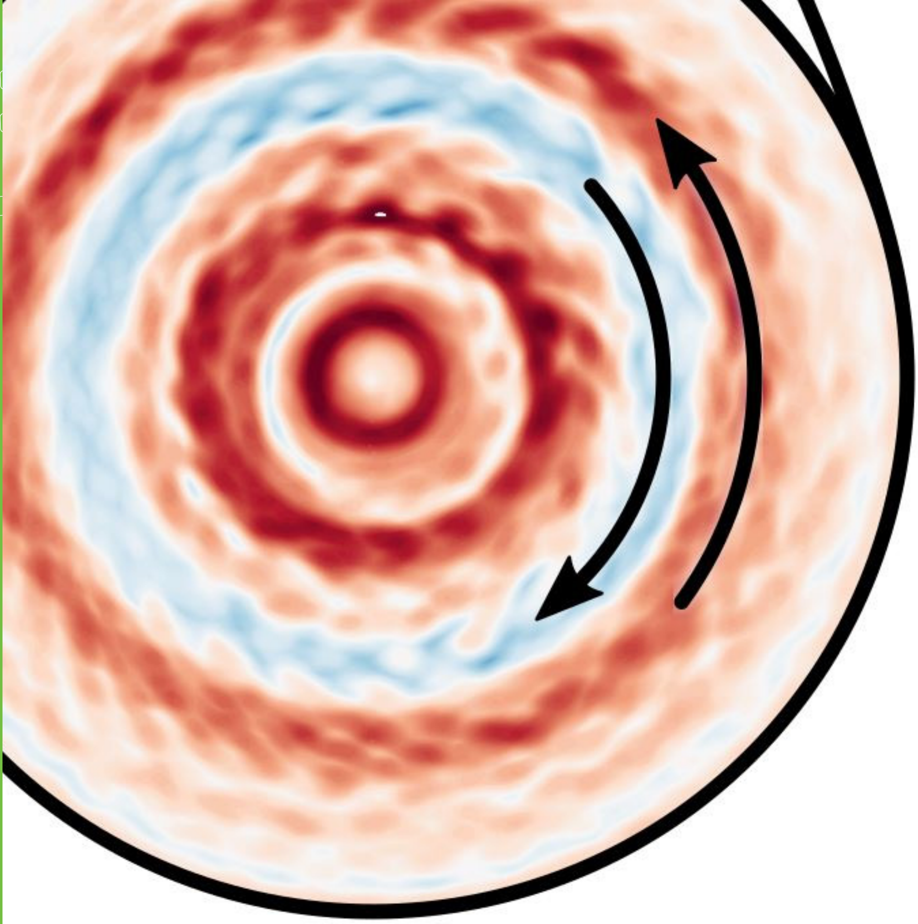

SCIENCE•TECHNOLOGY•RESEARCH HIGHLIGHTS•VISIONS

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FinnFusion Yearbook 2017

Jari Likonen | Markus Airila (Eds.)

VTT

VTT SCIENCE 179

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Jari Likonen and Markus Airila (Eds.)

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Cover image: Paavo Niskala. Zonal flows in a tokamak and in Jupiter.

Juvenes Print, Tampere 2018

Preface

The thirty-nine buildings and technical areas will house the ITER Tokamak and its plant systems. The heart of the facility—the Tokamak Building—is a seven-storey structure in reinforced concrete that will sit 13 metres below the platform level and 60 metres above. Europe, as part of its commitments to the project, is building nearly all of the platform buildings and site infrastructure. An estimated 2300 workers will participate in the construction of the ITER scientific facility. Over the next years each building, as it becomes ready for occupation, will be handed over to the ITER Organization for the start of assembly works.

The ITER project has progressed significantly faster by all measures in 2017 than in earlier years. The new leadership both in ITER and in F4E has been able to create a positive trend within the project. Re-sharing parts of the critical components, like the vacuum vessel between the domestic agencies or re-sharing the building construction between F4E and ITER Organization will shorten the construction time and be also cheaper.

Fusion research is progressing from plasma physics experiments into solving power plant scale industrial and nuclear technology challenges. Fission technology, that once matured quickly, has a lot to provide for fusion. Especially during the last years, FinnFusion has actively combined fusion know-how with the industrial experience of nuclear technology and realised various opportunities to promote the export of Finnish nuclear technology expertise. Together, Finnish industry and research have been able to participate in world-class consortia to deliver technology e.g. for process modelling, neutronics, licencing and remote maintenance. An example of these deliveries even outside the actual nuclear field are the superconductors for ITER.

In 2017, FinnFusion organized three major fusion events in Finland. The first one was the EUROfusion Joint Working Session for Integrated Plasma-Wall Modelling, organized in Tervaniemi in February. Fifty participants from Europe were gathered to discuss plasma boundary properties, material erosion & migration, fuel retention and formation of mixed materials in a tokamak device. In June, FinnFusion hosted the 2nd Joint Nordic Fusion Seminar in Espoo. 21 participants from Denmark and 25 from

Sweden together with 50 Finnish participants talked about their research and about how to enhance the Nordic collaboration further in the field of fusion. This was also the largest annual fusion seminar ever held in Finland. The ITPA (ITER Tokamak Physics Activity) meeting for the transport and pedestal groups was arranged in Espoo in September by VTT. Around 60 ITER physics experts worldwide had the pleasure to enjoy the beautiful autumn days with deep discussions on key ITER physics issues to be tackled and solved in the years to come.

Despite being in forefront and possessing excellence in many areas of fusion research, the Finnish fusion community and the researchers of the next generation nuclear technologies are now concerned about the future of the persistently developed success story. After Tekes ended the programme-type funding in 2017, the cohesive force, which enabled strategic steering by collecting all parts of national fusion research into a common research programme, has disappeared. Even though some of the research projects are still functional, the strong programme that worked together for a common goal practically ceased. Now we must together find a way to restore or compensate the domestic annual investment of about a million euro that would secure the success of Finnish fusion research also in the coming decades.

It has to be remembered that Europe is politically strongly committed for the next 40 years to promote economically viable fusion energy. ITER that is being built in France is most of all a demonstration of broad international collaboration since more than half of the humankind is participating in the project. At the same, it is practically the only big scientific initiative in Europe and with its 20 billion euro budget, it can be considered also as a notable primary market for new expertise.

As a member of EU Finland is also politically engaged into construction and use of ITER as well as the supporting research. Finland is participating yearly on average with around 10 M€ membership fee to ITER and fusion research. The key question is, how Finland is going to utilise this investment in the future so that we are getting the best possible benefit. Finland, known as a strong expert of nuclear technology and a trusted partner, would get a bad dent in its reputation, competence and ability to tempt talented students if we gave up fusion research at the EU level.

As Finland is a strong nuclear energy country, the fusion community and FinnFusion expect a positive result from the negotiation of the national fusion funding. Enhancing nuclear expertise both in industry and research and educating nuclear experts in top-level international environment must be a top priority among the national authorities to decide on funding.

Tuomas Tala
Head of Research Unit
FinnFusion Consortium

Contents

Abstract
Tiivistelmä

List of acronyms and names

AFSI	AFSI Fusion Source Integrator (simulation code)
AMNS	Atomic, Molecular, Nuclear and Surface (database)
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)
BIXS	β-ray induced X-ray spectrometry
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
DOF	Degree of freedom
DONES	DEMO oriented neutron source
DT	Deuterium-tritium
DTP2	Divertor test platform phase 2 (test facility in Tampere)
DTU	Danmarks Tekniske Universitet (Danish RU)
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

ENEA	Ente per le Nuove Tecnologie, l'Energia e l'Ambiente (Italian RU)
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)
FEM	Finite element method (numerical method)
FPA	Framework project agreement
FT-2	Tokamak facility
GAM	Geodesic acoustic mode (plasma instability)
HCD	Heating and current drive
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)
ITPA	International Tokamak Physics Activity
JET	Joint European Torus (tokamak facility)
JINTRAC	Set of plasma simulation codes
JSI	Jozef Stefan Institute (Slovenian RU)
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)

MPI	Message passing interface (interface for parallel computing)
NBI	Neutral beam injection
NBISIM	Computer code
NJOC	New JET Operating Contract
NPA	Neutral particle analyser
NUCLEARSIM	Computer code
OpenMP	Open multi-processing (programming interface for parallel computing)
PCS	Power conversion system
PFC	Plasma-facing component
PHTS	Primary heat transfer system
PINI	Positive ion neutral injector
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)
SPC	Swiss Plasma Center (Swiss RU)
TCV	Tokamak à Configuration Variable (tokamak facility)
TDS	Thermal desorption spectrometry
TOF-ERDA	Time-of-flight elastic recoil detection analysis
TOFOR	Time-of-flight spectrometer
Tekes	The Finnish Funding Agency for Innovation
TRANSP	Interpretative plasma transport code
TUMAN-3M	Tokamak facility
UH	University of Helsinki
TUT	Tampere University of Technology
VDC	Virtual decomposition control
VENUS-LEVIS	Computer code
VTT	VTT Technical Research Centre of Finland Ltd
WEST	Tungsten (W) environment in steady-state tokamak (tokamak facility)
ÅA	Åbo Akademi University, Turku, Finland

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 734 M€ grant (including NJOC) for the period 2014–2018 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.

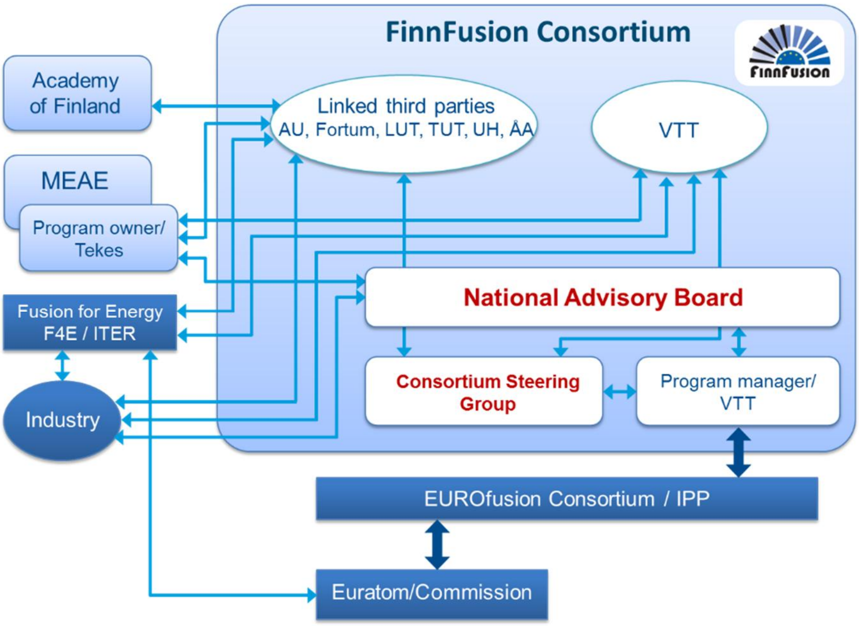

Figure 1.1. Organigram of Finnish Fusion Research Community in 2015–2020.

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 2017:

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, Mrs. Anne Kemppainen (administration), MSc. Seppo Koivuranta, Dr. Jaakko Leppänen, Dr. Jari Likonen (Project Manager), MSc. Sixten Norrman, Dr. Antti Salmi, MSc. Paula Sirén

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

Activities: Remote handling, DTP2
Members: MSc. Jarmo Alanen, Tech. Vesa Hämäläinen, Dr. Ali Muhammad (Project Manager), 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 (Project Manager), Dr. Risto Tiusanen, MSc. Outi Venho-Ahonen, MSc. Jarno Videnoja

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

Activities: Physics
Members: Prof. Mathias Groth (Head of Laboratory), Dr. Laurent Chone, MSc. Juuso Karhunen, Dr. Timo Kiviniemi, M.Sc. Joona Kontula, MSc. Tuomas Korpilo, Dr. Taina Kurki-Suonio, Dr. Susan Leerink, MSc. Paavo Niskala, Dr. Bartosz Lomawoski, MSc. Ivan Paradela Perez, Dr. Ronan Rochford, Dr. Seppo Sipilä, Dr. Christos Stavrou, MSc. Konsta Särkimäki, MSc. Jaroslavs Uljanovs, MSc Jari Varje
Students: Mathias Fontell, Andreas Holm, Saskia Kivistö, Patrik Ollus, Iiro Sallinen, Angelos Stathakis, Katarina Jirikova (ERASMUS, IPP Prague, Technical University Prague, Czech Republic)

University of Helsinki (UH), Accelerator Laboratory

Activities: Physics, materials
Members: Dr. Tommy Ahlgren, Dr. Carolina Björkas, MSc. Laura Bukonte, MSc. Jesper Byggmästar, Dr. Flyura Djurabekova, Dr. Fredric Granberg, Dr. Kalle Heinola, Dr. Antti Kuronen MSc. Aki Lahtinen, Dr. Kenichiro Mizohata, Prof. Kai Nordlund (Project Manager), Dr. Jussi Polvi, Prof. Jyrki Räisänen (Project Manager), MSc. Elnaz Safi, Dr. Andrea Sand

Tampere University of Technology (TUT)

Activities: Remote handling, DTP2
Members: MSc. Liisa Aha, MSc. Dario Carfora, Dr. Juha-Pekka Karjalainen, MSc. Janne Koivumäki, MSc. Ville Lyytikäinen, Prof. Jouni Mattila (Project Manager), MSc. Longchuan Niu, MSc. Jarmo Nurmi, MSc. Sergey Smirnov, MSc. Jyrki Tammisto, MSc. Janne Tuominen, MSc. Jukka Väyrynen

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

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

Fortum Power and Heat Ltd.

Activities: Power plant engineering
Members: Mr. Sami Herranen, Mr. Jaakko Iivanainen, MSc. Sami Kiviluoto, MSc. Antti Rantakaulio, Dr. Harri Tuomisto

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
	Lauri Muranen, Finnuclear
	Kristiina Söderholm, Fortum
	Mika Korhonen, Suisto Engineering
	Olli Pohls, Fluiconnecto
	Ben Karlemo, Luvata
	Liisa Heikinheimo, MEAE
	Jarmo Lehtonen, Metso Minerals
	Pertti Pale, PPF Consulting
	Anna Kalliomäki, Academy of Finland
	Janne Uotila, Sandvik
	Veera Sylvius, Space Systems Finland
	Hannu Juuso, Tekes
	Timo Laurila, Tekes
	Kari Koskela, Tekes
	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 did not convene in 2017.

1.5 Finnish members in the European Fusion Committees

1.5.1 Euratom Science and Technology Committee (STC)

- Rainer Salomaa, Aalto University

1.5.2 Euratom Programme Committee, Fusion configuration

- Tuomas Tala, VTT
- Arto Kotipelto, Tekes

1.5.3 EUROfusion General Assembly

- Tuomas Tala, VTT

1.5.4 EUROfusion Science and Technology Advisory Committee (STAC)

- Kai Nordlund, UH

1.5.5 EUROfusion HPC Allocation Committee

- Susan Leerink, AU

1.5.6 EUROfusion Project Boards

- WP JET2: Antti Hakola, VTT
- WP JET4: Mathias Groth, AU / Jari Likonen, VTT
- WP PFC: Jari Likonen, VTT
- WP DTT1: Leena Aho-Mantila, VTT
- WP CD: Timo Kiviniemi, AU
- WP S1 & S2: Taina Kurki-Suonio, AU
- WP BB & BOP: Markus Airila, VTT
- WP RM: Timo Määttä, VTT
- WP MAT: Kai Nordlund, UH
- WP ENS: Mikko Siuko, 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, Tekes
- 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 2017

- 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.
- Antti Hakola is a member of the programme committee of the 44th European Physical Society Conference on Plasma Physics (EPS) 2017.
- 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 Industry Liaison Officer (ILO) for F4E, Timo Määttä is the European Fusion Laboratory Liaison Officer (EFLO) and Pertti Pale is a consultant for Fusion-Industry matters.
- 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 2017

2.1 WP JET1: Analysis and modelling tasks 2017

Research scientists: M. Groth, B. Lomanowski, C. Stavrou, J. Uljanovs, J. Varje, AU
M. Airila, T. Kaltiaisenaho, J. Leppänen, A. Salmi, P. Sirén, T. Tala, VTT

2.1.1 Overview

After the successful completion of the 2016 experimental campaigns, the year 2017 in JET was dedicated to the preparation of the DT campaigns planned to take place gradually in 2018–2020. EUROfusion launched a set of analysis and modelling tasks for 2017 that included activities on the preparation of key operational and analysis tools and on the extrapolation of recent JET results to ITER. The tasks aimed at the main objectives defined in the annual programme 2017 for JET1.

