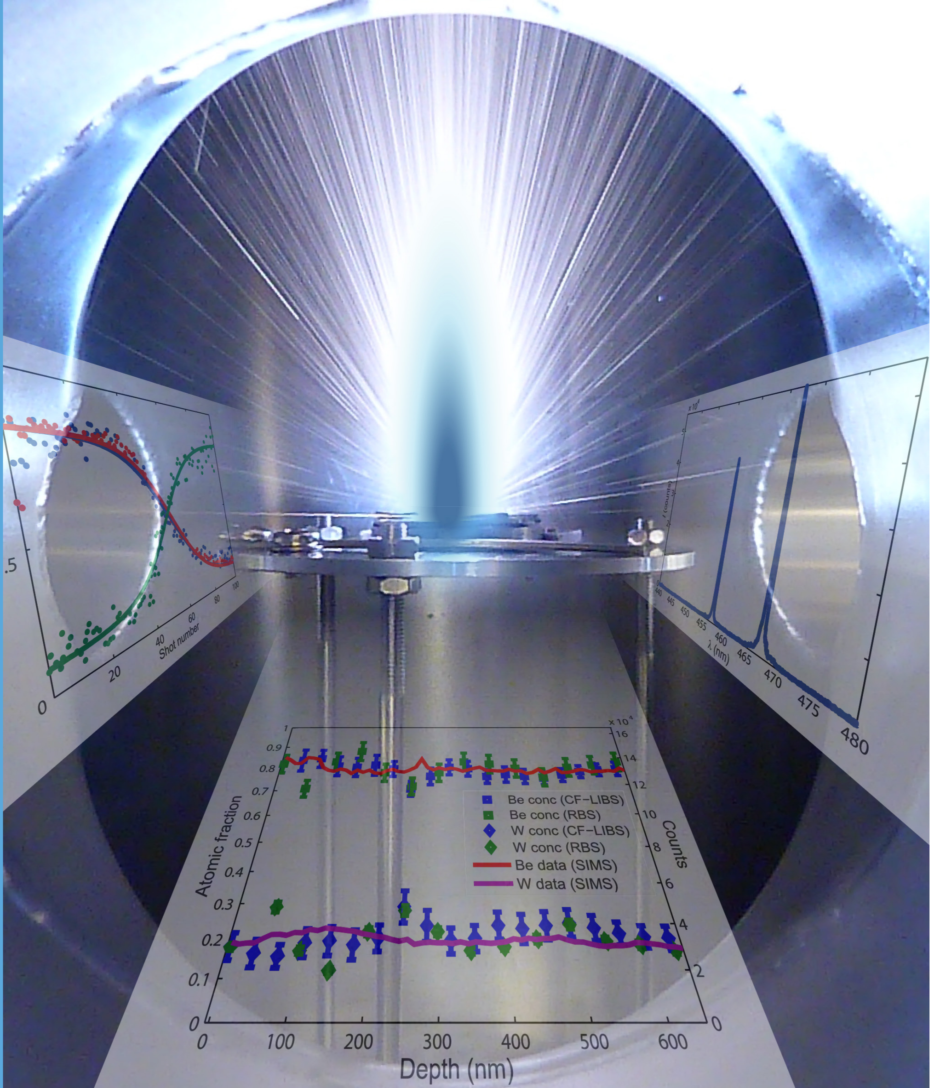

SCIENCE • TECHNOLOGY • RESEARCH HIGHLIGHTS • VISIONS •

30

Fusion Yearbook

Association Euratom-Tekes
Annual Report 2012

VTT SCIENCE 30

Fusion Yearbook

Association Euratom-Tekes
Annual Report 2012

Markus Airila & Antti Salmi (eds.)

This work was supported by EURATOM and carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

ISBN 978-951-38-7995-2 (Soft back ed.)
ISBN 978-951-38-7996-9 (URL: http://www.vtt.fi/publications/index.jsp)

VTT Science 30

ISSN-L 2242-119X
ISSN 2242-119X (Print)
ISSN 2242-1203 (Online)

JULKAISIJA – UTGIVARE – PUBLISHER

VTT
PL 1000 (Tekniikantie 4 A, Espoo)
02044 VTT
Puh. 020 722 111, faksi 020 722 7001

VTT
PB 1000 (Teknikvägen 4 A, Esbo)
FI-02044 VTT
Tfn. +358 20 722 111, telefax +358 20 722 7001

VTT Technical Research Centre of Finland
P.O. Box 1000 (Tekniikantie 4 A, Espoo)
FI-02044 VTT, Finland
Tel. +358 20 722 111, fax +358 20 722 7001

Cover picture: Juuso Karhunen. Flash of wit – a wide range of data can be extracted from the light emitted by an unknown sample in laser-induced ablation.

