples obtained by nanosecond and picosecond lasers, Nuclear Materials and Energy, accepted, 2018.

49. N. Vianello, D. Carralero, C. Tsui, V. Naulin, M. Agostini, I. Cziegler, B. Labit, C. Theiler, D. Aguiam, S. Allan, M. Bernert, J. Boedo, S. Costea, H. De Oliveira, J. Galdon-Quiroga, G. Grenfell, A. Hakola, C. Ionita, H. Isliker, A. Karpushov, J. Kovacic, B. Lipschultz, R. Maurizio, K. McClements, F. Militello, A. J. Nielsen, J. Olsen, J. J. Rasmussen, T. Ravensbergen, H. Reimerdes, B. Schneider, R. Schrittwieser, E. Seliunin, M. Spolaore, K. Verhaegh, J. Vicente, N. Walkden, W. Zhang, E. Wolfrum, the ASDEX

Upgrade Team, the TCV Team and the EUROfusion MST1 Team, Scrape-off Layer (SOL) transport and filamentary dynamics in high density tokamak regimes, Nuclear Fusion, submitted, 2018.

50. J. Byggmästar, F. Granberg, A.E. Sand, A. Pirttikoski, R. Alexander, M.-C. Marinica and K. Nordlund, Collision cascades overlapping with self-interstitial defect clusters in Fe and W, Journal of Physics: Condensed Matter, submitted, 2018.
51. A. Weckmann, A. Kirschner, J. Romazanov, A. Kreter, S. Brezinsek, K. Särkimäki, M. Airila, T. Kurki-Suonio and A. Hakola, Physics affecting heavy impurity migration in tokamaks: benchmarking test-ion code ASCOT against TEXTOR tracer experiment, Journal of Nuclear Materials, submitted, 2018.
52. E. Grigore, M. Gherendi, F. Baiasu, M. Firdaouss, C. Hernandez, A. Weckmann, P. Petersson and A.Hakola, The influence of N on the D retention within W coatings for fusion applications, Fusion Engineering and Design, submitted, 2018.
53. J. Romazanov, S. Brezinsek, D. Borodin, M. Groth, S. Wiesen, A. Kirschner, A. Huber, A. Widdowson, M. Airila, A. Eksaeva, I. Borodkina, Ch. Linsmeier and JET Contributors, Beryllium global erosion and deposition at JET-ILW simulated with ERO2.0, Nuclear Materials and Energy, submitted, 2018.
54. J. Likonen, K. Heinola, A. De Backer, A. Baron-Wiechec, N. Catarinod, I. Jepu, C.F. Ayres, P. Coad, G.F. Matthews, A. Widdowson and JET Contributors, Investigation of deuterium trapping and release in the JET divertor during the third ILW campaign using TDS, Nuclear Materials and Energy, submitted, 2018
55. J. Likonen, K. Heinola, A. De Backer, A. Baron-Wiechec, N. Catarino, I. Jepu, C.F. Ayres, P. Coad, S. Koivuranta, S. Krat, G.F. Matthews, M. Mayer, A. Widdowson and JET Contributors, Investigation of deuterium trapping and release in the JET ITER-like wall divertor using TDS and TMAP, Nuclear Materials and Energy, submitted, 2018.
56. A. Weckmann, A. Kirschner, A. Kreter, S. Brezinsek, J. Romazanov, K. Särkimäki, A. Hakola, M. Airila and T. Kurki-Suonio. Physics affecting heavy impurity migration in tokamaks: benchmarking test-ion code ASCOT against TEXTOR tracer experiment, Nuclear Materials and Energy, submitted, 2018.