FinnFusion contributed to investigations of fuelling and particle transport in the core and the edge, detachment studies, neutron and alpha rate validations, neutronics and related synthetic diagnostics as well as ammonia formation studies on plasma-facing components. In this Yearbook we highlight the detachment studies using the EDGE2D-EIRENE core and focusing on the role of impurities in particular.

2.1.2 Detachment studies

Heat flux densities incident on divertor targets in reactor-scale devices like ITER must be substantially reduced below the engineering limits of target materials. Radiative power dissipation in the edge plasma through extrinsic impurity seeding will therefore be a requirement for ITER operation. After completing impurity seeding experiments with nitrogen and neon at JET in 2016, an extensive integrated data and modelling analysis was carried out in 2017 aimed at i) advancing our understanding of the impurity distribution and radiation patterns within the edge and divertor plasma, ii) identifying the main mechanisms which lead to impurity induced detachment, and iii) validating advanced edge plasma simulation codes such as EDGE2D-EIRENE through interpretive modelling.

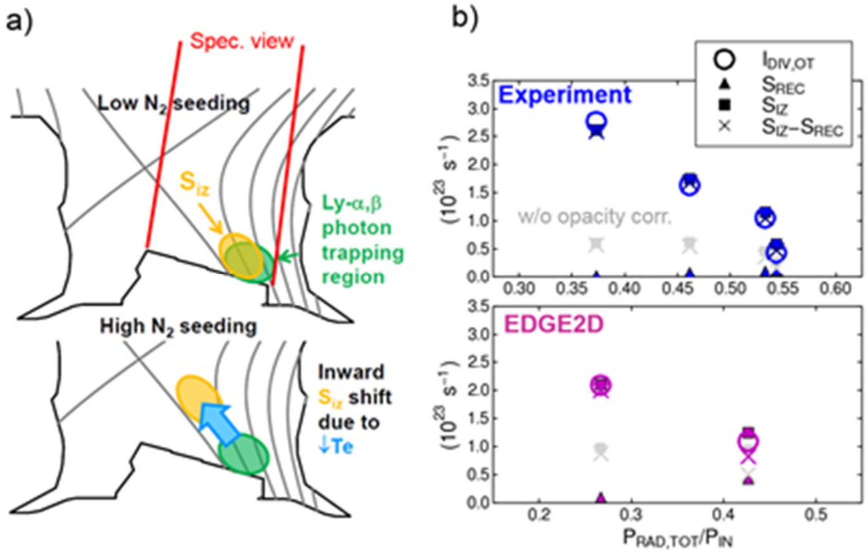

Figure 2.1: a) JET outer horizontal target plasma geometry showing the spectroscopic field-of-view and ionization source, S_{IZ}, regions at low and high nitrogen seeding rates; b) spectroscopically derived particle balance at the outer target derived from experiment and EDGE2D simulation with and without corrections for plasma opacity compared to the outer target ion current, $I_{DIV,OT}$, at increasing nitrogen radiative fractions

Detachment studies at JET offer unique diagnostic capabilities combining spatially resolved spectroscopic measurements in the vacuum-ultraviolet and visible spectral range, thus facilitating detailed estimates of the plasma properties and impurity radiation patterns. On the other hand, simulation codes provide the capability for detailed sensitivity studies of the dominant physics mechanisms that are not accessible through measurements directly. To bridge these respective capabilities, a synthetic spectroscopy framework was developed for post-processing EDGE2D-EIRENE simulations, providing a one-to-one basis for contrasting observations from experiment against simulation predictions. This strategy revealed that plasma opacity (i.e., local reabsorption of Ly series radiation) plays a potentially important role in increasing the ion target flux at the onset of detachment, thus extending the window for radiative dissipation prior to reaching full detachment, which can often lead to radiative collapse of the core plasma. Correcting for opacity in the interpretation of Ly series radiation yields good agreement in inferring the particle balance at the outer divertor target, such that the total ion current at the target, $I_{DIV,OT}$, is driven by the ionization source upstream, S_{iz}. Figure 2.1 a) shows the JET horizontal target plasma configuration, spectroscopic field-of-view, as well the ionization region at low and high nitrogen seeding rates. As the ionisation front moves inward due to cooler conditions at the plate, the ionization source is reduced, thus reducing the ion current to the target. Figure 2.1 b) shows the spectroscopically derived volumetric ionization source and only marginal recombination rate, S_{REC}, the balance of which is in good agreement with the ion current measured by Langmuir probes with increasing nitrogen radiative fraction. Implementing an *ad-hoc* opacity model into EDGE2D-EIRENE reproduces the increased S_{IZ} source, thus motivating additional efforts for the re-implementation of the full photon transport module in EIRENE.

2.2 WP JET2: Plasma-facing components

Research scientists: K. Heinola (Sub-Project Leader), A. Lahtinen, K. Mizohata,
J. Räisänen, UH
A. Hakola, S. Koivuranta, 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). So far there have been three experimental campaigns in 2011-2012 (ILW-1), 2013-2014 (ILW-2) and in 2015-2016 (ILW-3). Third set of wall and divertor tiles for post-mortem analyses were removed during the shutdown in 2016. 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.

The JET2 programme focused on post-mortem analysis of divertor and wall components and in-vessel erosion-deposition probes (EDP) in 2017 and VTT used Secondary Ion Mass Spectrometry (SIMS), Time of Flight Elastic Recoil Detection Analysis (TOF-ERDA), Thermal Desorption Spectrometry (TDS) and tile profiling for the analysis of divertor and wall components. The latter two techniques are available at CCFE. Analysis of the divertor tiles exposed in ILW-2 for erosion and deposition was completed in 2016 and fuel retention studies were completed in 2017. 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 ~40 µm thick at the lower part of the HFGC tile exposed in 2011–2014. The highest deuterium (D) amounts (~ $1 \cdot 10^{19}$ 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 2017 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 2017, T measurements were made from ILW-3 divertor tiles at VTT using imaging plate (IP) and β-ray induced X-ray spectrometry (BIXS). IP technique provides a 2D image of T distribution on tile surface whereas BIXS gives non-destructive depth profile for T. Figure 2. shows T distribution on HFGC inner divertor tiles exposed in ILW-3 and ILW-2. The IP images show that there is more T on the ILW-3 tile than on the ILW-2 tile.

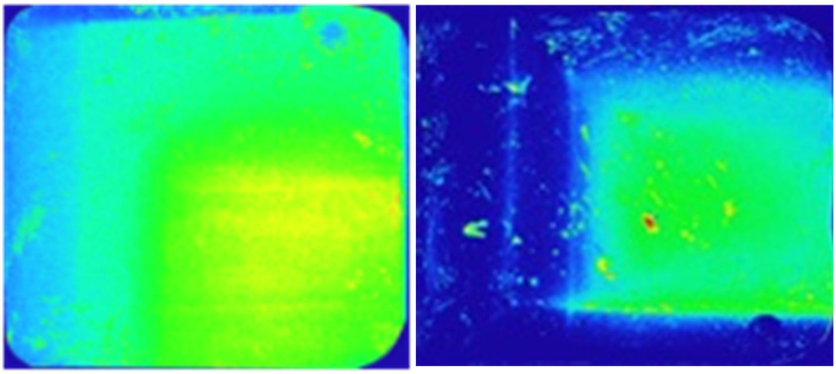

Figure 2.2. IP images of HFGC tiles at the inner divertor. T distribution on the ILW-3 tile on the left and on the ILW-2 tile on the right, respectively.

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

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

Plasma source coupled with Serpent in 2015 is based on ASCOT-AFSI simulations and it includes three separate components from different reaction types: thermal, NBI-thermal and NBI particle reactions. In DD plasma sensitivity tests, the steady state phase from one of the most analysed discharges, #86614 t=48.0-48.2s was used as a basis of the input. The same discharge was also used as a test case of the ideal synthetic neutron diagnostics in JET neutron camera (KN3) and TOFOR spectrometer.

Several sources with variations of ion temperature ($T_i=T_e$), temperature fraction (T_i/T_e), electron density (n_e) and Z_{eff} were generated. Additionally, sources with varied NBI settings (PINIs switched on/off) were also generated but they were not analysed in detail or used in the Serpent calculations. Scaling of temperature and density profiles were implemented by adjusting the temperature or density at $\rho=0$ while maintaining the shape and gradient of the profile.

Neutron sources were analysed locally at several points and globally comparing the total production rate. The difference (%) in the total production compared to the source, based on pure experimental data without scaling the profiles or Z_{eff}, is presented in Figure 2.3. Overall, the differences in fixed check points can be significant in synthetic diagnostics applications.

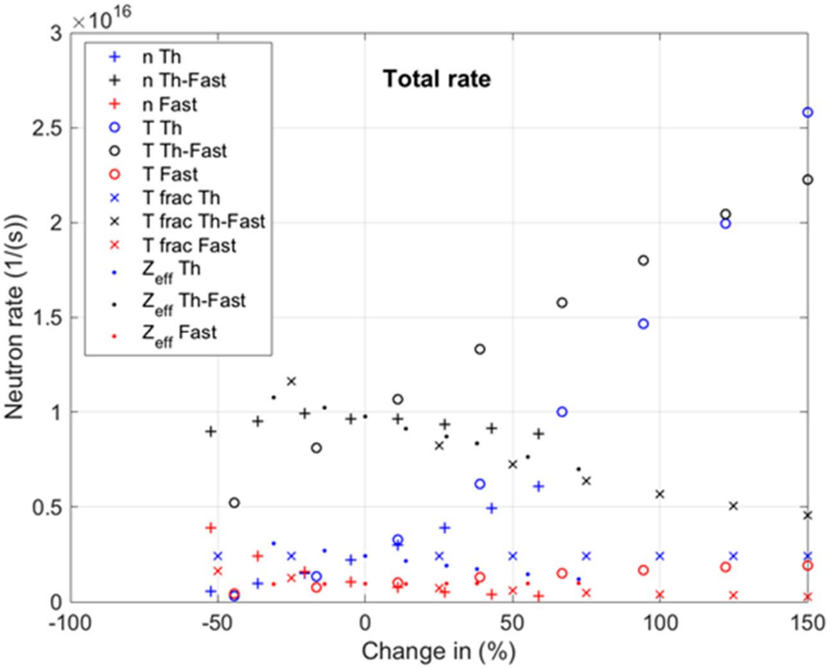

Figure 2.3. Neutron rate and change compared with the experimental (fission chamber KN1) value in the source simulations.

2.4 WP MST1: Medium-size tokamak campaigns

Research scientists: M. Groth,T. Kurki-Suonio, S. Sipilä, A. Snicker, K. Särkimäki, AU
A. Hakola, J. Likonen, A. Salmi, T. Tala, VTT
A. Lahtinen, J. Räisänen, UH

2.4.1 Overview

In 2017, MST1 experiments were run on two devices: ASDEX Upgrade (AUG) and TCV; the originally foreseen short campaign on MAST-U in late 2017 was deferred into 2018 due to the unavailability of the machine. The plasma operations on AUG suffered from technical mishaps, finally leading to an early end of the campaign due to a massive water leak. On TCV, there were no major issues with the machine but development of reliable ELMy H-mode scenarios at high currents and densities turned out to be a challenge. Nevertheless, 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, intrinsic torque investigations, as well as numerical modelling of fast ions and runaway electron beams. In this Yearbook we highlight the results of intrinsic torque experiments on AUG and TCV.

2.4.2 Intrinsic torque experiments on AUG and TCV

The main scope of the experiment on AUG is to investigate the sensitivity of intrinsic torque determination on plasma shape with respect to the previous results of the dimensionless ρ* scan and to validate experimental and analysis techniques by modelling of synthetic data and to assess the sensitivity to measurement errors. The experiment included NBI modulation at various frequencies and amplitudes, simultaneously, adding either ICRH or ECRH in either anti-phase with the NBI modulation or in-phase. The repeatability of the experimental data was very good and the temperature modulation, induced inevitably by the NBI power modulation was either compensated or reduced with anti-phase RF power or enhanced by in-phase RF power. To conclude, a complete benchmark dataset was obtained in the experiment, excellent dataset collected to validate NBH modulation analysis technique/codes. This also gives a very good dataset against gyro-kinetic code validation of the intrinsic torque theory.

On TCV, the NBI modulation experiment was performed for the first time with the newly installed NBI system. The strategy here is to test various options for NBI modulation, such as finding the optimum modulation frequencies and am-plitudes. We succeeded in developing two potentially usable NBH modulation scenarios on TCV, with different modulation frequency and amplitude. In both of them the plasmas were as long as possible, and the discharges, stationary and MHD-benign. This work will continue in 2018.

2.4.3 Deputy Task Force Leadership activities

In 2017, Antti Hakola continued his activities as a Deputy Task Force Leader (DTFL) of the MST1 Work Package. The DTFL term lasts until the end of 2018 and consists of coordinating specific experiments on AUG, TCV, and MAST-U as well as planning, monitoring, and reporting the outcomes of experimental campaigns on the three devices. In 2017, the MST1 activities were programmatically structured into 25 High-Level Topics (HLTs). This helped to focus the programme and emphasize the key strength of the MST1 programme, the multi-machine aspect. The HLTs spanned studies on several devices and were generally defined for multiple years. 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. In 2017, these were fully or partially addressed in 7 different HLTs, both experimentally on AUG and TCV and with the help of numerical modelling. The results were presented in different review meetings and a number of conference contributions and journal articles were submitted. The main highlights were: (i) Providing for a first time a direct link between thermionic current flow and the surface temperature during transient ELM events; (ii) Demonstrating the efficiency of Electron Cyclotron Resonance Heating (ECRH) in assisting plasma start-up at high impurity concentrations and background pressures; (iii) Obtaining a consistent picture for the development of a density shoulder in the edge plasma due to transport of filaments.

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

Research scientists: M. Groth, J. Karhunen, AU
T. Ahlgren, K. Heinola, A. Lahtinen, K. Nordlund,
K. Mizohata, J. Räisänen, E. Safi, UH
M. Airila, A. Hakola, 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 2017, the top three objectives were: (i) Characterizing preferential sputtering of EUROFER and advanced W-containing steels; (ii) Determining the balance between gross and net erosion of W on the ASDEX Upgrade tokamak; and (iii) Comparing plasma experiments in WEST with modelling efforts by the SOLEDGE-EIRENE code. Under FinnFusion, the focus areas of PFC were sur-face 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 effect of surface roughness on the erosion of W PFCs.

2.5.2 Effect of surface roughness on erosion behaviour of tungsten

Under reactor conditions, intense power and particle loads can damage the PFCs, leading to strongly modified and rough surfaces. Consequently, the erosion, deposition and retention characteristics of the surfaces may change. To study the effect of surface roughness on net erosion and deposition of W, a number of W-coated samples with varying surface roughness were exposed to plasma discharges using the DIM-II divertor manipulator of AUG.

Before coating, the surfaces of the samples were either polished (smooth samples, average surface roughness R_a~0.3 µm), milled (nominal samples, Ra~1 µm), or sandblasted (rough samples, R_a~4 µm). The samples were exposed to low-density, high-temperature L-mode deuterium plasma discharges with the overall exposure time of 80 s. Before and after the exposure, the thickness of the W surface layer of the samples was determined using Rutherford Backscattering Spectroscopy (RBS) using 2.0 MeV $^4He^+$ ion beam.

The poloidal net deposition/erosion rates for W on the different samples are shown in Figure 2.4. Net erosion of W is clearly visible close to the strike line while on both sides of it net deposition takes over. The net erosion rate increases from 0.03 nm/s (rough samples) to 0.08 nm/s (nominal samples) and finally to 0.2 nm/s (smooth samples). Net deposition shows a different dependence on surface roughness. For the smooth samples, deposition is observed only in the private flux region while for the nominal and rough samples, the deposition profiles are practically identical showing deposition peaks on both sides of the strike line.