Kopijyvä Oy, Kuopio 2013

Fusion Yearbook
Association Euratom-Tekes Annual Report 2012

Fuusio-vuosikirja. Euratom-Tekes-assosiaation vuosikertomus 2012.
Markus Airila & Antti Salmi (eds.). Espoo 2013. VTT Science 30. 180 p. + app. 13 p.

Abstract

This Annual Report summarises the fusion research activities of the Finnish and Estonian Research Units of the Association Euratom-Tekes in 2012. The emphasis of the work coordinated by EFDA was in ITER Physics, PPPT and the ITM Task Force. Other EFDA activities in 2012 were carried within EU Topical Groups, Emerging Technology and in Goal Oriented Training. In addition, a significant fraction of Tekes activities was directed to F4E grants and ITER contracts.

Fusion physics work is carried out at VTT, Aalto University, University of Helsinki and University of Tartu. The main activities are plasma experiments in collaboration with tokamak laboratories, modelling with related code development, and diagnostics related to the main European fusion facilities JET and AUG. In particular, Association Euratom-Tekes focused on (i) Heat and particle transport and fast particle studies, (ii) Plasma-wall interactions and material transport in the scrape-off layer, and (iii) Code development and diagnostics.

The Association participated in the EFDA JET Workprogramme 2012, including C29-30 experiments with the ITER-like wall, diagnostics development and code integration. Three physicists were seconded to the JET operating team and one to EFDA CSU. The Association participated also in the 2012 experimental programme of ASDEX Upgrade at IPP and the analysis of DIII-D and C-Mod data.

Technology work is carried out at VTT, AU, Tampere University of Technology (TUT) and Lappeenranta University of Technology (LUT) in close collaboration with Finnish industry. Industrial participation is co-ordinated by Tekes. The technology research and development includes the DTP2 facility at VTT Tampere, materials and joining techniques, vessel/in-vessel components, magnetic diagnostics by micromechanical magnetometers for ITER, upgrading of the JET NPA diagnostics, Power Plant Physics and Technology (PPPT) activities, plasma facing materials issues, erosion/re-deposition and material transport studies and development of coating techniques.

Association Euratom-Tekes is involved in Goal-Oriented Training in Remote Handling project, coordinated by Tampere University of Technology. In July 2013 Aalto University will organize the 40th EPS Plasma Physics Conference in Espoo.

Keywords nuclear fusion, fusion energy, fusion research, fusion physics, fusion technology, fusion reactors, fusion reactor materials, ITER remote handling, Euratom

Fuusio-vuosikirja
Euratom-Tekes-assosiaation vuosikertomus 2012

Fusion Yearbook. Association Euratom-Tekes Annual Report 2012.
Markus Airila & Antti Salmi (eds.). Espoo 2013. VTT Science 30. 180 s. + liitt.13 s.

Tiivistelmä

Tähän vuosikirjaan on koottu Suomen ja Viron fuusiotutkimusyksiköiden vuoden 2012 tulokset ja saavutukset. Työ on tehty Euratom-Tekes-assosiaation puitteissa. EFDAn koordinoima työ keskittyi ITERin fysiikkaan, DEMOn fysiikkaan ja tekniikkaan (power plant physics and technology, PPPT) ja integroituun mallinnukseen (integrated tokamak modelling, ITM). EFDA-työtä tehtiin vuonna 2012 myös EU:n ajankohtaisten aiheiden työryhmissä (topical groups), uusien teknologioiden alalla (emerging technology) ja uusien asiantuntijoiden koulutuksessa (goal oriented training in remote handling, GOTRH). F4E-organisaation myöntämällä rahoituksella ja ITER-sopimuksilla on ohjelmassa merkittävä osuus.

Fysiikan tutkimusta tehdään VTT:llä, Aalto-yliopistossa, Helsingin yliopistossa sekä Tarton yliopistossa, ja se keskittyy plasmakokeisiin yhteistyössä tokamaklaboratorioiden kanssa ja niiden mallinnukseen. Assosiaation erityisiä painopistealueita ovat (i) Lämmön ja hiukkasten kuljetus ja nopeiden hiukkasten fysiikka, (ii) Plasma–seinämä-vuorovaikutukset ja materiaalien kulkeutuminen kuorintakerroksessa sekä (iii) Simulointiohjelmistojen kehitys ja diagnostiikka.