11.5.2 Conference presentations

57. L. Niu, S. Smirnov, J. Mattila, A. Gotchev and E. Ruiz, Robust Pose Estimation with the Stereoscopic Camera in Harsh Environment, IS&T International Symposium on Electronic Imaging. IS&T/SPIE, Burlingame, United States, 28 January – 1 February 2018, Paper 126-1-126-6(6).
58. J. Wu, Y. Song, H. Wu, K. Wang, Y. Cheng, Compensation Application of EAST Articulated Maintenance Arm Software, 13th International Forum on Strategic Technology (IFOST), Harbin, China, 31 May – 1 June, 2018, Paper S4C-1.
59. J. Wu, H. Wu, Y. Song, Accurate Deformation Regression Analysis and estimation for EAST Articulated Maintenance Arm, 13th International Forum on Strategic Technology (IFOST), Harbin, China, 31 May – 1 June, 2018, Paper SP-104.
60. A. Hakola, K. Heinola, J. Likonen, C. Lungu, C. Porosnicu, E. Alves, R. Mateus, I. Bogdanović Radović, Z. Siketić, V. Nemanic, Production of ITER-relevant Be-containing laboratory samples for fuel retention investigations, 23rd International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Princeton, United States, 17 – 22 June 2018, Paper P-378.

61. J. Likonen, K. Heinola, A. De Backer, S. Koivuranta, C.F.Ayres, A.Baron-Wiechec, N. Catarino, P. Coad, I. Jepu, G.F. Matthews, A. Widdowson and JET Contributors, Investigation of deuterium trapping and release in the JET divertor during the third ILW campaign using TDS, 23rd International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Princeton, United States, 17 – 22 June 2018, Paper P-389.

62. P. Paris, J. Butikova, M. Laan, A. Hakola, M. Aints, J. Likonen, K. Piip, E. Grigore and C. Ruset, Comparison of LIBS results on ITER-relevant samples obtained by nanosecond and picosecond lasers, 23rd International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Princeton, United States, 17 – 22 June 2018, Paper P-295.

63. A. Weckmann, T. Kurki-Suonio, J. Romazanov, K. Särkimäki, A. Kirschner, A. Kreter, M. Airila, A. Hakola, P. Petersson, M. Rubel and S. Brezinsek, TEXTOR whole-tokamak high-Z migration modelling and parameter studies with ASCOT code, 23rd International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Princeton, United States, 17 – 22 June 2018, Paper P-204.

64. J. Byggmästar, F. Granberg, A. E. Sand and K. Nordlund, Comparing the differences in cascade damage accumulation in iron for different interatomic potentials, Cosires 2018, Shanghai, China 18 – 22 June 2018.

65. F. Granberg, E. Levo, J. Byggmästar, F. Djurabekova and K. Nordlund, Massively overlapping cascade simulations in metals and metal alloys, Cosires 2018, Shanghai, China 18 – 22 June 2018.

66. P. Mäkinen, T. Mononen and J. Mattila, Inertial Sensor-based State Estimation of Flexible Links Subject to Bending and Torsion, 14th IEEE/ASME International Conference on Mechatronic and Embedded Systems and Applications (MESA), Oulu, Finland, 2 – 4 July 2018, Paper 1570435439.

67. L. Chôné, A.D. Gurchenko, E.Z. Gusakov, T.P. Kiviniemi, S.I. Lashkul, S. Leerink and P. Niskala, Gyrokinetic simulation of the FT-2 tokamak edge, 45th EPS Conference on Plasma Physics, Prague, Czech Republic, 2 – 6 July 2018, Paper 1029.

68. D. Kouprienko, A. Altukhov, L. Askinazi, A. Belokurov, L. Esipov, L., A.D. Gurchenko, E. Gusakov, S. Lashkul, S. Leerink, P. Niskala, S. Shatalin and G. Troshin, Isotope effect in confinement in high density FT-2 tokamak regimes, 45th EPS Conference on Plasma Physics, Prague, Czech Republic, 2 – 6 July 2018, Paper 1097.

69. K.D. Lawson, M. Groth, D. Harting, S. Menmuir, D. Reiter, K.M. Aggarwal, S. Brezinsek, G. Corrigan, F.P. Keenan, C.F. Maggi, A.G. Meigs and S. Wiesen, An exploration of a low temperature regime in EDGE2D-EIRENE simulations of JET ITER-like wall L-mode discharges, 45th EPS Conference on Plasma Physics, Prague, Czech Republic, 2 – 6 July 2018, Paper 1072.