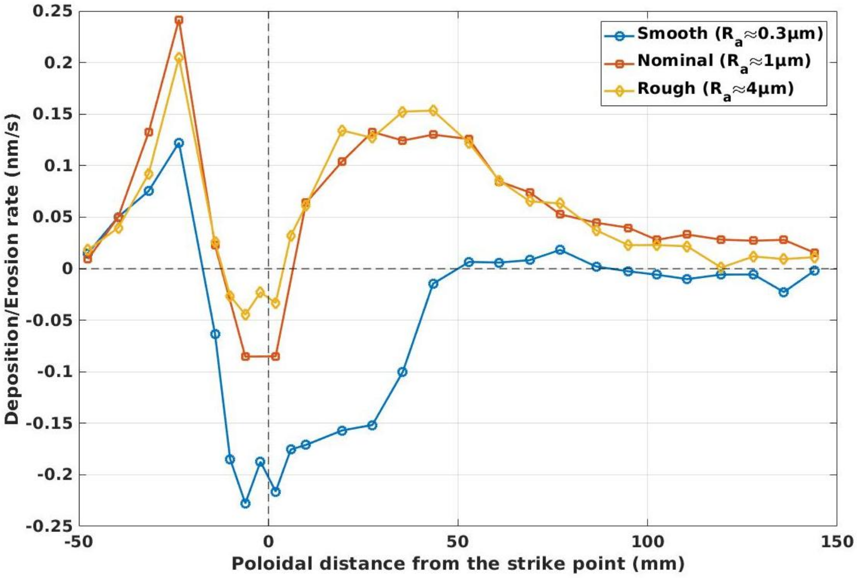

Figure 2.4. Poloidal net deposition/erosion profiles of W on different samples

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

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

The ASCOT code was used to assess heating, fuelling and current drive profiles due to neutral beams in various W7-X scenarios. Earlier work on ICRH modelling was continued by simulating the three-ion species ^{3}He-minority heating case. Ion and electron heating profiles were calculated from the fast ion distribution. The beams were found to deposit their energy mainly to ions in the plasma core, whereas at the edge the power distribution is more equal between electrons and ions.

The centrally-peaked heating in W7-X can result in a non-optimal "hollow" density profiles. We checked if beam injection could be used to fuel the W7-X core. The beam ionization rate in the core was found to increase with edge-т and decrease with density. The NBI thermal fuelling rate was relatively high near the core, where plasma fuelling is normally difficult to achieve. The W7-X configurations are sensitive to even slight changes in the edge rotational transform (т). Equilibrium optimization has to ensure low bootstrap current, but also any beam-driven current could be harmful. It was found that the beam-driven plasma current was low enough for safe operation in the studied scenarios.

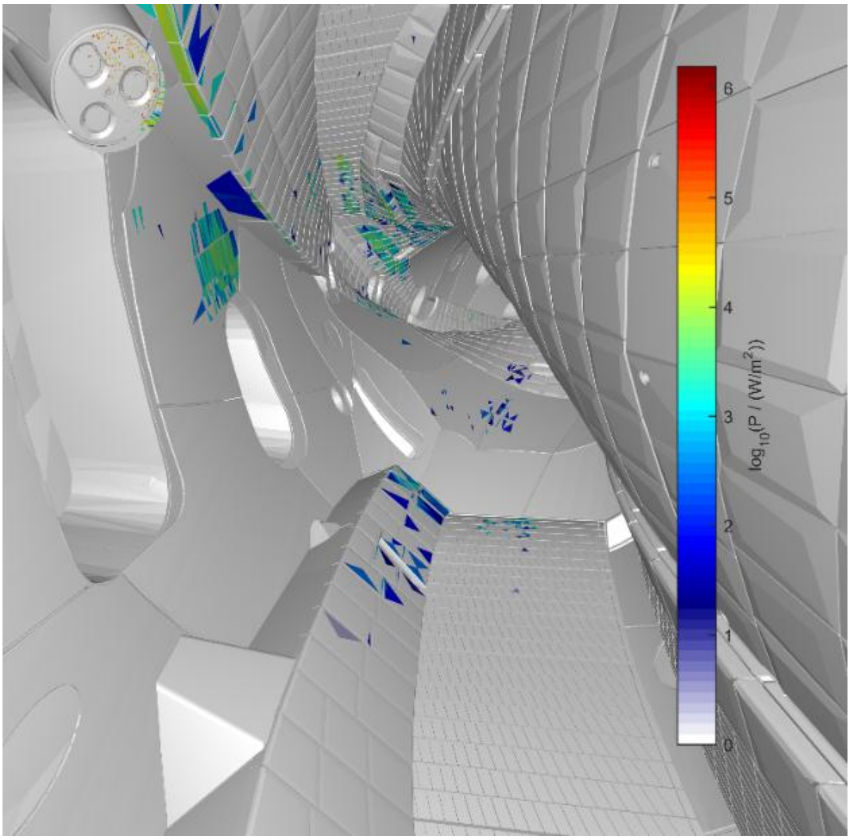

Figure 2.5. 3D view of the ICRH power loads to the W7-X wall. The high local wall loads to the immersion tube (top left) are faintly visible.

The work flow for ICRH simulations consists of first generating the ICRH-ion marker population at the last closed flux surface using the VENUS-LEVIS code, and following them with ASCOT to the detailed 3D wall. It was found that the wall loads were generally low (Figure 2.5), with some isolated hot spots that could be further investigated using a larger marker ensemble.

2.7 WP CD: Code development for integrated modelling

Research scientists: S. Sipilä, J. Varje, AU
P. Sirén, VTT

The main achievement of 2017 in the WPCD project was the deployment of ASCOT, AFSI and BBNBI actors to JET for analysis purposes in the European Transport Solver (ETS). The codes are responsible for simulating NBI ions and fusion products in the Heating and Current Drive (HCD) workflow. The codes were benchmarked against JINTRAC and TRANSP transport codes, with good agreement observed in several different JET discharges.

Main developments in 2017 involved adaptation of the existing actors to the new IMAS infrastructure. All main actors were successfully ported to the new framework, and the development and validation efforts will continue in 2018.

Neutron rate predictions with codes in the HCD workflow, including AFSI, NBISIM and NUCLEARSIM actors, were benchmarked with each other and with JINTRAC and TRANSP. Nuclear cross sections, crucial for accurate neutron rate predictions, in the AMNS (Atomic, Molecular, Nuclear and Surface) database were also evaluated, to be implemented in AFSI and other fusion product actors.

3. Power Plant Physics & Technology Work Programme 2017

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, Fortum
E. Dorval, S. Norrman, A. Salmi, T. Tala, VTT

3.1.1 Introduction

FinnFusion activities within WP PMI cover modelling tasks on DEMO neutral beams, and power plant processes. In this Yearbook, we report the progress of the task *Optimizing the DEMO neutral beams*. The task related to modelling of power plant processes is included in the report under WP BOP (see below).

3.1.2 Optimizing the DEMO neutral beams

Due to the very stringent limits on the first wall power loads in DEMO (1 MW/m^2 in DEMO vs 4.7 MW/m^2 in ITER), the powerful neutral beams (16.8 MW per injector) injecting ions at 800 keV to the DEMO plasma have to be carefully optimized to minimize the shine through as well as orbit losses. This work has been carried out as an Italian-Finnish collaboration, with Dr. Pietro Vincenzi, a EUROfusion engineer fellow, working with the ASCOT group. The changes in wall power loads due to changes in the injector design are evaluated using BBNBI and ASCOT codes, both developed in Finland. In addition, the new super computer Marconi, at Cineca, Italy, now allowed calculating the power load distributions with significantly better statistics, which is important when identifying peak power loads.

While the beam neutrals are predominantly ionized in the main plasma, there is a finite chance for a phenomenon that is a counter-part to shine-through: ionization can take place already before the beam particles cross the separatrix. Ions born between the first wall and the separatrix have a very high probability of getting lost on plasma-facing structures at their nominal energy, thus possibly causing damage. BBNBI and ASCOT can now take into account even these particles.

The first DEMO results were reported in the 44th European Physical Society Conference on Plasma Physics, Belfast, Ireland, and were submitted for publication in Nuclear Fusion.

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

Research scientists: E. Dorval, S. Norrman, VTT
S. Kiviluoto, Fortum

The system level analysis model of the helium cooled primary heat transfer system (PHTS) concept has been further developed within WP BOP. Compared to previous years, the work effort was doubled. Two main configurations were studied. The first configuration was the traditional one, including an intermediate heat transfer system (IHTS) with energy storage (ESS) in molten salt tanks. The new, second configuration features a direct coupling of the PHTS to the power conversion system (PCS). For the first concept, the PCS was substantially developed, with the turbine and overall feed water heating configurations based on investigations performed by KIT in cooperation with Siemens AG (see Figure 3.1). Also, dimensioning of heat exchangers matured based on cooperation with other research institutes working in WP BOP. Analyses showed that more detailed PCS configuration seems to be realizable, although there are uncertainties around certain component specifications and control strategies.

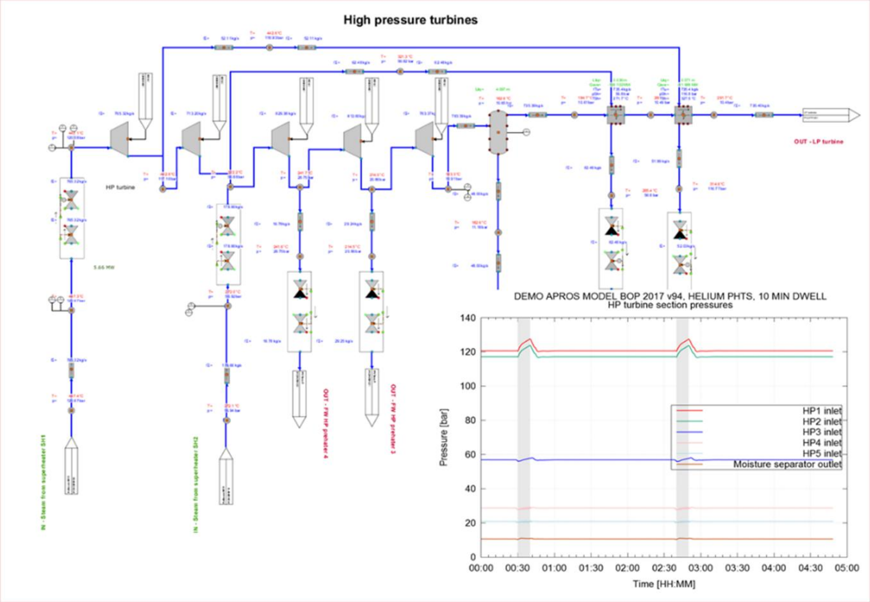

Figure 3.1. High pressure turbine sections of the power conversion system and pressure behaviour in BOP task 1.

The updated PCS configuration, together with a new molten salt (HITEC), with a lower freezing temperature than the solar salt previously used, have diminished the risk for molten salt solidification. In the case without IHTS and ESS, an auxiliary boiler with about 15 % of the full burn-time power supplies steam during dwell time, when the PHTS heat sources decrease to decay heat levels. Analysis showed that this concept faces many challenges concerning cycling behavior of pressure and temperature in several components, which is not desirable.

Two WP PMI tasks were performed. The first task, done by Fortum, comprised preliminary feasibility studies of the PHTS-PCS direct coupling configuration with emphasis on controllable power ramp-down and ramp-up of turbine power prior to and after transition to burn operation respectively, with the support of a low power, continuously operating, auxiliary boiler. The task also included feasibility studies of energy storage in water tanks for smoothing the pulsed behaviour of the PCS. The studies support further concept investigations. In the second PMI task, initial studies of the planned decay heat removal system performance was done. In an example transient, where the PHTS coolant flow was lost, decay heat in the breeding blanket was assumed to be transferred mainly by radiation to the vacuum vessel structure, which is actively cooled with water.

3.3 WP RM: Remote maintenance systems

Research scientists: J. Lyytikäinen, R. Sibois, M. Siuko, R. Tiusanen,
O. Venho-Ahonen, J. Videnoja, VTT
H. Wu, C. Li, LUT

3.3.1 DEMO Divertor remote maintenance system development

3.3.1.1 Divertor Cassette Handling Concept

In 2017, the divertor access port design was unfinished. Since the port is between the coils, the position affects on the port size. The lower it is, less there is space. However, to have access to the divertor cassettes, the port should be as low as possible. The risks the port position causes to the remote maintenance were analysed. Risks and consequences were defined and the impact assessment of each risk was conducted. Mitigation strategies were defined in order to avoid each single risk, or minimize the impact. Post-mitigation assessment were performed and high level risks that require R&D strategy actions were highlighted. After mitigation, there are no high level risks left, and appropriate strategies and actions are taken to reduce the risk level or even avoid it.

3.3.1.2 Divertor Cassette Transporter & Platform

In 2017 the scope was to develop further divertor cassette transporter concepts (see Figure 3.2) and cassette-handling end-effectors. Down-selection of the three end-effectors was done. It included evaluation of the options by a remote handling expert panel, relevant evaluation criteria as well as appropriate weighting were first selected. Reliability, maintainability, recoverability and robustness were considered as the most important criteria. Those were attributed higher weights in the down-selection matrix. Also LUT participated to the End-Effector design work by developing concepts.

3.3.1.3 Divertor Cassette Fixation and Tooling Development

Divertor cassette fixation is developed together with ENEA. The fixation system itself is part of the Cassette-design and DIV-group work. The requirements for fixation system are still living, so there is no base for fixation tool development. The fixation process, tool design, handling trajectories and handling manipulator set requirements also to the design of the transporter and end-effector.

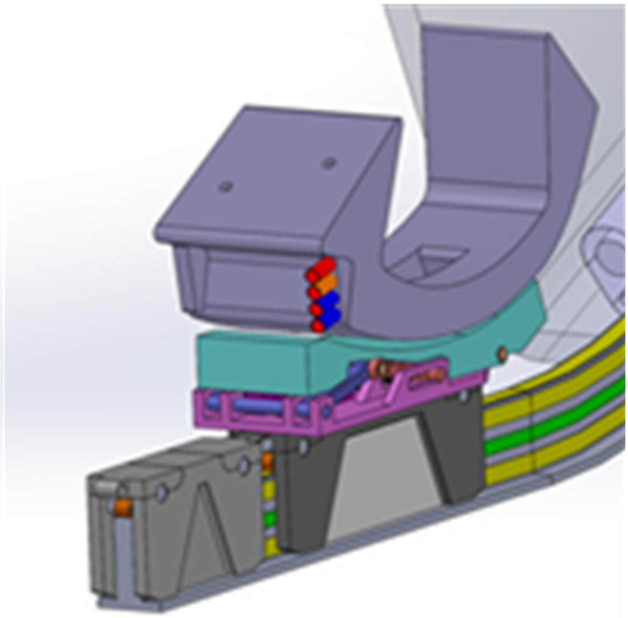

Figure 3.2. The Divertor Cassette is transported into the reactor along a rail in the divertor access port.

3.4 WP MAT: Materials

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

Iron and iron-based alloys are the materials used and the materials that will be used as structural materials in fusion power reactors. The harsh conditions in the power plant, due to high temperatures and intense radiation, will affect the properties of the materials. It is known that the dislocation structure and networks will determine the mechanical properties of the materials. Experimentally, two kinds of interstitial dislocation loops are seen in Fe and FeCr alloys, the ½ <111> loop and the <100> loop. The ½ <111> loop is glissile, which means that it can migrate to grain boundaries and annihilate. On the other hand, the <100> loop is sessile, which means that it will act as a defect sink in the material, and absorb and trap other defects. This may lead to a brittle material, which could have detrimental consequences in power plants. Computer simulations carried out in Fe and FeCr alloys have only showed the production of the ½ <111> loop, which leaves the question of where the <100> loop originate from unanswered. Some proposed mechanisms are available in the literature, but they all require strict conditions for the possible production of the <100> loop. We propose a new mechanism of the production of these <100> loops, that do not require a specific setup to start with, as this mechanism relies on the existence of random defects from a previous cascade that is overlapped by secondary cascades.

To study the defect production at higher doses, comparable with experiments, cascade overlap simulations were conducted in both pure Fe as well as in several FeCr alloys. The massively overlapping cascades simulations, up to a few thousand cascades, revealed the defect evolution in the different Fe-based alloys on the atomic level. These overlapping cascade simulations showed that both the ½ <111> loop and the <100> loop could form in Fe and FeCr alloys. In particular, the simulations showed that existing debris from previous cascades can be transformed into a <100> loop as a result of an overlapping cascade. A cascade in the vicinity of a mixed dislocation network could also trigger the transformation of the network into a perfect <100> loop as illustrated in Figure 3.3. These promising results showed that both types of loops can form in simulation of Fe and FeCr alloys. However, mainly ½ <111> loops were formed in the simulations, while experiments show significant populations of both types. This discrepancy can be explained by the difference in their mobility. The ½ <111> loops have plenty of time to reach the surface/grain boundary in the experimental setup, whereas the sessile <100> loops will remain.