Vuonna 2012 Euratom-Tekes-assosiaatio osallistui EFDA-JETin koekampanjoihin C29-30, diagnostiikan kehitykseen ja simulointiohjelmien integrointiin. Kolme fyysikkoa toimi JETin käyttöorganisaatiossa ja yksi EFDAn tukiorganisaatiossa (close support unit, CSU). Lisäksi assosiaatio osallistui ASDEX Upgrade -tokamakin vuoden 2012 koeohjelmaan sekä DIII-D- ja C-Mod-tokamakien tulosten analysointiin.

Teknologiatyötä tekevät VTT, Aalto-yliopisto, TTY ja LTY tiiviissä yhteistyössä suomalaisen teollisuuden kanssa. Yritysten osallistumista koordinoi Tekes. Kehitettäviin teknologioihin kuuluvat DTP2-laitteisto VTT:llä Tampereella, materiaalit ja niiden liitostekniikat, tyhjiökammioon liittyvät komponentit, MEMS-pohjaisten diagnostiikkojen kehitys ITERin magneettikenttien mittausta varten, JETin NPA-diagnostiikan päivitys, osallistuminen PPPT-tutkimukseen, ensiseinämän materiaalit, eroosion, deposition ja materiaalien kulkeutumisen tutkimus sekä pinnoitteiden kehittäminen.

Heinäkuussa 2013 Aalto-yliopisto järjestää EPS:n plasmafysiikan konferenssin Dipolissa Espoossa.

Avainsanat nuclear fusion, fusion energy, fusion research, fusion physics, fusion technology, fusion reactors, fusion reactor materials, ITER remote handling, Euratom

Foreword

The year 2012 meant a change in Association Euratom-Tekes as the former and so far the only head of the research unit, Dr. Seppo Karttunen, retired. I want to express my deep gratitude to Seppo on behalf of the whole association and its scientists and engineers for successfully leading Association Euratom-Tekes for 17 years. I also want to thank him personally for the invaluable guidance on the subtleties needed to lead the association. This, together with the fact that we are already in the middle of the two years' extension 2012–2013 of the Euratom program with no major changes in the fusion research infrastructure guaranteed that no discontinuity occurred in the Finnish fusion activities in 2012.

In 2012, the emphasis of Association Euratom-Tekes programme was in the EFDA work programme and in the exploitation of the JET tokamak with its ITER-like Wall. Several tasks in the areas of ITER physics, PPPT (Power Plant Physics and Technology) and ITM (Integrated Tokamak Modelling) were carried out. In diagnostics, the NPA upgrade was commissioned in JET and an F4E Grant for magnetic diagnostics based on micro-mechanical sensors was continued. Post-mortem analysis of the JET first wall and divertor tiles and related plasma-wall studies continued under JET Technology Task Force.

Two Tekes scientists acted as deputy task force leaders (E2 and FT) for the ILW-experiments. In addition, Tekes provided three JOC secondees, one CSU secondee and a member to HLST (high level support team for high performance computing). Collaboration with the AUG team at IPP Garching continued in 2012 and has been very important and productive activity for several years. International activities included tokamak experiments in the US on C-Mod and DIII-D under IEA Implementing Agreement and members in two ITPA groups.

The second grant on the F4E work on ITER divertor maintenance development and testing on DTP2 test facility at VTT Tampere was finished in 2012, and a new grant was signed for the further exploitation of the facility. Remote handling and methods and tools needed for reliability and availability design and assurance for DEMO have been actively studied under the EFDA department PPPT.

In Europe, a major effort was put in place in creating a document called "The roadmap to the realisation of fusion energy to the grid by 2050". This roadmap will give a strong guidance to the Euratom Fusion Programme during Horizon 2020. As the Finnish fusion research is already now almost fully aligned with the present EFDA priorities, I am very confident that the Finnish fusion research will give a valuable contribution to the Euratom Fusion Programme, F4E and ITER also during Horizon 2020. Finally, I would like to express my most sincere thanks to Tekes and the scientists and engineers of the Finnish and Estonian Research Units for their excellent and dedicated work in fusion physics and technology R&D in 2012.

Tuomas Tala
Head of Research Unit,
Association Euratom-Tekes

Contents

Executive Summary

Overview

Highlights of fusion research carried out by the Association Euratom-Tekes in 2012 are given below. The main activities are plasma experiments in collaboration with tokamak laboratories, modelling with related code development, and diagnostics related to the main European fusion facilities JET and AUG. The emphasis in the EFDA work by Tekes was in ITER Physics, PPPT and the ITM Task Force. Other EFDA activities in 2012 were carried within EU Topical Groups, Emerging Technology and in Goal Oriented Training. A significant fraction of Tekes activities was directed to F4E grants and ITER contracts.