70. A. Salmi, T. Tala, A. Järvinen, D. Dunai, R. Gomes, P. Lomas, L. Meneses, S. Mordijck, V. Naulin, J. Juul Rasmussen, M. Romanelli, A.C.C. Sips, JET Contributors, Particle sources and SOL dynamics in JET strike point sweeping experiments, 45th EPS Conference on Plasma Physics, Prague, Czech Republic, 2 – 6 July 2018, Paper 1068.

71. S. Sipilä, J. Varje, T. Johnson, T. Kurki-Suonio, J. Galdón Quiroga and J.González Martín, Monte Carlo ion cyclotron heating and fast ion loss detector simulations in ASDEX Upgrade, 45th EPS Conference on Plasma Physics, Prague, Czech Republic, 2 – 6 July 2018, Paper 1067.

72. M. Vallar, M. Agostini, T. Bolzonella, S. Coda, J. Garcia, B. Geiger, G. Giruzzi, T. Goodman, M. Gorelenkova, A.N. Karpushov, T. Kurki-Suonio, C. Piron, L. Pigatto, O. Sauter,

N. Vianello, P. Vincenzi and M. Yoshida, Nonlinear contribution of neutral beam injection in TCV EC-heated advanced tokamak scenarios, 45th EPS Conference on Plasma Physics, Prague, Czech Republic, 2 – 6 July 2018, Paper 1068.

73. P. Mustalahti and J. Mattila, Nonlinear Model-Based Controller Design for a Hydraulic Rack and Pinion Gear Actuator, ASME/BATH 2018 Symposium on Fluid Power and Motion Control. American Society of Mechanical Engineers, Bath, United Kingdom, 12 – 14 September 2018, Paper FPMC2018-8841.

74. P. Mäkinen, O. Dmitrochenko and J. Mattila, Floating Frame of Reference Formulation for a Flexible Manipulator with Hydraulic Actuation – Modelling and Experimental Validation, ASME/BATH 2018 Symposium on Fluid Power and Motion Control. American Society of Mechanical Engineers, Bath, United Kingdom, 12 – 14 September, 2018, Paper FPMC2018-8846.

75. A. Hakola, E. Grigore, C. Ruset, F. Baiasu, M. Firdaouss, C. Hernandez, A. Weckmann, P. Petersson, The influence of nitrogen on the deuterium retention within tungsten coatings for fusion applications, 30th Symposium on Fusion Technology, SOFT 2018, Sicily, Giardini Naxos, Italy, 16 – 21 September 2018, Paper P4-117.

76. P. Siren, J. Varje, H. Weisen, Recent develoment and physical improvements of AFSI-ASCOT based synthetic neutron diagnostic at JET, 30th Symposium on Fusion Technology, SOFT 2018, Sicily, Giardini Naxos, Italy, 16 – 21 September 2018, P3.006.

77. J Varje, T. Kurki-Suonio, A. Snicker, K. Särkimäki, P. Vincenzi, P. Agostinetti, E. Fable, P. Sonato, F. Villone, Sensitivity of fast ion losses to magnetic perturbations in the European DEMO, 30th Symposium on Fusion Technology, SOFT 2018, Sicily, Giardini Naxos, Italy, 16 – 21 September 2018, P3.044.

78. S. Shi, Y. Cheng, H. Pan, W. Zhao, H. Wu, Development and Error Compensation of a Flexible Multi-Joint Manipulator Applied in Nuclear Fusion Environment, 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Madrid, Spain, 1 – 5 October 2018, Page 3587- 3592.

79. C. Chrystal, B.A. Grierson, S.R. Haskey, J.S. deGrassie, G.M. Staebler, T. Tala and A. Salmi, Predicting the Toroidal Rotation Profile for ITER, 27th IAEA Fusion Energy Conference, Ghandhinagar, Ahmedabad, India, 22 – 27 October 2018, Paper EX/5-2.