In addition to the knowledge that <100> loops can form, we studied these occurrences in more detail. We continued the study by investigating the effect of only secondary/ternary cascade overlap, i.e. one cascade hitting the debris of a single/two previous cascade/cascades. These simulations were carried out at a higher recoil energy, and the results showed that there is already a considerable fraction of <100> loops formed in this setup. It was seen that when these cascades overlapped and produced a dislocation loop, around 20% were in the <100> configuration. Also, several different interatomic potentials were used in order to get rid of the possibility that this is just a property of the selected potential. This further strengthens this mechanism to be one of the possible reasons for the vast occurrence of <100> loops in Fe, as already two cascades in the same volume is enough for their formation.

To continue the investigation and to understand the defect production and evolution in Fe and FeCr alloys, cascades on top of perfect interstitials loops were conducted. As starting points, different-sized ½ <111> loop and <100> loops were subjected to a single overlapping cascade. These simulations were carried out under several different conditions, and the dislocation transformations were studied. The results showed that transformations occur on a regular basis, in both directions, ½ <111> to <100> loop and vice versa. The obtained probabilities of transformation can be used to take into account cascade-induced transformations of dislocation loops also in higher scale models, such as Kinetic Monte Carlo simulations.

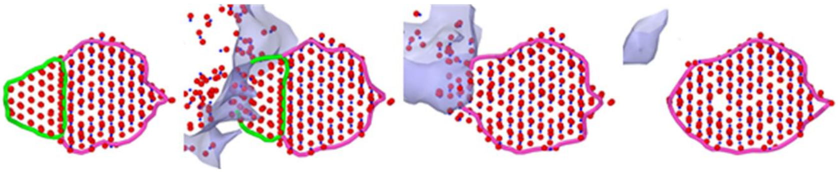

Figure 3.3. Destruction of the ½<111> segment of a mixed interstitial dislocation loop by an overlapping cascade, and transformation into a perfect <100> loop.

3.5 WP ENS: Early Neutron Source definition and design

Research scientists: A. Helminen, I. Karanta, T. Sikanen, T. Tyrväinen, VTT
A. Rantakaulio, J. Iivanainen, 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 2017. 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.

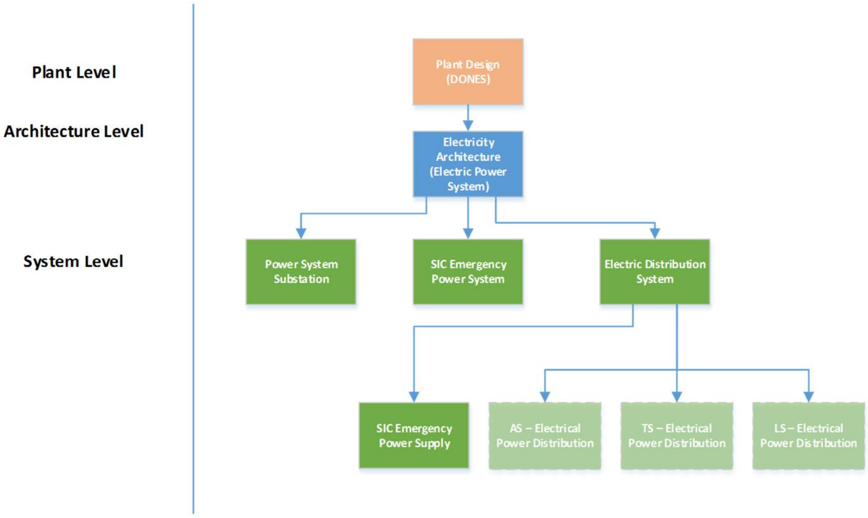

Figure 3.5. Requirement hierarchy of electrical power system.

4. Communications

The FinnFusion Annual Seminar was held at VTT, Espoo, as a 2nd Joint Nordic seminar on 15–16 June 2017. Invited speakers were Jorma Routti, former DG Research in EC, Leonardo Biagioni, F4E, Søren Korsholm, DTU, Denmark, Xavier Litaudon, EUROfusion, and Simppa Äkäslompolo, IPP Greifswald, Germany. The number of participants was 94. The Annual Report, *FinnFusion Yearbook 2016,* VTT Science **157** (2017) 81 p., was published for the Annual Seminar.

During 2017, Finnish and international media published several articles and interviews on the fusion research activities in Finland:

- Tuomas Tala, *FinnFusion: Advancing fusion research in Finland*, Open Access Government, 10 May 2017 (https://www.openaccessgovernment.org/finnfusionadvancing-fusion/33544/)
- Paavo Niskala, radio interview on the national broadcast channel Yle Puhe, 10 July 2017 (https://areena.yle.fi/1-4160068)

Thematic issue of ATS Ydintekniikka (journal of the Finnish Nuclear Society) on fusion, 4/2017:

- Markus Airila, *Elämme fuusion teollistumisen aikaa - onko Suomi mukana?* (*Fusion is industrialising - is Finland part of it?*), Editorial.
- Antti Hakola, *Fuusiosähköä joka kotiin 50 vuoden päästä - miten Euroopassa edistetään tätä tavoitetta?* (*Fusion electricity to every home in 50 years - How is this goal promoted in Europe?*)
- Taina Kurki-Suonio, *Uudet fuusiolaitteet rakentavat siltaa kohti ITERiä* (*New fusion devices are bridging the gap towards ITER*).
- Markus Airila, Sami Herranen, Sami Kiviluoto and Tuomas Tala, *DEMO tarvitsee yritysten osaamista* (*DEMO needs the expertise of industry*).
- Otto Asunta and Tomas Lindén, *Yksityisrahoitteinen fuusiotutkimus* (*Privately funded fusion research*).

Lecture courses at Aalto University, School of Science:

- *Fusion Energy Technology (Mathias Groth, Spring 2017)*
- *Fundamentals of Plasma Physics for Space and Fusion Applications (S. Leerink, T., Kurki-Suonio, spring 2017)*
- *Energialukutaito (Energy literacy) (T. Kurki-Suonio, J. Ala-Heikkilä, fall 2017)* Education and training

Other communications and outreach activities included:

- Markus Airila, *Fusion – Taming the energy of the stars*, presentation in the LAPSody Festival, Theatre Academy Helsinki, 26 May 2017.

- Markus Airila, Presentation in the Annual Seminar of the Finnish Nuclear Society, Helsinki, 2 November 2017: *Fuusiotutkimus tänään – Katsaus maailmalle ja Suomen tutkimusohjelman tilanne* (*Fusion research today – Global overview and the status of the Finnish research programme*).
- Markus Airila reviewed the manuscript (author and director Katri Hyötyläinen) *Äiti-Aurinko ja fuusiolapset* (*Mother Sun and Fusion Kids;* http://tukkateatteri.fi/ohjelmisto/esitysarkisto/aiti-aurinko-ja-fuusiolapset/). The play was put on in Tukkateatteri, Tampere, Finland, October-November 2017.

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 2017, three doctoral dissertations and three Master's theses were completed (see Section 10.5.4).

5.1.2 Doctoral students

Student: Juuso Karhunen (AU)
Supervisor: Mathias Groth (AU)
Instructors: Mathias Groth (AU), Antti Hakola (VTT)
Topic: *SOLPS 5.0 simulations of the inner divertor detachment of L-mode plasmas in AUG with convection-dominated radial SOL transport*
Report: Description of detached inner divertor conditions in ASDEX Upgrade L-mode discharges was improved by SOLPS 5.0 simulations in which the typically applied diffusive radial ion transport was replaced with a convection-dominated model. This led to good correspondence between the simulations and the experimental data in terms of the target ion flux, inner divertor volume density and sub-divertor neutral fluxes, as well as the upstream n_e and T_e profiles. The observations were attributed to decreased diffusive leakage of the HFS high-density front from the inner divertor into the core, which allowed increasing the D_2 fuelling in the simulations to experimental levels.

Student: Paavo Niskala (AU)
Supervisor: Mathias Groth (AU)
Instructor: Timo Kiviniemi (AU)
Topic: *Isotope effect in transport and flows of fusion plasmas*
Report: Numerical studies of isotope effect on turbulent transport and flows in Ohmic tokamak discharges are conducted in collaboration with experimental researchers from the Ioffe Institute. The neoclassical physics predictions of the gyrokinetic ELMFIRE code are verified against theoretical estimates. Meanwhile, simulations with ELMFIRE and GENE predict smaller particle fluxes for deuterium

compared to hydrogen with otherwise similar plasma parameters at the FT-2 tokamak. Experimental measurements validate the finding qualitatively. Simulations and experiments also demonstrate the modulation of turbulent particle transport by oscillating flows and agree qualitatively on the isotopic scaling of flow frequency, wavelength, and amplitude.

Student: Konsta Särkimäki (AU)
Supervisor: Mathias Groth (AU)
Instructor: Taina Kurki-Suonio (AU)
Topic: *Stochastic processes and particle transport in tokamaks*
Report: The transport of fast particles in tokamaks, e.g. alpha particles and runaway electrons, at times can become stochastic in itself or driven by a stochastic process. In such cases, the mathematical treatment differs from the familiar deterministic dynamics, and some models might break down while new ones become available. The student has so far studied two instances of stochastic transport: stochastic field line transport and stochastic ripple diffusion, and in addition collisional transport where the driving mechanism is stochastic. The studies so far have resulted in a new transport model for runaway electrons in broken flux surfaces, and a new collision operator whose novel features include adaptivity and applicability in the relativistic regime. Ongoing project is to assess how ELM control coils affect fast ion transport in ITER.

Student: Jaro Uljanovs (AU)
Supervisor: Mathias Groth (AU)
Instructor: Mathias Groth (AU)
Topic: *Study of the effects of Hydrogen isotopes on the divertor and edge physics in JET*
Report: Understanding the impact of isotope mass and divertor configuration on the divertor conditions and neutral pressures is critical for predicting the performance of the ITER divertor in DT operation. Ohmically-heated hydrogen and deuterium plasma experiments were conducted in JET with the ITER-like wall in varying divertor configurations. These plasmas are simulated with EDGE2D-EIRENE outfitted with a sub-divertor model, to predict the neutral pressures in the plenum with similar fashion to the experiments. EDGE2D-EIRENE predictions show that the increased isotope mass results in up to a 25% increase in peak electron densities and 15% increase in peak ion saturation current at the outer target in deuterium when compared to hydrogen for all horizontal divertor configurations. Indicating that a change from hydrogen to deuterium as main fuel decreases the neutral mean free path, leading to

higher neutral density in the divertor. Consequently, this mechanism also leads to higher neutral pressures in the sub-divertor. The experimental data provided by the hydrogen and deuterium ohmic discharges shows that closer proximity of the outer strike point to the pumping plenum results in a higher neutral pressure in the sub-divertor. The diaphragm capacitance gauge pressure measurements show that a two to three-fold increase in sub-divertor pressure was achieved in the corner and nearby horizontal configurations compared to the far-horizontal configurations, likely due to ballistic transport (with respect to the plasma facing components) of the neutrals into the sub-divertor. The corner divertor configuration also indicates that a neutral expansion occurs during detachment, resulting in a sub-divertor neutral density plateau as a function of upstream density at the outer midplane.

Student: Jing Wu (LUT)
Supervisor: Huapeng Wu (LUT)
Instructor: Huapeng Wu (LUT)
Topic: *Soft computing methods for performance improvement of the robot in a fusion reactor application*
Report: Building the foundations needed for developing sensor fusion in a timely way can be facilitated by not only familiar hypothesis-driven or first principles approaches, but also engaging modern big-data-driven statistical methods featuring machine learning (ML), which is an exciting R&D approach that is increasingly deployed in many scientific and industrial domains. An especially time-urgent and very challenging task in the development of an intelligent RH services today is to reliably deal with large-scale major disruptions in magnetically-confined tokamak device in the near future. The prediction methods with better than 95% predictive capability are required to provide sufficient advanced warning for disruption avoidance or mitigation strategies to be effectively applied before critical error occurs. This truly formidable task in this research demands accuracy beyond the near-term reach of hypothesis-driven or first-principles simulations that dominates current research and development in the field. The ML methods trained on very large data sets hold significant promise for delivering the much-needed EAMA (The EAST's articulated maintenance arm system) robot predictive tools that can be generalizable at the basic level to be used in multiple application domains. In particular, the signal data from the superconducting tokamak plasmas of the high temperature (80–120 ℃) and high vacuum (~ 10^{-5} Pa), such as the EAST, is of significant interest to explore. In addition, the topic of vibration control, as an extension of our ML capabilities, is also a viable and timely subject to be studied. The main contributions of this dissertation include:

the design, development and analysis of the whole EAMA hardware system; the optimization of the EAMA trajectory by the gentic algorithm minimizing the end-point jerk; studying two different methods: extended kalman estimator and adaptive neural fuzz system to predict the pitch and yaw errors of manipulator system; eventually developing the estimation algorithm of the EAMA dynamic vibration to predict the operation of the EAMA system.

Student: Adeyemi Adeleke (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 non-linearities*
Report: A spherical wrist can be achieved in robotic manipulators by a combination of three actuated rotary joints. These actuated joints may be realized using heavy-duty hydraulic rotary actuators, which produce high torque in compact size leading to high power density known with hydraulics. When used, these actuators introduce additional nonlinearities in the form of backlash to a hydraulic system, which already has strong inherent nonlinearities.

To combat the heavy nonlinearity and realize robust and stability-assured control of such manipulator system, a nonlinear model-based control is desired. The crux of the research was to develop a Virtual Decomposition Control (VDC) algorithm for a single degree of freedom (DOF) robotic manipulator actuated with a rotary actuator and compensate the effect of backlash with an adaptive control algorithm. The objective is that success in controlling the 1-DOF system can be generalized to n-DOF systems, since the VDC approach is subsystem based. The control objective was achieved and the research results have been published.

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: 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 environment as in ITER project is performed using tele-operated manipulators. Remote handling operators rely on a variety of tools to perform cassette maintenance tasks. Our study focuses on developing a 3D vision system, namely 3D Node, which is a stereoscopic vision system mounted on the last joint of a robot manipulator. Integration of vision to pre-existing robot control system can include heterogeneous subsystems. These systems can encounter different challenging issues only because of the dissimilarity among subsystems and need for cross-platform software development for time-critical tasks. Inside a fusion reactor, the design and implementation requirements of vision systems has to be taken into account of several constraints, such as limited resolution of radiation tolerant camera sensors, reflective metallic surfaces, limited illumination and high level of noises. The details of the methods for tackling these problems have been published.

Student: Laura Bukonte (UH)
Supervisor: Kai Nordlund (UH)
Instructor: Tommy Ahlgren (UH)
Topic: *Hydrogen induced vacancy formation and sink strengths for rate equation multi scale simulations*
Report: Hydrogen induced vacancy formation in metals and metal alloys has been of great interest during the past couple of decades. The main reason for this phenomenon, often referred to as the superabundant vacancy formation, is the lowering of vacancy formation energy due to the trapping of hydrogen. The vacancy formation was studied by means of thermodynamics. The results show that the divacancy fraction gives the major contribution to the total vacancy fraction at high H concentrations and cannot be neglected when studying superabundant vacancies. The results lead to a novel conclusion that at high hydrogen fractions, superabundant vacancy formation takes place regardless of the binding energy between vacancies and hydrogen.

The sink strength is an important parameter for the mean-field rate equations to simulate temporal changes in the micro-structure of materials. However, there are noteworthy discrepancies between sink strengths obtained by the Monte Carlo and analytical methods. We showed the reasons for these differences, present the equations to estimate the statistical error for sink strength calculations and show the way to determine the sink strengths for multiple traps. A novel, very fast Monte Carlo method to obtain sink strengths was developed. The results show that, in addition to the well-known sink strength dependence of the trap concentration, trap radius and the total sink strength, the sink strength also depends on the defect diffusion jump length and the total trap volume fraction. Taking these factors into account, allows us to obtain a very accurate analytic expression for the sink strength of spherical traps.