Confinement and transport

JET experiments utilising gas puff modulation technique were executed to study neutral fuelling of the plasma. Particle transport coefficients were extracted from the C27 L-mode plasmas and found to be independent of collisionality. In a single dedicated H-mode discharge in C29 the proof-of-principle density modulation in H-mode was observed giving impetus for further studies to be conducted in C31. [JET Orders and Notifications]

Momentum transport and sources were analysed and experiments were carried out on AUG and JET. The preliminary database analysis shows that the intrinsic torque is relatively small both in JET and AUG. Experiments to further improve the data quality are planned for 2013. Furthermore, data from selected non-NBI JET discharges have been processed to a state where they can be entered in a European intrinsic rotation database. [WP12-IPH-A04, JET Orders and Notifications]

Multi-scale investigations of drift-wave turbulence and plasma flows have been conducted with successful comparisons of measurements and full-*f* gyrokinetic simulations in FT-2 tokamak for DR spectra, mean equilibrium ExB flows, GAM amplitude and frequency, and transport diffusion coefficients. Investigation of properties of geodesic acoustic modes in TEXTOR using ELMFIRE has continued. Radial eigenmode of GAMs in rough agreement with analytic theory was found and this was observed to create relatively high local rotation shear values.

Energetic particle physics

The full orbit following capability of ASCOT has been utilized to study the effect of Test Blanket Modules (TBM) on fast ion confinement. A good agreement with the results of the OFMC and SPIRAL codes as well as with recent DIII-D experimental results was found. ASCOT was also used to assess the effect of changes in neutral beams and plasma impurities on neutral beam ion losses in JET-ILW. Losses from the upgraded neutral beams were found to be slightly reduced, and the plasma heating profiles were found to decrease slightly at plasma mid-radius and shift towards the axis and the edge. The effect of tungsten impurity on beam power deposition was found to be very small when the impurity density was assumed constant on flux surfaces. [JET Orders and Notifications, ITPA EPP activity]

Power and particle exhaust, plasma-wall interactions

Euratom-Tekes played the main role in the coordination and execution of experiments of JET C29–30, and in providing edge modelling expertise. Experiments included divertor detachment and impurity seeding in L-mode as well as the campaign C30c aiming at steady-state wall conditions before the removal of long-term samples. EDGE2D/EIRENE was used to assess the impact of the wall materials on the scrape-off layer and divertor performance, showing a 30–50 % reduction in radiated power and a corresponding increase in conducted power to the target plates, consistent with experiments in 2009 and 2011. EDGE2D/EIRENE H-mode simulations show that ELMs lead to transient sheath-limited phases in the SOL, enhancing W sputtering and penetration into the core. SOLPS simulations of JET L-mode plasmas show that drifts are the primary cause for in-out asymmetries in divertor temperature, density and impurity radiation. Finally, simulations of ^{10}Be migration with ASCOT revealed a possible Be impurity transport path from the limiter to the core and the scrape-off layer in a sequence of an inner-wall limited and an Ohmic diverted plasma scenario. [JET Orders and Notifications]

Surface analyses with SIMS and optical microscopy were completed for last carbon tiles from JET campaign C27. Complex, yet regular erosion/deposition patterns were observed on inner wall guard limiters, outer poloidal limiters and the upper dump plate ICRH antenna. It was estimated that the deuterium retention by all divertor tiles during 2007–09 is about 2 %, which is the same as the D retention observed during 2001–2004. [JET Orders and Notifications]

First wall erosion studies in ASDEX Upgrade continued in 2012. Campaign-integrated erosion profiles of dedicated markers of varying roughness were determined and they showed that rough coatings were eroded 4–8 times slower than smooth layers. Also, ERO simulations of erosion probe data exposed to AUG L-mode plasmas reproduced the measured erosion of W, C, and Ni markers. In H-mode a satisfactory agreement was achieved for W only. [WP12-IPH-A01]

Development of LIBS for in-situ characterisation of plasma-wall interactions continued in 2012. ITER-relevant Be-W samples were studied and the quantitative composition of an unknown sample could be determined with better than 5 % accuracy, as compared with the standard post mortem analyses. [WP12-IPH-A03]

Studies to compare two different tritium retention measurements were performed for JET divertor tiles. Both full combustion (FC) and accelerator mass spectrometry (AMS) proved to measure tritium efficiently and accurately in the plasma facing materials. Due to their inherent differences the two methods are, however, most useful in combination, especially when high and low tritium activities have to be measured. [JET Orders and Notifications]

Tungsten fuzz formation mechanisms were investigated with MD simulations, reproducing the experimentally found $t^{1/2}$ dependence of the fuzz layer thickness growth. Bubble formation and rupture are the key events in this fuzz formation onset. [WP12-IPH-A11]