80. B.A. Grierson, D.R. Ernst, C. Chrystal, T. Tala, T.L. Rhodes, G.R. McKee, S.R. Haskey, L. Bardoczi and A. Salmi, Rotation Profile Hollowing in DIII-D Low-Torque Electron-Heated H-Mode Plasmas, 27th IAEA Fusion Energy Conference, Ghandhinagar, Ahmedabad, India, 22 – 27 October 2018, Paper EX/P6-3.

81. A. Hakola, N. Vianello, D. Carralero, C. Tsui, V. Naulin, M. Agostini, J. Boedo, B. Labit, C. Theiler, D. Aguiam, S. Allan, M. Bernert, S. Costea, I. Cziegler, H. de Oliveira, J. Galdon-Quiroga, G. Grenfell, C. Ionita, H. Isliker, A. Karpushov, J. Kovacic, B. Lipschultz, R. Maurizio, K. McClements, F. Militello, J. Olsen, J. Juul Rasmussen, T. Ravensbergen, H. Reimerdes, B. Schneider, R. Schrittwieser, M. Spolaore, K. Verhaegh, J. Vicente, N. Walkden, W. Zhang and E. Wolfrum, SOL Transport and Filamentary Dynamics in High Density Tokamak Regimes, 27th IAEA Fusion Energy Conference, Ghandhinagar, Ahmedabad, India, 22 – 27 October 2018, Paper EX/P8-13.

82. S. Mordijck, L. Zeng, T.L. Rhodes, L. Schmitz, J.W. Hughes, T. Tala and A. Salmi, Y. Baranov, C.C. Petty, R.J. Groebner and A.L. Moser, Particle Transport From the Bottom Up, 27th IAEA Fusion Energy Conference, Ghandhinagar, Ahmedabad, India, 22 – 27 October 2018, Paper EX/P6-5.

83. P. Strand, A. Figueiredo, D. Coster, D. Kalupin, D. van Eester, D. Yadikin, E. Tholerus, E. Lerche, F. Casson, G. Falchetto, I. Ivanova-Stanik, J. Ferreira, M. Poradzinski, M.

Romanelli, P. Siren, P. Huynh, R. Coelho, S. Moradi, T. Jonsson, J. Varje, Towards a predictive modelling capacity for DT plasmas: European Transport Simulator (ETS) verification and validation, 27th IAEA Fusion Energy Conference, Ghandhinagar, Ahmedabad, India, 22 – 27 October 2018, P6-14

84. T. Tala, J.W. Hughes, S. Mordijck, H. Nordman, A. Salmi, C. Bourdelle, J. Citrin, C. Agatha, C. Giroud, J. Hillesheim, A.E. Hubbard, C.F. Maggi, P. Mantica, M. Maslov, L. Meneses, S. Menmuir, V. Naulin, M. Oberparleiter, A.C.C. Sips, A. Skyman, D. Tegnered, M. Tsalas, E.A. Tolman, and H. Weisen, Core Density Peaking Experiments in JET, DIII-D and C-Mod in Various Operational Scenarios Driven by Fuelling or Transport, 27th IAEA Fusion Energy Conference, Ghandhinagar, Ahmedabad, India, 22 – 27 October 2018, Paper EX/4-4.
85. J. Byggmastar, F. Granberg, A.E. Sand and K. Nordlund, Defect production in cascade overlap with defect clusters in iron and tungsten, 9th Multiscale Materials Modeling, Osaka, Japan, 28 October – 2 November 2018.
86. F. Granberg, H. Xu and K. Nordlund, Multiscale modelling of radiation damage evolution in Fe and Fe-based alloys, 9th Multiscale Materials Modeling, Osaka, Japan, 28 October – 2 November 2018.
87. C. Chrystal, B.A. Grierson, S.R. Haskey, J.S. deGrassie, G.M. Staebler, T. Tala, and A. Salmi, Predicting the Toroidal Rotation Profile for ITER, 60th Annual Meeting of the APS Division of Plasma Physics, Portland, United States, 5 – 9 November 2018, Paper UP11.00062.
88. A. Salmi, T. Tala, S. Mordijck, H. Nordman, J.W. Hughes, Density profile peaking on DIII-D and JET – fuelling versus transport, 60th Annual Meeting of the APS Division of Plasma Physics, Portland, United States, 5 – 9 November 2018, Paper BO5.00012.
89. S. Mordijck, R.J. Groebner, T. Osborne, T.N. Carlstrom, F. Glass, P.B. Snyder, J.W. Hughes, A.E. Järvinen, A. Salmi, T. Tala, F. Laggner, G.R. McKee, R.A. Moyer, T.L. Rhodes, L. Zeng, Effect of opacity on the density pedestal structure in DIII-D and Alcator C-Mod, 60th Annual Meeting of the APS Division of Plasma Physics, Portland, United States, 5 – 9 November 2018, Paper UP11.00043.
90. L. Niu, M. M. Aref and J. Mattila, Clustering Analysis for Secondary Breaking Using a Low-Cost Time-of-Flight Camera, Ninth International Conference on Intelligent Control and Information Processing (ICICIP), Wanzhou, China, 9 – 11 November 2018, Pages 318-324.