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 studied the atom-level damage produced when collision cascades overlap with pre-existing damage in iron, using molecular dynamics simulations. We found that the energetically less favoured <100> type interstitial dislocation loops can form with significant probabilities when a cascade overlaps with existing cascade damage. Furthermore, we explored the differences in the produced damage predicted by different interatomic potentials, and found that an accurate short-range repulsive potential is important when quantifying the damage produced by single cascades. However, at higher damage doses when cascade overlap frequently occur, the damage evolution is more dependent on the near-equilibrium part of the potential. Different potentials can lead to vastly different defect structures at higher doses.

Student: Aki Lahtinen (UH)
Supervisor: Jyrki Räisänen (UH)
Instructors: Antti Hakola (VTT), Jari Likonen (VTT)
Topic: *Plasma-wall interactions in fusion devices*
Report: In 2017, the work concentrated on plasma-wall interaction studies in AUG and JET tokamaks. AUG studies focused on the effect of surface roughness on tungsten erosion and pre-characterization of marker samples for 2018 experiments. JET studies focused on the analysis of the limiter tiles of 2013–2014 campaign and sample preparation of the divertor tiles of 2015–2016 campaign. Observed deuterium (D) profiles on 2013–2014 limiter tiles were similar to 2011–2012 campaign, D concentration is low at the centre of the tiles and higher on the wing segments, but D amounts were signif-

icantly lower. Reasons for lower D retention are probably the isotopic exchange during the hydrogen plasma experiments at end of the campaign, increased plasma interaction and higher surface temperatures during the campaign due to the higher heating powers.

Student: Elnaz Safi (UH)
Supervisor: Kai Nordlund (UH)
Instructors: Carolina Björkas (UH), Jussi Polvi (UH)
Topic: *Multiscale modeling of plasma-wall interactions: (i) A top-to -bottom multi-scale approach of Be erosion by D; (ii) MD simulations of the effect of Ar, Ne and D co-bombardment on W and Be*
Report: Molecular Dynamics (MD) simulations were run on mixed beryllium-deuterium sample surfaces at different temperatures varying impact energies. MD surfaces were prepaid carefully and with more confident according to previous Kinetic Monte Carlo (KMC) simulations to estimate D distribution in Be in conditions closer to experiment. 4000 dynamic D irradiations on Be surface were performed scanning over different parameters such as substrate temperature, impact energy and incoming ion angle and the Be-D erosion yield was reported with higher confidence.

In the second work, to study the effect of plasma impurities on the erosion and surface morphology of wall materials, MD simulations were carried out. Therefore, we modelled irradiation of both W and Be surfaces with Ar-deuterium (D) and Ne-D mixtures, varying the fraction of Ar and Ne impurities from 0 to 20 percent at different impact energies and surface temperatures. In general, W and Be sputtering yields were higher in the presence of Ar and Ne plasma impurities in comparison with pure D ion irradiations and sputtering yield's magnitude increased with increasing impact energy. Moreover, we found that W and Be surfaces were more damaged at higher impurity concentration.

Student: Paula Sirén (VTT)
Supervisor: Filip Tuomisto (AU)
Instructor: Jaakko Leppänen (VTT)
Topic: *Improvements of AFSI-ASCOT based synthetic neutron diagnostics at JET*
Report: Recent development in AFSI-ASCOT based synthetic diagnostics includes physical improvements such as implementation of plasma rotation and reduction of the fast particle contribution in thermal reactant distribution. The rotation typically changes the beam-thermal reaction rates by 1-5%, while accounting for the fast particle density consistently decreases calculated neutron rate by up to 15% depending on the discharge.

Further developments include implementation of angular dependence of differential fusion cross sections (especially in DD reaction) and accounting for finite Larmor radius effect, which is important for high-energy particles such as ICRH ions. Additionally, the role of data based analysis in synthetic diagnostics development with the help of comprehensive database of JET operating conditions (JETPEAK) will be studied.

5.2 WP TRA – EUROfusion Researcher Grant

Modelling primary radiation damage with extended molecular dynamics - defect morphology in the presence of electronic effects

Research scientist: A. Sand, UH

The objective of this project has been to obtain reliable data from molecular dynamics (MD) simulations of primary radiation damage formation in W and Fe, accounting for electronic energy-loss effects, and to extract statistical distributions of defects, to facilitate efficiently generating cascade debris for larger scale models. The project was finalized in September 2017.

Predictions of defect statistics in Fe and W show marked differences in the size-frequency distribution of defect clusters. To further the objective of generating input for microstructural evolution codes, the upper limit of the size-frequency distribution of defects was investigated, providing a full model describing the deviation from a simple power law (Figure 5.1), which shows good agreement with TEM observations.

The spatial distributions of cascade debris in MD has also been studied, and compared to TEM images of low-dose irradiation at cryogenic temperatures. Discrepancy between MD and experiment indicate a possible effect of defect size. Small defects are invisible in TEM, while large defects are too rare to be seen frequently in MD, hence extensive statistics would be needed to resolve this question. Indications are that larger defects are produced in closer proximity to each other than the smaller, TEM-invisible defects. The initial proximity of larger defects would mean that they are more likely to be elastically trapped, affecting the microstructural evolution.

The defect configurations from this work have been used explicitly in object Kinetic Monte Carlo simulations of microstructural evolution, and compared with results using randomly generated debris. The work showed that the detailed morphology of cascade debris does have an effect on predictions.

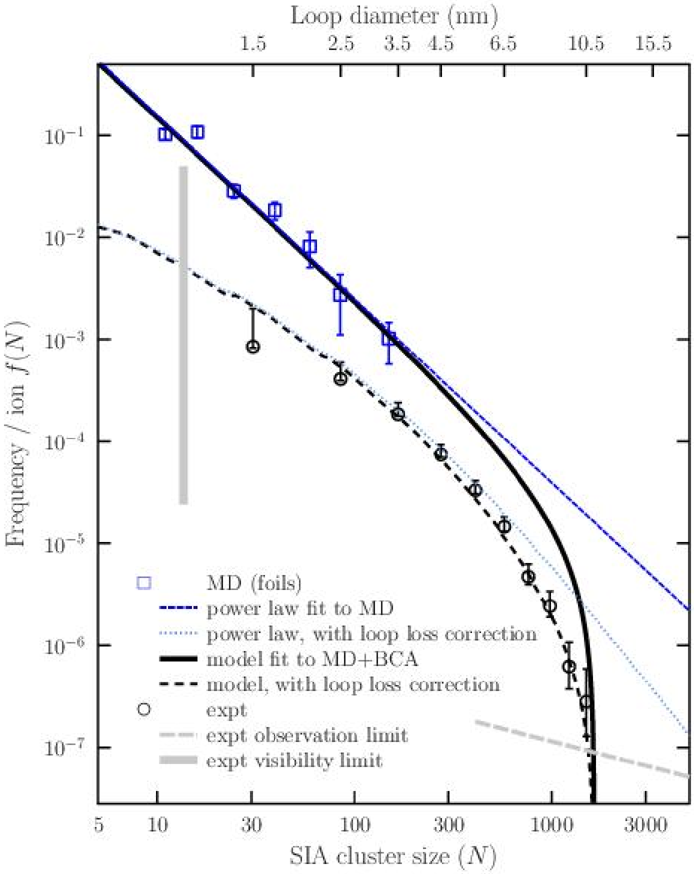

Figure 5.1. Size-frequency distribution of defect clusters in 150 keV self-ion irradiated W. Comparison between our model fitted to MD predictions, and in-situ TEM observations performed at cryogenic temperatures.

5.3 WP TRA – EUROfusion Engineering Grant

Design of control systems for remote handling of large components

Research scientist: Ming Li, LUT

The objective in current research stage is to develop generic deformation modelling methods for the heavy-duty remote handling manipulators for DEMO.

Even though the research work has been conducted in depth, more challenges have raised, which were not envisaged in the original work plan. It has been noticed that not only the extreme payload, large-scale complex mechanical structure and kinematics have significant effect on the overall deformation of a manipulator, but also the challenging environments including neutron radiation, high thermal effect and mechanical transmission uncertainties etc., have a notable synthetic effect on the material deformation physics. It is acknowledged that the conventional continuum mechanics is incompetent in modelling the deformation of a realistic manipulator due to many practical uncertainties, in sense of that some material physical phenomenon (such as material property deviations) in challenging environments are still open scientific questions.

Artificial neural networks (ANNs) have been used to address complexities and uncertainties in deformation modelling in challenging environments, and it outperforms the parametric models based on the continuum mechanics. Bayesian inference based on Markov Chain Monte Carlo method has been developed to identify high dimensional weight parameters of ANNs. A joint assembly from TARM is taken as a study target in current research stage, and the modelling results show that the ANN is competent in modelling deformation complexities due to nonlinear geometrics and joints kinematics. The performance of deformation model, developed by the ANNs, for a joint assembly is presented in Figure 5.3.

The squares in the figures stand for the deformation data (as a benchmark) obtained by FEM, with the unit in micrometres, whereas the continuous lines stand for deformation model predictions under the same loads and kinematic patterns. Left figure shows the trained deformation model by 91 set of different payloads in 91 different kinematics, and the right figure shows the model prediction performance for untrained data, which is under another 91 set of different payloads and kinematics. The comparison results indicate that the ANN modelling method is competent to model deformation physics of mechanisms assembly, which is kinematic dependent, under the force payload.

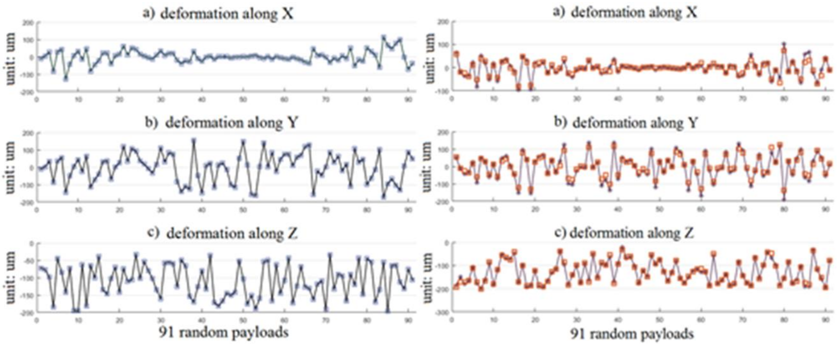

Figure 5.3. Prediction performance of ANNs deformation model in trained (left) and untrained domains (right).

5.4 WP TRA – EUROfusion Researcher Grant

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

Research scientist: A. Snicker, AU

FinnFusion (Aalto University) has actively developed and utilized Monte-Carlo fast-ion following code ASCOT to understand the confinement and transport of fast-ions. In the lastdecade or so predictive ITER studies have inherently used fully 3D magnetic fields including increasing complexity of external perturbations. These perturbations are essential to capture the key transport mechanism affecting the fast-ions. It has been realized that internal 3D perturbations caused by various magnetohydrodynamic (MHD) instabilities play a key role in the transport process. In this task, started in late 2017, the goal is to study the interplay between the internal and external 3D perturbations on the fast-ion transport.

In 2017 this goal was pursued by various means. As the plan is to use reduced phase-space to ease the computational efforts, it is necessary to verify that the guiding center approximation is valid for the simulations including 3D internal perturbations. As ASCOT includes both reduced and full phase space treatment, it is a perfect tool to study this. The verification process will be finalized in 2018.

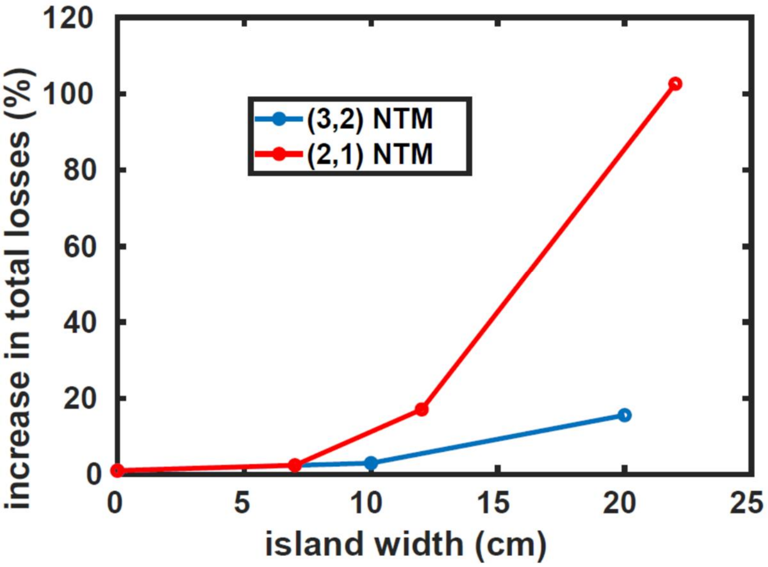

Figure 5.2. The increase in the lost power as a function of island width for the (2,1) and (3,2) NTMs.

The next step to gain further confidence in the simulation tools is to validate the numerical models using existing measurements from ASDEX Upgrade tokamak. Specifically, a discharge where both external RMP coils and internal NTM was present, a combined effect of the two on the fast-ion loss detector (FILD) measurement was observed. The modeling of this discharge started by a code-code benchmark of ASCOT and LOCUST codes, showing that the codes agree well for MHD-quiescent plasma conditions. The study will be extended to synthetic diagnostic comparison in 2018.

The ultimate goal of this grant is to provide reliable estimates of the fast-ion transport in ITER scenarios including all levels of 3D perturbations. To get started with this, the first simulations including full set of external perturbations and internal NTMs was carried out. It was observed that, in particular edge localized, NTMs can significantly increase the losses of alpha particles in ITER (see Figure 5.2).

6. Enabling Research

Research scientists: T. Kiviniemi, T. Kurki-Suonio, S. Leerink, K. Särkimäki, AU
K. Heinola, UH
J. Likonen, VTT

FinnFusion participated in four Enabling Research projects in 2017:

- AWP15-ENR-01/CCFE-08: Tritium and deuterium retention in metals with variable radiation-induced microstructure (TriCEM)
- AWP15-ENR-01/CEA-09: Kinetic modelling of runaway electron dynamics
- AWP15-ENR-01/IPP-01: Verification and development of new algorithms for gyrokinetic codes (NumKin)

In this report, we highlight the TriCEM project coordinated by CCFE.

6.1 Tritium and deuterium retention in metals with variable radiation-induced microstructure

Tritium interaction with fusion materials and its retention and release from materials under realistic operating conditions is one of the major unknowns in fusion science and technology. This project aims at combining expertise in experimental and modelling areas related to Plasma Facing Components and Structural Materials.

The role of University of Helsinki (UH) and VTT is to use Thermal Desorption Spectroscopy (TDS) for the characterization of defects and traps, and release of hydrogen isotopes from EUROFER and tungsten materials, and to use Secondary Ion Mass Spectrometry (SIMS) for depth profiling of deuterium and tritium as well as to characterise the impurities in these materials.

TriCEM activities at UH comprises of self-irradiation of tungsten, EUROFER and Iron-Chromium (Fe8%Cr) samples in order to provide damage network to the materials studied further within TriCEM for hydrogen isotope retention.

The self-irradiations were carried out using a 5 MeV Tandem accelerator, and a 500 keV implanter. For each material three self-irradiation doses were used: 10^{12}, 10^{13}, and 10^{14} at/cm^2 corresponding to 0.01, 0.1 and 1.0 dpa. For the W samples a 2.0 MeV $^{184}W^{++}$ beam was used, and for the EUROFER and Fe8%Cr samples a 500 keV $^{56}Fe^{+}$ beam was used.

In 2017 SIMS was used to investigate the retention of D in damaged Eurofer and W samples. Figure 6.1 shows SIMS depth profiles for D in undamaged and damaged Eurofer. The retention of D is higher in the damaged Eurofer than in the undamaged but the D retention decreases with the damage dose.