Diagnostics

Commissioning of the new detector flange with thin silicon detectors for JET NPA diagnostic was completed and the performance was demonstrated during spring 2012 experimental campaign of JET. [JET Orders and Notifications]

ERO modelling with novel synthetic diagnostics supported the development of a SOL flow diagnostic for AUG. The spectroscopic measurement detects low-charge-state carbon originating from methane injection, and modeling is necessary in the interpretation of partly equilibrated particle velocities. [WP12-IPH-A01]

AUG fast ion measurement campaign was supported by participating in setting up the Fast Ion Loss Diagnostic probe and the activation probe of AUG. To this end, ASCOT was expanded to calculate neutron and other particle fluxes onto the probes and preparatory simulations were completed. [WP12-IPH-A09]

Modelling for ITER, code development and integration

ITER-relevant material mixing was investigated by generating sputtering and reflection data with MD for several Be/W/C compounds and implementing the data into the ERO code. In first simulations for ITER and JET the effect of new data on plasma-wall interactions remains modest. [WP12-IPH-A01, WP11-PWI-05]

In code development, a major effort was the complete rewriting the ASCOT code from scratch, using most modern programming standards, into a new version. ASCOT4 is now used for production runs alongside with the old ASCOT. A method was developed for combining time-dependent MHD modes and realistic 3D magnetic field, at the same time allowing orbit-following up to the first wall in either guiding-center or full-orbit formalism. [WP12-IPH-A09]

With the full f gyrokinetic global Elmfire code, a detailed agreement with mean equilibrium $\mathbf{E} \times \mathbf{B}$ flows, oscillating fine-scale zonal flows and turbulence spectra observed by a set of sophisticated microwave back-scattering techniques as well as a good fit of the thermal diffusivity data were demonstrated [WP12-IPH-A04]. Supporting numerical work included the derivation and implementation of an interpolation algorithm for momentum conservation in gyrokinetic PIC codes and enhanced memory handling of coefficient matrix construction in Elmfire. Elmfire is being modified in hybrid form including openMP and MPI features.

Work towards a highly standardized and sophisticated computing environment was continued within ITM, focusing on a fast ion sources from NBI (BBNBI), a module for calculating local fusion reaction source rates (AFSI), some synthetic diagnostics, and an ASCOT Kepler actor. In addition, ERO was interfaced with the ITM database. [WP12-ITM-EDRG, WP12-ITM-IMP3, WP12-ITM-IMP5]

Emerging technology and PPPT

N_2 seeded discharges were characterized in ASDEX Upgrade and JET in order to build an experimental basis for power exhaust predictions and the associated model validation. SOLPS simulations were prepared to describe these experiments, yielding radiation patterns and divertor in-out asymmetries qualitatively similar to those observed in the experiments. [WP12-PEX-01]

The formation and migration of vacancies in W was investigated with MD and DFT. The results show that vacancy formation close to W surface and in bulk is mainly driven by the H concentration, whereas temperature plays a strong role in the mobility of vacancies. [WP12-IPH-A11]

In the field of remote handling, the work focused on the development of efficient maintenance practices that can greatly improve the availability of a fusion power plant. The study produced recommendations on the establishing of an effective RAMI management process for the DEMO development work. [WP12-DAS-06, WP12-DTM-02]

Fusion for Energy and ITER

Manufacturing of a new MEMS magnetic field sensor continued, and processed silicon wafers were completed for wafer bonding. Sensor enclosure was designed and 3D modelled. Several prototype versions of the readout electronics were constructed and measurements were carried out with existing sensors up to 1.1 T flux density. Measured resolution in laboratory environment meets the specifications. [F4E-GRT-156]

The effect of 3D magnetic field perturbations on fast particle losses in ITER was investigated using ASCOT. Simulations suggest that the total power load to the wall depends strongly on the NTM perturbation amplitude, but remains below the design limits of the wall materials. No additional hot spots on the walls were observed. Simulations of the effect of TAEs indicate that the alpha particle wall power load will stay at the MHD-quiescent level but that alpha particles are quite strongly redistributed in the core plasma. The inclusion of the magnetic perturbation of ELM control coils (so far without plasma response) in the simulations made the magnetic field stochastic deep inside the pedestal. [F4E-GRT-379, ITPA EPP activity]

1. Overview of 2012 Activities

This Annual Report summarises the fusion research activities of the Finnish and Estonian Research Units of the Association Euratom-Tekes in 2012. The Estonian Research Unit was established by the Agreement between Tekes and the University of Tartu in 2007. The emphasis of the present EFDA is in exploiting JET, physics support for ITER and in DEMO activities coordinated by the EFDA department of Power Plant Physics and Technology (PPPT). In addition, Tekes Association participated in the Goal Oriented Training (GOT) programme, HPC Implementing Agreement and SERF studies under EFDA. ITER related technology R&D is an active area of research within the association and takes place under the responsibility of F4E – the European Domestic Agency for ITER (Joint European Undertaking for ITER and the Development of Fusion Energy – Fusion for Energy, Barcelona).