11.5.3 Research reports

91. J. Likonen (ed.), M. Airila (ed.), FinnFusion Yearbook 2017, VTT Science **179** (2018).

11.5.4 Academic theses

92. Pekka Alho, “Service-based Fault Tolerance for Cyber-Physical Systems: A Systems Engineering Approach”, Tampere University of Technology, PhD thesis, Tampere 2016 (missing from earlier FinnFusion Yearbooks).
93. Luis Orona Dominguez, Principles and Techniques to Systematically Define, Analyze, and Develop Remote Maintenance Tasks for Machines Operating in Ionizing Radiation Environments, PhD thesis, Tampere University of Technology, Tampere 2017 (missing from earlier FinnFusion Yearbooks).

94. Tuomo Kivelä, Increasing the Automation Level of Serial Robotic Manipulators with Optimal Kinematic Design and Collision-free Path Control, PhD thesis, Tampere University of Technology, Tampere, 2017 (missing from earlier FinnFusion Yearbooks).

95. Jarmo Nurmi, On Increasing the Automation Level of Heavy-Duty Hydraulic Manipulators with Condition Monitoring of the Hydraulic System and Energy-Optimized Redundancy Resolution, PhD thesis, Tampere University of Technology, Tampere 2017 (missing from earlier FinnFusion Yearbooks).

96. Juuso Karhunen, Spectroscopic measurements of impurity migration, deposition and fuel retention in fusion devices, PhD thesis, Aalto University, Espoo 2018.

97. Paavo Niskala, Simulations of turbulence-flow interplay in tokamak plasmas, PhD thesis, Aalto University, Espoo 2018.

98. Paula Siren, Modelling of JET and ITER reactor relevant plasma neutron source for neutronics calculation chain, PhD thesis, Aalto University, Espoo 2018.

99. Wenlong Zhao, Reliability Based Design, Analysis and Control of the Remote Handling Maintenance System for Fusion Reactor, PhD thesis, Lappeenranta University of Technology, Lappeenranta 2018.

100. Mohammad M. Aref, Vision-Based Macro-Micro Mobile Manipulation, PhD thesis, Tampere University of Technology, Tampere 2018.

101. Elnaz Safi, Atomistic simulations of plasma-material interactions in fusion reactors, PhD thesis, University of Helsinki, Helsinki, 2018.

102. Andreas Holm, UEDGE-predicted impact of molecules on plasma detachment in DIII-D L-mode plasmas, MSc thesis, Aalto University, Espoo 2018.

103. Emil af Björkesten, Assessment of two-point model using SOLPS-ITER, BSc thesis, Aalto University, Espoo 2018.

104. Joel Kilpeläinen, Improving the statistics of synthetic fast-ion loss detector simulations in ASCOT, BSc thesis, Aalto University, Espoo 2018.