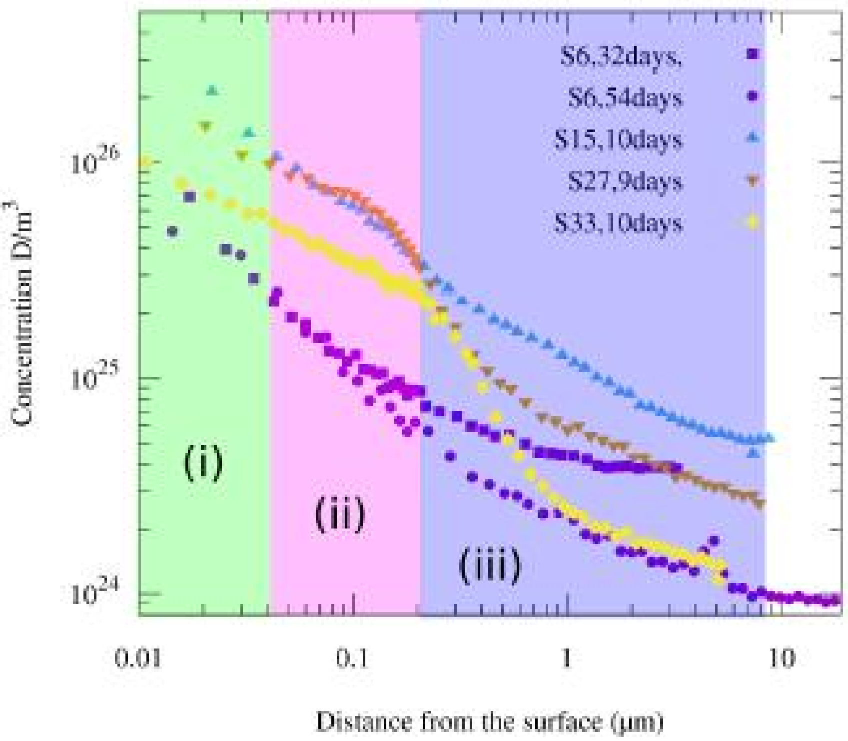

Figure 6.1. SIMS depth profiles of deuterium in damaged Eurofer samples (S6 undamaged sample, S15 0.01 dpa, S27 0.1 dpa and S33 1 dpa).

7. Full-f gyrokinetic turbulence code ELMFIRE

Research scientists: T. Kiviniemi, T. Korpilo, S. Leerink, P. Niskala, R. Rochford, AU

The behaviour of Geodesic acoustic modes has been investigated using ELMFIRE code as part of the co-operation with FT-2 and TUMAN-3M groups both located in Ioffe Institute, St. Petersburg, Russia, and in the context of the EUROfusion Enabling research project “Numerical Methods for the Kinetic Equations of Plasma Physics”. Special emphasis has been on the radial propagation of the mode and on the role of the mode in regulating particle confinement in the isotope effect. Transport analysis have continued for the FT-2 tokamak discharges and new results have indicated that small scale fluctuations might have a contribution to the overall transport for the higher density regime.

In addition, the code has been further developed to include a more physical treatment of the boundary and a MPI/OpenMP hybrid version to reduce the memory imprint. First results of the optimised boundary conditions have been published as part of Tuomas Korpilo’s doctoral thesis work and the implementation of the logical boundary condition and more realistic FT-2 limiter has been presented at the Plasma Edge Theory meeting in Marseille, France. The MPI/OpenMP hybrid version of ELMFIRE has been extensively tested and has greatly reduced the memory imprint, which allows for much higher resolution and accuracy.

8. International collaborations

8.1 DIII-D tokamak

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

8.1.1 Plasma detachment studies

The deuterium (Lyman-series, molecular Lyman-Werner band) and carbon line radiation in the extreme ultraviolet (EUV) wavelength range were measured in DIII-D utilising the new divertor Survey, Poor Resolution, Extended Domain (SPRED) spectrometer. The experiment supports ITPA-DSOL proposal 32 and the general topic of heat and particle fluxes on divertor targets (divertor detachment). The instrument is a single line-of-sight, vertically viewing system coinciding with several other plasma and optical diagnostics, foremost the divertor Thomson scattering system.

The experiment was carried out successfully – in 35 discharges on a single runday – in December 2017, taking data in the ultraviolet region across the outer divertor leg, as well as in the visible wavelength range using the multi-chord divertor spectrometer for the deuterium Balmer series and the Fulcher band emission. In addition to the spectroscopic measurements, the plasma conditions at the target plates were measured with a set of fixed Langmuir probes, and within the outer divertor plasma with divertor Thomson scattering and a reciprocating probe (the latter including SOL turbulence measurements). The plasma conditions were varied in L-mode for low-recycling (T_e,outer strike point (OSP) ~30 eV), high-recycling, at the ion saturation current roll-over (T_e,OSP ~2 eV), and in partially detached conditions (T_e,OSP ~1 eV). In H-mode, partially detached conditions with T_e,OSP ~1 eV and electron densities of up to $5\text{x}10^{20}$ m^{-3}, were diagnosed for their radiation profiles. The Balmer α, β, and γ emission, the Lyman-α, and the Fulcher band emission were routinely measured with the divertor spectrometers. However, there were little to no indications of prominent emission at the Lyman-Werner band in the EUV wavelength range.

Standalone Eirene is used to simulate both the Lyman and Balmer series, and the Fulcher band emission. The EIRENE calculations will include an assessment of the impact of Ly-a photon trapping and vibrationally excited molecules, in collaboration with Forschungszentrum Juelich, Germany.

8.1.2 ρ* scaling of intrinsic torque (ITPA TC-17)

Tuomas Tala and Antti Salmi visited General Atomics (San Diego, USA) for the DIII-D part of the ITPA TC-17 experiment to study the scaling of intrinsic torque with collisionality in TEM range. Despite technical and operational difficulties electron cyclotron heating was successfully applied to DIII-D plasmas similar to ITER baseline to mitigate core MHD, to prevent impurity accumulation and to transition from the usual ITG turbulence to TEM dominated turbulence regime as planned. Mid-radius rotation reversal was observed when no significant MHD was present while the rotation reversal disappeared when the MHD returned. This is tentatively interpreted as an indirect evidence of TEM generated counter current intrinsic torque. Furthermore, balanced beam torque modulations were added for some selected discharges to extract the experimental estimate of the magnitude of the intrinsic torque. Understanding all significant sources of plasma rotation is important to allow predictions and optimization the plasma scenarios for stability and fusion performance.

8.2 KSTAR tokamak

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

Tuomas Tala and Antti Salmi 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). The emphasis is on the JET and AUG comparison with KSTAR. KSTAR has long pulse capability (>20s) which is very helpful in measuring accurately the rotation perturbations with reduced noise level. Very unfortunately, on the day before the experiment KSTAR broke and the whole remaining campaign (some 3 weeks) was cancelled. This experiment will be scheduled during the next KSTAR experimental campaign in 2018. The visit was very successful in setting up VTT-KSTAR collaboration and pushing forward the multi-machine ITPA experiment on ρ* scaling of intrinsic torque on a new tokamak.

8.3 MIT collaboration

Research scientists: T.Tala, VTT

The purpose of the C-Mod experiment was to measure the particle pinch in a set of dimensionless scaling experiments in which collisionality was varied using the gas puff modulation technique developed in JET. The key feature different in C-Mod with respect to JET and DIII-D is the missing NBI fuelling component. Furthermore, the collisionality scan I-mode provides a unique set of data not performed elsewhere.

The steady-state data already shows certain trends with collisionality in I-mode, which are rather similar to the ones in JET. The analysis of the modulation data will be more challenging on C-Mod than on JET due to the less stationary plasma background, such as an increasing plasma density at each modulation cycle and due to the shorter duration of the modulation phases. To get more compelling results, the I-mode database on density peaking was initiated. The scope of the database work was defined and the very first steps taken.

8.4 Ioffe Institute

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

Financed by the Finnish academy and, previously by the Commission for the Scientific Technological Cooperation between Finland and Russia a long standing collaboration has been established between the Finnish fusion groups at Aalto University and VTT and the Ioffe PhysicoTechnical Institute in St. Petersburg since 1992. In recent years the focus of the collaboration has been on understanding transport phenomena and flows in the FT-2 and Tuman-3M tokamak plasmas, hosted by the high temperature plasma physics laboratory of the Ioffe Institute.

The FT-2 tokamak is equipped with a sophisticated diagnostic setup including Doppler reflectometry, spectroscopy, enhanced scattering and probes to monitor turbulent transport processes and flows. Scientists at Aalto University and VTT have been able to simulate turbulent and neoclassical transport in a realistic FT-2 plasma environment from a first principle basis while using the full-f gyrokinetic code ELMFIRE. In 2015 turbulence modulation at the GAM frequency were for the first time observed by reflectometry measurements at the FT-2 tokamak and confirmed by ELMFIRE simulations, predicting strong modulations of the electron thermal diffusivity induced by GAMs, which propagates inward and possesses the GAM temporal and spatial structure. In 2017 the investigations into the correlation between heat and particle transport and flows in FT-2 plasmas continued while varying the fuel isotopes and ELMFIRE simulations were performed and validated.

8.5 JT-60SA

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

JT-60SA tokamak, currently under construction in Japan, is part of Broader Approach and a joint experiment between Japan and Europe. It starts operating in 2019 and will serve as a bridge between present-day tokamaks and ITER. It is the size of JET but with modern, ITER-relevant technology: it has super-conducting coils, allowing extended pulse lengths, and it features negative neutral beams (NNB) allowing particles with very high energy. JT-60SA also features quite large toroidal field (TF) ripple, having the same number of TF coils as ITER (18). This, together with the high energy of the beams, makes it important to study beam ion confinement.

In addition to 10MW of NNB power at 500keV, JT-60SA has additional 24MW of conventional (positive) beam power. We have used the ASCOT code to investigate the power loads for all beams. Unfortunately, the equilibria available in 2017 were not consistent with the real 3D wall, so the results were obtained with simplified 2D wall structures and can be considered qualitative at best. The simulations were carried out for scenarios S2L and S5, with ‘L’ standing for low density.

Simulations with axisymmetric magnetic field revealed losses mainly due to the (artificial) proximity of the wall to the separatrix. Including the TF ripple substantially increased losses on the low-field side as indicated in Figure 8.1. However, future simulations that will include the effect of ripple-mitigating ferritic inserts are expected to dramatically lower the losses.

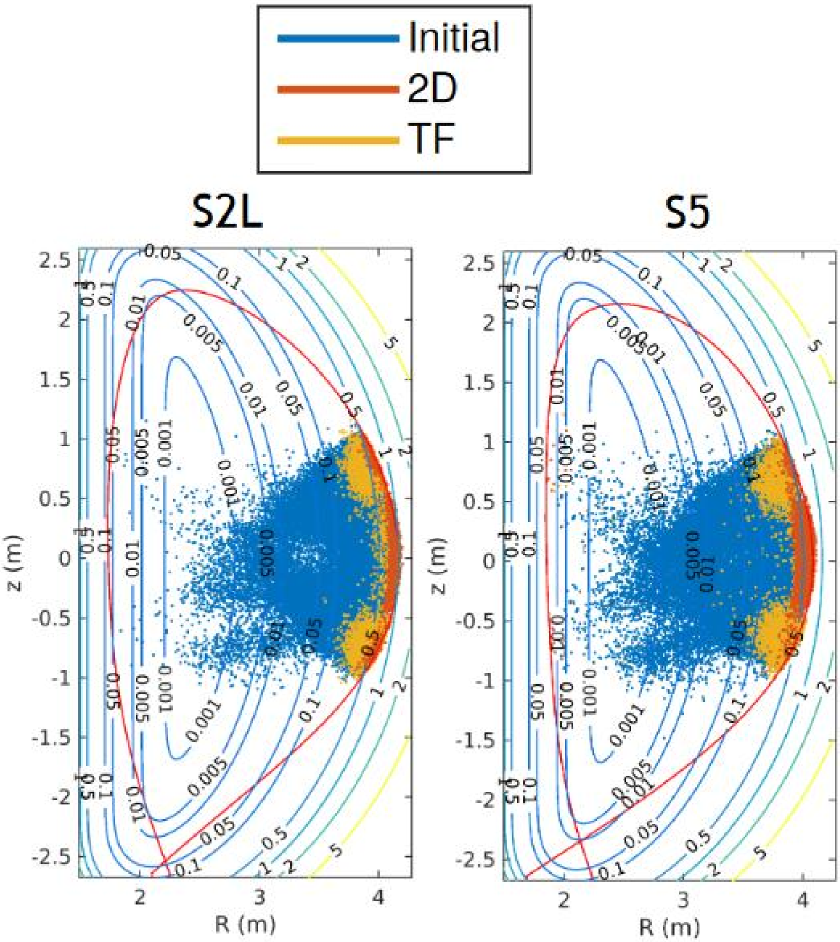

Figure 8.1. Ripple maps and beam particle losses in JT-60SA scenarios S2L and S5. Initial positions of markers that were confined are indicated by blue dots, while those that were lost in axisymmetric case are indicated by red dots and those lost with toroidal field ripple present are indicated by yellow dots.

9. Fusion for Energy activities

9.1 System level design for the Remote Handling Connector and ancillary components

F4E grant: F4E-FPA-328-SG05

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

VTT as a partner in a Hungarian Consortium within the F4E Framework Project Agreement (FPA) has finalised on the Concept design of Divertor Remote Handling Connector (RHC) within a special grant (SG05). The RHC project has been a part of the development project on Diagnostics System for ITER.

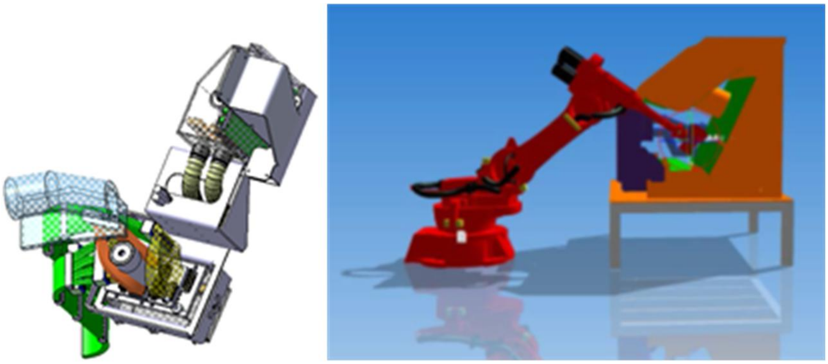

Figure 9.1. Remote Handling Connector Concept and the RHC Test platform.

The purpose of a RHC is to connect divertor cassette diagnostic sensors to ex-vessel diagnostics system. When exchanging the divertor cassettes the connection to the diagnostic system must be un-plugged. Because of the hazard environment in the vessel the un-plugging will be performed by Remote Handling System. The amount of diagnostics signals varies between different cassettes and in the most challenging case, the amount of pins to be connected in a RHC is over 200. Out of the 54 divertor cassettes 17 contain diagnostics sensors. The concept and test platform are illustrated in Figure 9.1.

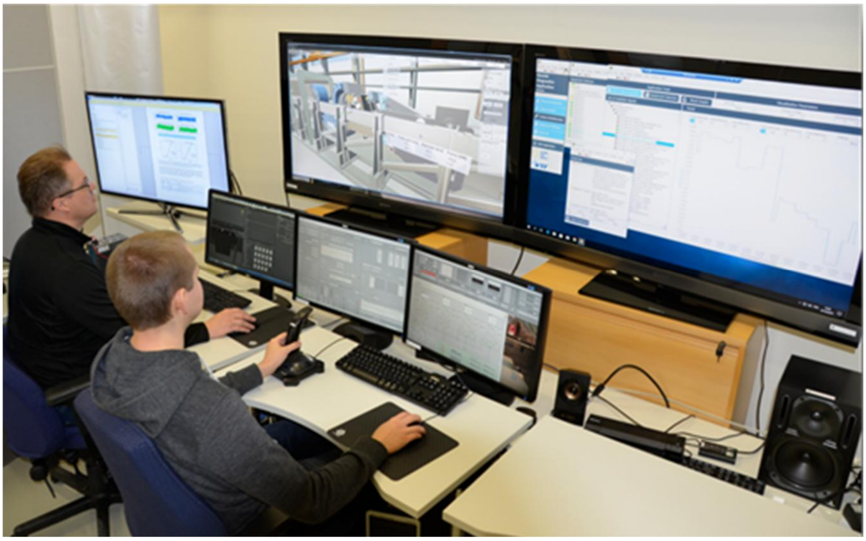

Figure 9.2. The operator room of the ITER Divertor Test Platform (DTP2) at VTT.

The goal of the grant was to design the RHC at a system level and support the design through mock-up testing. The design has represented the conceptual design phase of the connector taking into account space limitations, harsh environment requirements (thermal load, irradiation, vacuum) and needs for reliability and remote handling ability. The work has continued in 2017 with demonstrations of the chosen solution. For the demonstration of the design, several mock-ups were created and tested in a mock-up testing platform. One of the critical part of the RHC was the flexible cable solution, which is due to the needs for compliance during the assembly and operation. This solution was demonstrated successfully in the final meeting of the grant.