The activities of the Tekes' Research Unit are divided in the fusion physics under the Contract of Association and EFDA. The F4E R&D Grant work on magnetic diagnostics and the second F4E Grant for ITER divertor maintenance continued in 2012, and a new F4E Grant on modelling of fast ion wall loads in 3D geometry started in 2012. In addition, two direct ITER contracts on are on-going; one on the Divertor cassette locking system that will be tested on DTP2 test platform in practise before ordering all cassettes for ITER and another one on tritium dust studies.

The Physics Programme is carried out at VTT Technical Research Centre of Finland, Aalto University (AU), University of Helsinki (UH) and University of Tartu (UT, Estonia). The research areas of the Physics and EFDA Programme are:

- Heat, particle and momentum transport, fast particle physics and plasma edge phenomena
- Plasma-wall interactions and material transport in the SOL region
- Code development and HPC activities
- Diagnostics.

Association Euratom-Tekes participated actively in the EFDA JET Workprogramme 2012 preparing and participating in the experimental campaigns C29 and C30. Three persons were seconded to the CCFE operating team (JOC) in JET, a physicist in codes & modelling, a physicist in plasma diagnostics and a physicist in the plasma edge group. One person was seconded to EFDA-JET CSU being responsible for codes and modelling in the experimental department. Tekes provided two Deputy TFLs for JET TF-E2 and Fusion Technology. Practically all physics activities of the Research Unit are carried out in co-operation with other Associations with the focus on EFDA JET work, physics support for ITER and experimental programme of ASDEX Upgrade (AUG).

Several staff mobility visits of total 805 days took place in 2012. The visits were hosted by the Associations IPP Garching (429 days, MA Art. 1.2.b collaboration), JET/CCFE Culham (76 days), VTT (29 days), University of Innsbruck (26 days), University of Cyprus (20 days), DIFFER Rijnhuizen (18 days), ENEA Frascati (18 days), KTH Stockholm (12 days), FZ Jülich (5 days), IST Lisbon (3 days) and Uppsala University (2 days). Other staff mobility actions were EFDA meetings (PWI, ITM, FT, TGs; 93 days), ITPA meetings (27 days) and MIT US (9 days), GA San Diego (38 days) for IEA Large Tokamak experiments.

The Technology work is carried out at VTT and Tampere University of Technology (TUT) in close collaboration with Finnish industry. Industrial participation is coordinated by Tekes. The technology research and development is focused on the remote handling, fabrication methods for vessel/in-vessel and TF components plus some activities in ITER and JET diagnostics and JET Technology related to ILW:

- Divertor Test Platform (DTP2) at VTT in Tampere for remote handling of divertor maintenance and development of water hydraulic tools and manipulators and cassette locking systems
- Magnetic diagnostics based on micromechanical sensors (MEMS) for ITER
- Application of powder HIP method for fabrication of ITER vessel/in-vessel and TF components
- Plasma facing materials issues, erosion/re-deposition and material transport studies and developing coating techniques
- In-reactor mechanical testing and characterisation of materials under neutron irradiation
- Modelling of ripple losses and wall loadings for ITER
- Tritium dust studies for ITER
- Upgrading of the NPA diagnostics for JET
- Feasibility study for micromechanical magnetometers.

The two days Annual Fusion Seminar of the Association Euratom-Tekes was hosted by the University of Tartu in Estonia. 46 participants attended the seminar, and the invited speaker was Dr. Duarte Borba from EFDA presenting the EFDA programme. Tekes decided to continue the present fusion programme for the next two years 2012–2013 in harmony with the Euratom FP7 extension.

2. Fusion Programme Organisation

2.1 Programme Objectives

The Finnish Fusion Programme, under the Association Euratom-Tekes, 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:

- To develop fusion technology for the ITER project in collaboration with Finnish industry
- To provide a high-level scientific contribution to the accompanying Euratom Fusion Programme.

This can be achieved by close collaboration between the Research Unit and Finnish industry, and by strong focusing the R&D effort on a few competitive areas. Active participation in the JET and EFDA Work Programmes and accomplishing ITER technology development Grants by Fusion for Energy provide challenging opportunities for top level science and technology R&D work in research institutes and Finnish industry.