105. Unna Lauranto, Flux surface particle distributions for ASCOT5, BSc thesis, Aalto University, Espoo 2018.

Series title and number

VTT Technology 352

Title	**FinnFusion Yearbook 2018**
Author(s)	Jari Likonen and Markus Airila (Eds.)
Abstract	This Yearbook summarises the 2018 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, Fortum Power and Heat Ltd., Lappeenranta University of Technology, Tampere University of Technology, 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 2018 focused on system level design for ITER Remote Handling Connector and remote diagnostics application software development. EUROfusion supports post-graduate training through the Education work package that allowed FinnFusion to partly fund 12 PhD students in FinnFusion member organizations. In addition, three EUROfusion post-doctoral research and engineering fellowships were running in 2018. The FinnFusion annual seminar in 2018 was organized by VTT in Espoo in June.
ISBN, ISSN, URN	ISBN 978-951-38-8686-8 (Soft back ed.) ISBN 978-951-38-8685-1 ISSN-L 2242-1211 ISSN 2242-1211 (Print) ISSN 2242-122X (Online) DOI: 10.32040/2242-122X.2019.T352
Date	May 2019
Language	English, Finnish abstract
Pages	77 p.
Name of the project	
Commissioned by	
Keywords	nuclear fusion, fusion energy, fusion technology, fusion reactors, fusion reactor materials, ITER, DEMO, remote handling
Publisher	VTT Technical Research Centre of Finland Ltd P.O. Box 1000, FI-02044 VTT, Finland, Tel. 020 722 111, https://www.vttresearch.com

Julkaisun sarja ja numero

VTT Technology 352

Nimeke	**FinnFusion Yearbook 2018**
Tekijä(t)	Jari Likonen ja Markus Airila (toim.)
Tiivistelmä	Tähän vuosikirjaan on koottu FinnFusion-konsortion vuoden 2018 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, Fortum Power and Heat Oy, Lappeenrannan teknillinen yliopisto, Tampereen teknillinen yliopisto, Helsingin 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 12 jatko-opiskelijan työtä jäsenorganisaatioissaan. Lisäksi vuoden 2018 aikana oli käynnissä kolme EUROfusionin rahoittamaa tutkijatohtorin projektia. FinnFusionin vuosiseminaari 2018 järjestettiin VTT:llä kesäkuussa.
ISBN, ISSN, URN	ISBN 978-951-38-8686-8 (nid.) ISBN 978-951-38-8685-1 ISSN-L 2242-1211 ISSN 2242-1211 (Painettu) ISSN 2242-122X (Verkkojulkaisu) DOI: 10.32040/2242-122X.2019.T352
Julkaisuaika	Toukokuu 2019
Kieli	Englanti, suomenkielinen tiivistelmä
Sivumäärä	77 s.
Projektin nimi	
Rahoittajat	
Avainsanat	nuclear fusion, fusion energy, fusion technology, fusion reactors, fusion reactor materials, ITER, DEMO, remote handling
Julkaisija	Teknologian tutkimuskeskus VTT Oy PL 1000, 02044 VTT, puh. 020 722 111, https://vtt.fi

FinnFusion Yearbook 2018

This Yearbook summarises the 2018 research and industry activities of the FinnFusion Consortium. FinnFusion participates in several EUROfusion work packages, the largest being experimental campaigns at JET and European Medium-size tokamaks and related analyses, as well as materials research, plasma-facing components and remote maintenance.

EUROfusion supports post-graduate training through the Education work package that allowed FinnFusion to partly fund 12 PhD students in FinnFusion member organizations. In addition, three EUROfusion post-doctoral research and engineering fellowships were running in 2018.

F4E projects in 2018 focused on system level design for ITER Remote Handling Connector and remote diagnostics application software development.

The FinnFusion annual seminar in 2018 was organized by VTT in Espoo in June.

ISBN 978-951-38-8686-8 (Soft back ed.)
ISBN 978-951-38-8685-1
ISSN-L 2242-1211
ISSN 2242-1211 (Print)
ISSN 2242-122X (Online)
DOI: 10.32040/2242-122X.2019.T352

VTT beyond the obvious