In addition to the RHC test platform the DTP2 platform at VTT has been in very important role in the development of the mock-ups and the final connector. The special connector types and the development of demanding remote operated connectors can contribute new special products for the Finnish industry.

9.2 Remote Diagnostics Application Software for Remote Handling Equipment

F4E grant: F4E-GRT-0689

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

The ITER Remote Handling equipment controllers provide measurement and diagnostics data about the remote handling equipment and devices they control, about themselves and about their operating environment. This information is aimed for the ITER RH operators to reduce down time of the Remote Handling systems by anticipating maintenance needs and failure conditions.

The purpose of this task was to develop Remote Diagnostics Application (RDA) software for the analysis and archiving of diagnostics data. RDA aims to become one of the standard High-Level Control System applications of the ITER Remote Handling Control System. RDA provides a basic set of diagnostics tools for the ITER RH operators that can be extended for specific RH equipment needs. RDA facilitates the incorporation at run-time of LabView Visual Instruments addressing specific diagnostics cases not presumed at the time of RDA development and programming. This has been achieved by a three-layered architecture consisting of (1) the RDA Framework, (2) its Workbenches and (3) Diagnostics Primitives (rules, analysis functions, filters, etc.).

The RDA has the following features by default:

- data collection from several RH equipment controllers;
- time domain plotting of data (trends);
- frequency domain analysis (spectra);
- amplitude domain analysis (histograms);
- scatter plots;
- cross-correlation plots;
- archiving and retrieval of history data.

The RDA enables ITER RH operators to:

- monitor performance data;
- run diagnostics tests and rules on equipment systems;
- analyse historical data.

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10. Other activities

10.1 Missions and secondments

Tuomas Tala to IPP Garching, Garching, Germany, 16 – 19 Jan 2017 (WP MST1).

Antti Salmi to IPP Garching, Garching, Germany, 17 – 20 Jan 2017 (WP MST1).

Jari Likonen to JET facilities, United Kingdom, 23 – 27 Jan 2017 (WP JET2).

Antti Hakola to IPP Garching, Garching, Germany, 24 – 27 Jan 2017 (WP MST1).

Bartosz Lomanowski and Christos Stavrou to JET facilities, United Kingdom, 30 Jan – 2 Feb 2017 (WP JET1).

Antti Salmi to General Atomics, San Diego, California, USA, 6 – 16 Feb 2017 (International Collaborations).

Antti Hakola to IPP Garching, Garching, Germany, 13 – 17 Feb 2017 (WP MST1).

Jari Likonen to JET facilities, United Kingdom, 22 Feb – 3 Mar 2017 (WP JET2).

Juuso Karhunen to IPP Garching, Garching, Germany, 6 – 10 Mar 2017.

Antti Hakola to IPP Garching, Garching, Germany, 7 – 10 Mar 2017 (WP MST1).

Antti Hakola to IPP Garching, Garching, Germany, 19 – 24 Mar 2017 (WP MST1).

Jari Likonen to JET facilities, United Kingdom, 27 – 31 Mar 2017 (WP JET2).

Jari Varje to JET facilities, United Kingdom, 27 March - 7 April 2017 (WP JET1).

Aki Lahtinen to JET facilities, United Kingdom, 27 Mar – 21 Apr 2017 (WP JET2).

Antti Hakola to IPP Garching, Garching, Germany, 3 – 7 Apr 2017 (WP MST1).

Juuso Karhunen to IPP Garching, Garching, Germany, 3 – 13 Apr 2017.

Tuomas Tala to IPP Garching, Garching, Germany, 3 – 13 Apr 2017 (WP MST1).

Antti Salmi to IPP Garching, Garching, Germany, 10 – 13 Apr 2017 (WP MST1).

Antti Hakola to IPP Garching, Garching, Germany, 11 – 13 Apr 2017 (WP MST1).

Mathias Groth to General Atomics, San Diego, California, USA, 11 Apr – 9 May 2017 (International Collaborations).

Jari Likonen to JET facilities, United Kingdom, 24 – 28 Apr 2017 (WP JET2).

Antti Hakola to IPP Garching, Garching, Germany, 25 – 28 Apr 2017 (WP MST1).

Antti Hakola to IPP Garching, Garching, Germany, 2 – 5 May 2017 (WP MST1).

Antti Hakola to IPP Garching, Garching, Germany, 9 – 24 May 2017 (WP MST1).

Taina Kurki-Suonio to IPP Garching, Garching, Germany, 15 – 19 May 2017 (WP MST1).

Jari Varje to JET facilities, United Kingdom, 15 May - 2 June 2017 (WP JET1).

Antti Salmi to SPC, Lausanne, Switzerland, 29 May – 2 Jun 2017 (WP MST1).

Tuomas Tala to SPC, Lausanne, Switzerland, 29 May – 2 Jun 2017 (WP MST1).

Juuso Karhunen to IPP Garching, Garching, Germany, 29 May – 9 Jun 2017.

Antti Snicker to IPP Garching, Garching, Germany, 1 Jun – 17 Aug 2017 (TRA-ERG).

Antti Hakola to SPC, Lausanne, Switzerland, 6 – 14 Jun 2017 (WP MST1).

Antti Hakola to IPP Garching, Garching, Germany, 19 – 22 Jun 2017 (WP MST1).

Jari Likonen to JET facilities, United Kingdom, 26 Jun – 14 Jul 2017 (WP JET2).

Jari Varje to JET facilities, United Kingdom, 3 July - 14 July 2017 (WP JET1).

Antti Hakola to SPC, Lausanne, Switzerland, 10 – 13 Jul 2017 (WP MST1).

Antti Hakola to IPP Garching, Garching, Germany, 14 – 21 Jul 2017 (WP MST1).

Mathias Groth to JET facilities, United Kingdom, 17–20 Jul 2017 (WPJET1).

Mathias Groth to Lawrence Livermore National Laboratory, Livermore, California, USA, 14-18 Aug 2017 (International Collaborations).

Juuso Karhunen to SPC, Lausanne, Switzerland, 21 Aug 2017.

Mathias Groth to DIII-D/General Atomics, 20 Aug–16 Sep 2017 (International Collaborations).

Antti Hakola to IPP Garching, Garching, Germany, 18 – 21 Sep 2017 (WP MST1).

Antti Hakola to IPP Garching, Garching, Germany, 25 – 29 Sep 2017 (WP MST1).

Andrea Sand to Lawrence Livermore National Laboratory, Livermore, California, USA, 26 Sep – 26 Oct 2017.

Mathias Groth to FZ Juelich, Germany, 4 – 6 Oct 2016 (WPJET1).

Antti Hakola to SPC, Lausanne, Switzerland, 2 – 6 Oct 2017 (WP MST1).

Antti Hakola to IPP Garching, Garching, Germany, 15 – 19 Oct 2017 (WP MST1).

Jari Varje to JET facilities, United Kingdom, 16 October - 20 October 2017 (WP JET1).

Jari Likonen to JET facilities, United Kingdom, 16 – 20 Oct 2017 (WP JET2).

Antti Hakola to SPC, Lausanne, Switzerland, 23 Oct – 2 Nov 2017 (WP MST1).

Antti Salmi to SPC, Lausanne, Switzerland, 30 Oct – 3 Nov 2017 (WP MST1).

Tuomas Tala to SPC, Lausanne, Switzerland, 30 Oct – 3 Nov 2017 (WP MST1).

Jari Varje to JET facilities, United Kingdom, 6 November - 17 November 2017 (WP JET1).

Antti Hakola to IPP Garching, Garching, Germany, 7 – 10 Nov 2017 (WP MST1).

Mathias Groth to DIII-D/General Atomics, San Diego, California, USA, 13 Nov – 11 Dec 2017 (International Collaborations).

Taina Kurki-Suonio to IPP Garching, Garching, Germany, 13 – 17 Nov 2017 (WP MST1).

Aki Lahtinen to IPP Garching, Garching, Germany, 20 – 24 Nov 2017 (WP MST1).

Jari Likonen to IPP Garching, Garching, Germany, 20 – 24 Nov 2017 (WP MST1).

Antti Hakola to IPP Garching, Garching, Germany, 27 – 30 Nov 2017 (WP MST1).

Juuso Karhunen to IPP Garching, Garching, Germany, 29 Nov – 1 Dec 2017.

Aki Lahtinen to IPP Garching, Garching, Germany, 3 – 7 Dec 2017 (WP MST1).

Jari Likonen to IPP Garching, Garching, Germany, 3 – 7 Dec 2017 (WP MST1).

Antti Snicker to IPP- Garching, Garching, Germany, 3 – 15 Dec 2017 (TRA-ERG).

Antti Hakola to IPP Garching, Garching, Germany, 4 – 13 Dec 2017 (WP MST1).

10.2 Conferences, seminars, workshops and meetings

Markus Airila, Mathias Groth, Antti Hakola, Andreas Holm, Juuso Karhunen, Kai Nordlund, Ivan Paradela Perez, Elnaz Safi, Christos Stavrou, and Jaro Uljanovs participated in Joint Working Session for Integrated Plasma Modelling, Tervaniemi, Finland, 31 Jan – 3 Feb 2017.

Fredric Granberg participated in Towards Reality in Nanoscale Materials IX, Levi, Finland, 13 – 16 Feb 2017.

Tuomas Tala participated in the 37th F4E Governing Board meeting, Barcelona, Spain, 20 – 21 Feb 2017.

Taina Kurki-Suonio and Konsta Särkimaki participated in 4th WPSA Project Planning Meeting, CIEMAT, Madrid, Spain, 5 – 10 Mar 2017 (WP SA).

Mikko Siuko participated in Divertor attachment concept development -kick-off meeting, IPP - Garching, Germany, 6 – 7 Mar 2017 (WP RM).

Seppo Sipilä and Jari Varje participated in Code Camp at ITER, Cadarache, France, 20 – 24 Mar 2017 (WP CD).

Mathias Groth, Fredric Granberg and Jesper Byggmästar participated in the 51th Annual Meeting of the Finnish Physical Society (Physics Days 2017), Helsinki, Finland, 22 – 24 Mar 2017.

Antti Hakola participated in the Programme Committee meeting of the 44th European Physical Society Conference on Plasma Physics, Belfast, United Kingdom, 26 – 29 Mar 2017.

Andrea Sand participated in meeting on IAEA hosting a database of cascades, Vienna, Austria, 27 – 29 Mar 2017 (WP MAT).

Atte Helminen participated in WPENS Technical Meeting #3, ENEA, Frascati, Italy, 3 – 7 Apr 2017 (WP ENS).

Tuomas Tala participated in the 17th EUROfusion General Assembly meeting, Cadarache, France, 10 – 11 Apr 2017.

Jari Varje participated in 2nd European Conference on Plasma Diagnostics, Bordeaux, France, 18 – 21 Apr 2017.

Konsta Särkimäki, Taina Kurki-Suonio participated in 18th ITPA-EPP meeting, CIEMAT, Sevilla, Spain, 25 – 29 Apr 2017 (Internaional collaborations).

Tuomas Tala participated in the ITPA meeting, Princeton, USA, 30 Apr – 12 May 2017 (International Collaborations).

Jari Varje participated in 16th International School of Fusion Reactors Technology, Erice, Italy, 28 Apr– 4 May 2017.

Otto Asunta and Jari Varje participated in WPCD code camp, PSNC, Poznan, Poland, 8 – 12 May 2017 (WP CD).

Kalle Heinola, Aki Lahtinen and Jari Likonen participated in 16th International Conference on Plasma-Facing Materials and Components for Fusion Applications, Neuss/Duesseldorf, Germany, 16 – 19 May 2017.

Andrea Sand participated in Third International Workshop on Models and Data for Plasma-Material Interaction in Fusion Devices (MoD-PMI 2017), Jülich, Germany, 22 – 24 May 2017.

Mathias Groth, Antti Hakola, and Bart Lomanowski participated in the 24th ITPA DivSol meeting, University of York, York, United Kingdom, 29 May – 2 Jun 2017.

Konsta Särkimäki participated in 5th Runaway Electron Meeting, Liblice, Czech Republic, 5-8 June 2017.

Jesper Byggmästar and Kai Nordlund participated in IREMEV Monitoring Meeting, RBI, Zagreb, Croatia, 6 – 8 Jun 2017 (WP MAT).

Markus Airila, Jesper Byggmästar, Fredric Granberg, Antti Hakola, Juuso Karhunen, Taina Kurki-Suonio, Aki Lahtinen, Kai Nordlund, Paavo Niskala, Antti Salmi, Roman Sibois, Paula Siren, and Tuomas Tala partic-ipated in 2nd Joint Nordic Fusion Energy Seminar, Espoo, Finland, 15 – 16 Jun 2017.

Mikko Siuko participated in Divertor Attachment Workshop, IPP - Garching, Germany, 19 – 21 Jun 2017 (WP RM).

Fredric Granberg participated in Nanopatterning 2017, Helsinki, Finland, 26 – 28 Jun 2017.

Antti Hakola, Joona Kontula, Bart Lomanowski, Antti Salmi, Antti Snicker, Tuomas Tala, and Jari Varje participated in 44th European Physical Society Conference on Plasma Physics, Belfast, United Kingdom, 26 – 30 Jun 2017.

Fredric Granberg participated in FOR3NANO, Helsinki, Finland, 28 – 30 Jun 2017.

Markus Airila participated in the 38th F4E Governing Board meeting, Cadarache, France, 3 – 4 Jul 2017.

Antti Hakola participated in the 18th EUROfusion General Assembly meeting, Culham, United Kingdom, 13 – 14 Jul 2017.

Paula Sirén and Jari Varje participated in WPCD code camp, Ljubljana, Slovenia, 4 – 15 Sep 2017 (WP CD).

Tuomas Tala participated in the General Task Force Meeting in JET, CCFE, United Kingdom, 4 – 8 Sep 2017 (WP JET1).

Taina Kurki-Suonio participated in 19th ITPA-EPP meeting, Princeton, USA, 11 – 12 Sep 2017 (International Collaborations).

Andrea Sand participated in EUROMAT, Thessaloniki, Greece, 17 – 21 Sep 2017.

Romain Sibois, Mikko Siuko and Jarno Videnoja participated in DEMO Divertor Port Integration Workshop at RACE, CCFE, United Kingdom, 3 – 5 Oct 2017 (WP RM).

Mathias Groth participated in EIRENE, EDGE2D-EIRENE and SOLPS-ITER for JET meeting, FZJ, Jülich, Germany, 3 – 6 Oct 2017 (WP JET1).

Mikko Siuko participated in Divertor Fixation meeting, IPP - Garching, Germany, 17 – 18 Oct 2017 (WP RM).

Paula Sirén and Jari Varje participated in the WPCD code camp, FESB, Split, Croatia, 23 – 27 Oct 2017 (WP CD).

Jesper Byggmästar and Fredric Granberg participated in 18th International Conference on Fusion Reactor Materials, Aomori, Japan, 5 – 10 Nov 2017.

Tuomas Tala participated in the 19th EUROfusion General Assembly meeting, Wroclaw, Poland, 9 – 10 Oct 2017.

Romain Sibois and Mikko Siuko participated in Design Progress Review Meeting #2, IPP - Garching, Germany, 7 – 9 Nov 2017 (WP RM).

Antti, Hakola, Jari Likonen and Tuomas Tala participated in the MST1 Planning Meeting, CCFE, United Kingdom, 13 – 17 Nov 2017 (WP MST1).

Fredric Granberg participated in Finlandssvenska Fysik och Kemidagarna 2017, Helsinki, Finland, 17 – 19 Nov 2017.

Antti Hakola, Kalle Heinola and Elnaz Safi participated in Joint Annual Meeting of WP JET2/PFC, JSI, Ljubljana, Slovenia, 20 – 24 Nov 2017.

Atte Helminen, Jaakko Iivanainen and Antti Rantakaulio participated in WPENS Technical meeting #4, KIT, Karlsruhe, Germany, 24 – 27 Oct 2017 (WP ENS).

Andrea Sand participated in IREMEV monitoring meeting, Garching, Germany, 22 – 24 Nov 2017.

Andrea Sand participated in 25th European Fusion Programme Workshop, Dubrovnik, Croatia, 27 – 29 Nov 2017.