2.2 Association Euratom-Tekes

The Finnish Funding Agency for Technology and Innovation (Tekes) is funding and co-ordinating technological research and development activities in Finland. The Association Euratom-Tekes was established on 13 March 1995 when the Contract of Association between Euratom and Tekes was signed. Other agreements of the European Fusion Programme involving Tekes are the multilateral agreements: European Fusion Development Agreement (EFDA), JET Implementing Agreement (JIA), Staff Mobility Agreement and HPC Implementing Agreement. Tekes and the University of Tartu (Estonia) signed an Agreement in 2007 to establish the Estonian Research Unit under the Association Euratom-Tekes offering for Estonia a full participation in the European Fusion Programme. The fusion programme officer in Tekes

is Mr. Kari Koskela. The fusion related industrial activities were co-ordinated by Tekes. The Finnish Industry Liaison Officer (ILO) is Mr. Hannu Juuso from Tekes.

2.3 Research Unit

The Finnish Research Unit of the Association Euratom-Tekes consists of several research groups from VTT and universities. The Head of the Research Unit is Mr. Tuomas Tala from VTT (Mr. Seppo Karttunen until March 2012). The following institutes and universities participated in the fusion research during 2012:

1. VTT Technical Research Centre of Finland
   - VTT Materials for power engineering (co-ordination, physics, materials, diagnostics)
   - VTT Systems engineering (remote handling, beam welding, DTP2)
   - VTT Sensors and wireless devices (diagnostics)
   - VTT Energy systems (SERF)
2. Aalto University, School of Science
   - Department of Applied Physics (physics, code development, erosion)
3. University of Helsinki (UH)
   - Accelerator Laboratory (physics, materials)
4. Tampere University of Technology (TUT)
   - Institute of Hydraulics and Automation (remote handling, DTP2).

The Estonian Research Unit of the Association Euratom-Tekes consists of research groups from the University of Tartu. The Head of the Estonian Research Unit is Mr. Madis Kiisk from University of Tartu.

There are four Finnish persons in the ITER IO team, in Cadarache and three Finns in the F4E staff in Barcelona.

2.4 Association Steering Committee

The research activities of the Finnish Association Euratom-Tekes are directed by the Steering Committee, which comprised the following members in 2012:

Chairman	Vito Marchese, European Commission, Research DG
Members	Marc Cosyns, European Commission, Research DG
	Pentti Kauppinen, VTT
	Harri Tuomisto, Fortum Oy
	Kari Koskela, Tekes
	Kimmo Kanto, Tekes
Head of Research Unit	Tuomas Tala, VTT
Head of Estonian RU	Madis Kiisk, UT, Estonia
Finnish ILO	Hannu Juuso, Tekes
Secretary	Markus Airila, VTT

The Association Steering Committee (ASC) had one meeting in 2012 held in Tampere, Finland, 26 October 2012. Vito Marchese and Marc Cosyns from the Commission were present and Duarte Borba from EFDA CSU participated through the video link. All Finnish and Estonian ASC members except Harri Tuomisto participated in the meeting.

2.5 National Steering Committee

The national steering committee advises on the strategy and planning of the national research effort and promotes collaboration with Finnish industry. It sets also priorities for the Finnish activities in the EU Fusion Programme.

The research activities are steered by three Topical Advisory Groups for 1) physics and diagnostics chaired by Seppo Nenonen Oxford Instruments Analytical, 2) for materials research chaired by Ilkka Vuoristo, Luvata Oy and 3) for remote handling systems chaired by Olli Pohls, Hytar Oy. In 2012, the national steering committee consisted from the members of the three advisory groups.

Chairman	Janne Ignatius, CSC
Members	Henrik Immonen, Abilitas Group
	Hannu Juuso, Tekes
	Juhani Keinonen, HY
	Jukka Kolehmainen, Diarc Oy
	Mika Korhonen, Hollming Works Oy
	Risto Kuivanen, VTT
	Juha Lindén, Tekes/ELY
	Pasi Latva-Pukkila, Sandvik Underground Technology
	Timo Laurila, Tekes
	Seppo Nenonen, Oxford Instruments Analytical Oy,
	Pertti Pale, PPF Projects
	Olli Pohls, Hytar Oy
	Pentti Pulkkinen, Suomen Akatemia
	Reko Rantamäki, Fortum Oyj
	Solveig Roschier, Tekes

	Rainer Salomaa, Aalto University
	Pekka Siitonen, Metso Powdermet Oy
	Sisko Sipilä, Tekes
	Arto Timperi, Comatec Oy
	Pekka Tuunanen, Teknologiateollisuus ry
	Matti Vilenius, TUT/IHA
	Ilkka Vuoristo, Luvata Oy
Head of Research Unit	Tuomas Tala, VTT
Secretary	Markus Airila, VTT

The national steering committee had two meetings in 2012.