Tuomas Tala participated in the 39th F4E Governing Board meeting, Barcelona, Spain, 30 Nov – 1 Dec 2017.

Paula Siren participated in JET3 Monitoring Meeting, CCFE, Abingdon, United Kingdom, 4 – 7 Dec 2017 (WP JET3).

Longchuan Niu participated in International Conference on Robotics and Mechantronics, Hong Kong, 14 – 17 Dec 2017.

Tuomas Tala participated in the 20th EUROfusion General Assembly meeting, Barcelona, Spain, 18 – 19 Dec 2017.

10.3 Other visits

Timo Määttä and Matti Paljakka participated in ITER Business Forum 2017, Avignon, France, 28 – 30 Mar 2017.

Harri Mäkinen and Timo Avikainen participated in Load Specification Training, ITER site, 25 – 26 Apr 2017.

Timo Määttä visited F4E Barcelona on 5 – 6 Jul 2017 and participated in F4E ILO meeting on 6 Jul 2017.

Timo Määttä and Tuomas Tala participated in F4E 10 year Anniversary Event, Barcelona, 30 Nov 2017.

10.4 Visitors

Prof. Yuji Hatano, University of Toyama, visited VTT on 12 – 13 Jan 2017.

Tatiana Fedina, Oleg Kocznikov, Galina Vodovozova and Sergey Bazyshkov from SeverStal visited DTP2/ROViR on 23 Jan 2017.

Jae-Sun Park, KAIST, Dejon, South Korea, visited Aalto University as exchange student on 18 Feb – 19 March 2017.

Jarmo Lehtonen, TENO-Lokomo, visited ROViR, 21 Apr 2017.

Katerina Jirakova from IPP Prague/Technical University Prague, Czech Republic, Jan-May 2017 as ERASMUS exchange student.

Alain Brizard from Saint Michael's College, Colchester, United States, visited Aalto University on 2-15 May 2017.

Emilio Ruiz and Salvador Esque from F4E, Barcelona, Spain visited Lab of Automation and Hydraulic Engineering, TUT, 15-17 May, 2017.

Dr. Mikhail Irzak, Dr. Evgeniy Gusakov, Dr. Alexey Gurchenko, Dr. Leonid Askinazy, Dr. Oleg Krutkin, Dr. Alexander Bulokurov, Dr. Denis Kouprienko, Ioffe Institute, Saint Petersburg, Russia, visited Aalto University on 4-10 Jun 2017.

Alain Brizard from Saint Michael's College, Colchester, United States, visited Aalto University on 2-15 July 2017.

Pietro Vincenzi from Consorzio RFX, Padova, Italy, visited Aalto University on 31 July - 11 August 2017.

Matteo Vallar from Consorzio RFX, Padova, Italy, visited Aalto University on 31 July - 4 August 2017.

Dr. David Tshakaya for Tuomas Korpilo's defense, Oct 2017.

Prof. Yuji Hatano, University of Toyama, visited VTT on 9 – 13 Oct 2017.

21 visitors from Opto Fidelity, Business Finland, Forciot, Unseen Technology, TAMK, Koja, Nokeval, Intel Finland, Hydac, UPM Raflatac, University of Tampere, Innorent Solution, Vaisto Solutions, Novatron and Nomicam at ROViR, 11 Oct 2017.

SDIC (State Development & Investment Corporation, China) and Realmax (China) delegation visit to ROViR, 11 Nov 2017.

Emmi Tholerus from CCFE, United Kingdom, visited Aalto University on 21 November - 1 December 2017.

Dr. Leonid Askinazi, Dr. Alexandr Belokurov, Dr. Alexei Gurchenko, Dr. Evgeniy Gusakov, Dr. Denis Kouprienko, Dr. Sergei Lashkul, Ioffe Institute, Saint Petersburg, Russia, visited Aalto University on 17-23 Dec 2017.

Tomi Parmasuo, Meconet Ltd, visited ROViR, 20 Dec 2017.

Publications 2017

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

10.5 Publications

10.5.1 Refereed journal articles

1. J. Byggmästar, F. Granberg, K. Nordlund, Molecular dynamics simulations of thermally activated edge dislocation unpinning from voids in alpha-Fe, Physical Review Materials **1** (2017) 053603.
2. P.T. Lang, R. Maingi, D.K. Mansfield, R.M. McDermott, R. Neu, E. Wolfrum, R. Arredondo Parra, M. Bernert, G. Birkenmeier, A. Diallo, M. Dunne, E. Fable, R. Fischer, B. Geiger, A. Hakola, V. Nikolaeva, A. Kappatou, F. Laggner, M. Oberkofler, B. Ploeckl, S. Potzel, T. Pütterich, B. Sieglin, T. Szepesi and ASDEX Upgrade Team, Impact of lithium pellets on plasma performance in the ASDEX Upgrade all-metal-wall tokamak, Nuclear Fusion **57** (2017) 016030.
3. M.J. Lanctot, J.A. Snipes, H. Reimerdes, C. Paz-Soldan, N. Logan, J.M. Hanson, R.J. Buttery, J.S. deGrassie, A.M. Garofalo, T.K. Gray, B.A. Grierson, J.D. King, G.J. Kramer, R.J. La Haye, D.C. Pace, J.-K. Park, A. Salmi, D. Shiraki, E.J. Strait, W.M. Solomon, T. Tala and M.A. Van Zeeland, A path to stable low-torque plasma operation in ITER with test blanket modules, Nuclear Fusion **57** (2017) 036004.
4. R. Wenninger, R. Albanese, R. Ambrosino, F. Arbeiter, J. Aubert, C. Bachmann, L. Barbato, T. Barrett, M. Beckers, W. Biel, L. Boccaccini, D. Carralero, D. Coster, T. Eich, A. Fasoli, G. Federici, M. Firdaouss, J. Graves, J. Horacek, M. Kovari, S. Lanthaler, V. Loschiavo, C. Lowry, H. Lux, G. Maddaluno, F. Maviglia, R. Mitteau, R. Neu, D. Pfefferle, K. Schmid, M. Siccinio, B. Sieglin, C. Silva, A. Snicker, F. Subba, J. Varje, H. Zohm, The DEMO wall load challenge, Nuclear Fusion **57 (**2017) 046002.
5. M. Salewski, M. Nocente, A.S. Jacobsen, F. Binda, C. Cazzaniga, G. Ericsson, J. Eriksson, G. Gorini, C. Hellesen, A. Hjalmarsson, V.G. Kiptily, T. Koskela, S.B. Korsholm, T. Kurki-Suonio, F. Leipold, J. Madsen, D. Moseev, S.K. Nielsen, J. Rasmussen, M. Schneider, S.E. Sharapov, M. Stejner, M. Tardocchi and JET Contributors, MeV-range velocity-space tomography from gamma-ray and neutron emission spectrometry measurements at JET, Nuclear Fusion **57** (2017) 056001.
6. W. Guttenfelder, A.R. Field, I. Lupelli, T. Tala, S.M. Kaye, Y. Ren and W.M. Solomon, Perturbative momentum transport in MAST L-mode plasmas, Nuclear Fusion **57** (2017) 056022.
7. P. Sonato, P. Agostinetti, T. Bolzonella, F. Cismondi, U. Fantz, A. Fassina, T. Franke, I. Furno, C. Hopf, I. Jenkins, E. Sartori, M.Q. Tran, J. Varje, P. Vincenzi, L. Zanotto, Conceptual design of the DEMO neutral beam injectors: Main developments and R&D achievements, Nuclear Fusion **57** (2017) 056026.
8. D. Carralero, M. Siccinio, M. Komm, S.A. Artene, F.A. D'Isa, J. Adamek, L. Aho-Mantila, G. Birkenmeier, M. Brix, G. Fuchert, M. Groth, T. Lunt, P. Manz, J. Madsen, S. Marsen, H.W. Müller, U. Stroth, J.H. Sun, N. Vianello, M. Wischmeier, E. Wolfrum, Recent progress towards a quantitative description of filamentary SOL transport, Nuclear Fusion **57** (2017) 056044.

9. K. Heinola, J. Likonen, T. Ahlgren, S. Brezinsek, G. De Temmerman, I. Jepu, G.F. Matthews, R.A. Pitts, A. Widdowson, Long-term fuel retention and release in JET ITER-Like Wall at ITER-relevant baking temperatures, Nuclear Fusion 57 (2017) 086024.

10. R.C. Wolf et al. (incl. T. Kurki-Suonio and S. Sipilä), Major results from the first plasma campaign of the Wendelstein 7-X stellarator, Nuclear Fusion 57 (2017) 102020.

11. A. Hakola, S. Brezinsek, D. Douai, M. Balden, V. Bobkov, D. Carralero, H. Greuner, S. Elgeti, A. Kallenbach, K. Krieger, G. Meisl, M. Oberkofler, V. Rohde, P. Schneider, T. Schwarz-Selinger, A. Lahtinen, G. De Temmerman, R. Caniello, F. Ghezzi, T. Wauters, A. Garcia-Carrasco, P. Petersson, I. Bogdanovic Radovic, Z. Siketic, ASDEX Upgrade Team and EUROfusion MST1 Team, Plasma-wall interaction studies in the full-W ASDEX upgrade during helium plasma discharges, Nuclear Fusion **57** (2017) 066015.

12. S. Wiesen, S. Brezinsek, M. Wischmeier, E. De la Luna, M. Groth, A. E. Järvinen, E. de la Cal, U. Losada, A.M. de Aguilera, L. Frassinetti, Y. Gao, C. Guillemaut, D. Harting, A. Meigs, K. Schmid, G. Sergienko and JET contributors, Impact of the JET ITER-like wall on H-mode plasma fueling, Nuclear Fusion **57** (2017) 066024.

13. H. Weisen, Hyun-Tae Kim, J. Strachan, S. Scott, Y. Baranov, J. Buchanan, M. Fitzgerald, D. Keeling, D.B. King, L. Giacomelli, T. Koskela, M.J. Weisen, C. Giroud, M. Maslov, W.G. Core, K.-D. Zastrow, D.B. Syme, S. Popovichev, S. Conroy, I. Lengar, L. Snoj, P. Batistoni, M. Santala and JET Contributors, The 'neutron deficit' in the JET tokamak, Nuclear Fusion **57** (2017) 076029.

14. L. Moser, R.P. Doerner, M.J. Baldwin, C.P. Lungu, C. Porosnicu, M. Newman, A. Widdowson, E. Alves, G. Pintsuk, J. Likonen, A. Hakola, R. Steiner, L. Marot, E. Meyer and JET Contributors, Investigation and plasma cleaning of first mirrors coated with relevant ITER contaminants: beryllium and tungsten, Nuclear Fusion **57** (2017) 086019.

15. P. Mantica, C. Bourdelle, Y. Camenen, R. Dejarnac, T. Evans, T. Görler, J. Hillesheim, Y. Idomura, M. Jakubowski, P. Ricci, A. White and The Participants to the 21st Joint EU-US Transport Task Force Workshop (incl. A. Salmi), Summary of 21st joint EU-US transport task force workshop (Leysin, September 5–8, 2016), Nuclear Fusion **57** (2017) 087001.

16. J. Marian, C. S. Becquart, C. Domain, S. L. Dudarev, M. R. Gilbert, R. J. Kurtz, D. R. Mason, K. Nordlund, A. E. Sand, L. L. Snead, T. Suzudo, B. D. Wirth, Recent advances in computational materials modeling of tungsten as plasma-facing material for fusion energy applications, Nuclear Fusion **57** (2017) 092008.

17. X. Litaudon at el. (incl. T. Ahlgren, L. Aho-Mantila, M. Airila, O. Asunta, C. Björkas, M. Groth, A. Hakola, K. Heinola, A. Järvinen, J. Karhunen, S. Koivuranta, T. Koskela, T. Kurki-Suonio, A. Lahtinen, A. Lasa, J. Likonen, B. Lomanowski, J. Lönnroth, T. Makkonen, J. Miettunen, K. Nordlund, S.-P. Pehkonen, E. Safi, A. Salmi, M.I.K. Santala, J. Simpson, S.K. Sipilä, P. Sirén, T. Tala, J. Uljanovs, J. Varje and JET Contributors), Overview of the JET results in support to ITER, Nuclear Fusion **57** (2017) 102001.

18. S. Coda et al. (incl. A. Hakola, B. Lomanowski and the EUROfusion MST1 team), Overview of the TCV tokamak program: scientific progress and facility upgrades, Nuclear Fusion **57** (2017) 102011.

19. H. Meyer et al. (incl. A. Hakola, L. Aho-Mantila, J. Karhunen, T. Kurki-Suonio, A. Lahtinen, S.-P. Pehkonen, A. Salmi, J. Simpson, A. Snicker, T. Tala and the ASDEX Upgrade, MAST and TCV Teams), Overview of progress in European medium sized tokamaks towards an integrated plasma-edge/wall solution, Nuclear Fusion **57** (2017) 102014.

20. S. Brezinsek et al. (incl. A. Hakola, T. Ahlgren, M. Airila, C. Björkas, K. Heinola, J. Karhunen, A. Lahtinen, A. Lasa, J. Likonen, T. Makkonen, J. Miettunen, K. Nordlund, J. Räisänen and WP PFC contributors), Plasma–wall interaction studies within the EUROfusion consortium: progress on plasma-facing components development and qualification, Nuclear Fusion **57** (2017) 116041.

21. J.M. Canik, A.R. Briesemeister, A.G. McLean, M. Groth, A.W. Leonard, J.D. Lore, A.L. Moser, Testing the role of molecular physics in dissipative divertor operations through helium plasmas at DIII-D, Physics of Plasmas **24** (2017) 056116.

22. A. Biancalani, A. Bottino, C. Ehrlacher, V. Grandgirard, G. Merlo, I. Novikau, Z. Qiu, E. Sonnendrücker, X. Garbet, T. Görler, S. Leerink, F. Palermo, and D. Zarzoso, Cross-code gyrokinetic verification and benchmark on the linear collisionless dynamics of the geodesic acoustic mode, Physics of Plasmas **24** (2017) 062512.

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120. Joona Kontula, Neutral beam injection simulations in the Wendelstein 7-X stellarator, MSc thesis, Aalto University, Espoo 2017.
121. Changyang Li, Design and analysis of robot for the maintenance of divertor in DEMO fusion reactor, MSc thesis, Lappeenranta University of Technology, Lappeenranta 2017.
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Title	**FinnFusion Yearbook 2017**
Author(s)	Jari Likonen and Markus Airila (Eds.)
Abstract	This Yearbook summarises the 2017 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 2017 focused on system level design for ITER Remote Handling Connector and remote diagnostics application software development. In 2017, FinnFusion organized three major fusion events in Finland: • EUROfusion Joint Working Session for Integrated Plasma-Wall Modelling, Tervaniemi, in February, • The 2nd Joint Nordic Fusion Seminar, Espoo, in June, • ITER Tokamak Physics Activity (ITPA) meeting for the transport and pedestal groups, Espoo, in September. Altogether, these events attracted about 200 participants from all over the world. EUROfusion supports post-graduate training through the Education work package that allowed FinnFusion to partly fund 13 PhD students in FinnFusion member organizations. In addition, three EUROfusion post-doctoral research and engineering fellowships were running in 2017.
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Nimeke	**FinnFusion-vuosikirja 2017**
Tekijä(t)	Jari Likonen ja Markus Airila (toim.)
Tiivistelmä	Tähän vuosikirjaan on koottu FinnFusion-konsortion vuoden 2017 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. FinnFusion järjesti Suomessa vuoden 2017 aikana kolme merkittävää fuusioalan tapahtumaa: • EUROfusion Joint Working Session for Integrated Plasma-Wall Modelling (Tervaniemessä helmikuussa), • The 2nd Joint Nordic Fusion Seminar (Espoossa kesäkuussa), • ITER Tokamak Physics Activity (ITPA) meeting for the transport and pedestal groups (Espoossa syyskuussa). Yhteensä näissä tapahtumissa oli noin 200 osallistujaa eri puolilta maailmaa. EUROfusion tukee jatko-opiskelua omalla rahoitusinstrumentillaan, jonka turvin FinnFusion rahoitti osittain 13 jatko-opiskelijan työtä jäsenorganisaatioissaan. Lisäksi vuoden 2017 aikana oli käynnissä kolme EUROfusionin rahoittamaa tutkijatohtorin projektia.
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