2.6 Finnish Members in the European Fusion Committees

- Rainer Salomaa is a member of Euratom Science and Technology Committee (STC).
- Reijo Munther, Tuomas Tala, Seppo Karttunen, (until 31 March 2012), Kari Koskela, Marco Kirm and Madis Kiisk are members of the Consultative Committee for the Euratom Specific Research and Training Programme in the Field of Nuclear Energy – Fusion (CCE-FU).
- Kari Koskela, Tuomas Tala and Madis Kiisk are members of EFDA Steering Committee.
- Jukka Heikkinen is a member of the Science and Technology Advisory Committee (STAC).
- Kari Koskela, Tuomas Tala, Rein Kaarli and Ergo Nõmmiste are members of the Governing Board for the Joint European Undertaking for ITER and the Development of Fusion Energy, “Fusion for Energy” (F4E GB).
- Herkko Plit is a member of the Executive Committee for the Joint European Undertaking for ITER and the Development of Fusion Energy, “Fusion for Energy” (F4E ExCo).

2.7 Other international duties

- Seppo Karttunen and Reijo Munther are members of the IEA Fusion Power Co-ordinating Committee (FPCC).
- Jukka Heikkinen is the Chairman of the International Programme Committee of the Plasma Edge Theory Workshop (PET).
- Taina Kurki-Suonio is the Chairman of the Local Organisation Committee on the 40th EPS Plasma Physics Conference, Espoo, Finland, July 2013.

- Tuomas Tala is a member of the ITPA expert group on transport and confinement. Taina Kurki-Suonio is a member of the ITPA expert group on energetic particles.
- Taina Kurki-Suonio is a member of the Programme Committee of the ASDEX Upgrade project, Max-Planck-Institut für Plasmaphysik.
- Salomon Janhunen is a member of the High Level Support Team for HPC-FF.
- Jukka Heikkinen is a Comments Editor of Physica Scripta.
- Markus Airila is the Tekes administrative contact person in EFDA JET matters.
- Markus Airila is The Tekes representative in EFDA Public Information Network (PIN).
- Hannu Juuso is an Industry Liaison Officer for F4E and Pertti Pale is a consultant for Fusion-Industry matters.
- Harri Tuomisto is a member of the Fusion Industry Innovation Forum Management Board (FIIF MB).

2.8 Public Information Activities

The Annual Report of the Association Euratom-Tekes, *Fusion Yearbook 2011,* VTT Science 7 (2012) 187 pp. was published for the Annual Seminar and distributed to Head of Research Units and key persons of the Euratom Associations, EFDA and F4E.

A combined press release on JET ITER-like wall results, the dissertation of Antti Salmi and the role of the Association in the European programme was distributed on 8 November 2012. Several online news services published the release:

- *VTT: Lupaavia tuloksia seuraavan sukupolven fuusioreaktorista*, 3T 8 November 2012.
- *VTT arvioi: Lupaavat tulokset voivat jouduttaa ITER-reaktorin fuusiokokeita*, Kauppalehti 8 November 2012.
- *Fuusioreaktori otti askeleen kohti kaupallistamista – saadut tulokset nopeuttavat aikataulua*, Talouselämä 8 November 2012.
- *JET-fuusiokoelaitteesta lupaavia tuloksia – parin vuoden päästä toiveena kymmenien megawattien teho*, Tekniikka & Talous 9 November 2012.

Also, Tekniikka & Talous reported the PhD work of Yongbo Wang (*Lappeenrannassa kehitetään robottia fuusiovoimalan rakentamiseen*, 11 December 2012).

Lecture course *Fusion energy technology* by J. Heikkinen, S. Karttunen and R. Salomaa was given in fall 2012 at the School of Science in the Aalto University.

Aalto University and VTT will host the 40th EPS Conference on Plasma Physics in Finland in July 2013. The venue is Dipole Congress Centre in Otaniemi Campus just a few kilometres from the downtown Helsinki.

2.9 Funding and Research Volume 2012

In 2012, the expenditure of the Association Euratom-Tekes was about € 5.05 million including Staff Mobility actions and F4E & ITER contracts (see Figure 2.1). The major part of the national funding comes from Tekes. The rest of the national funding comes from other national institutions, such as the Finnish Academy, research institutes and universities participating in the fusion research (VTT, Aalto, TUT, UH, LUT and UT) and from industry. The total research volume of the 2012 activities was about 50 professional man-years.

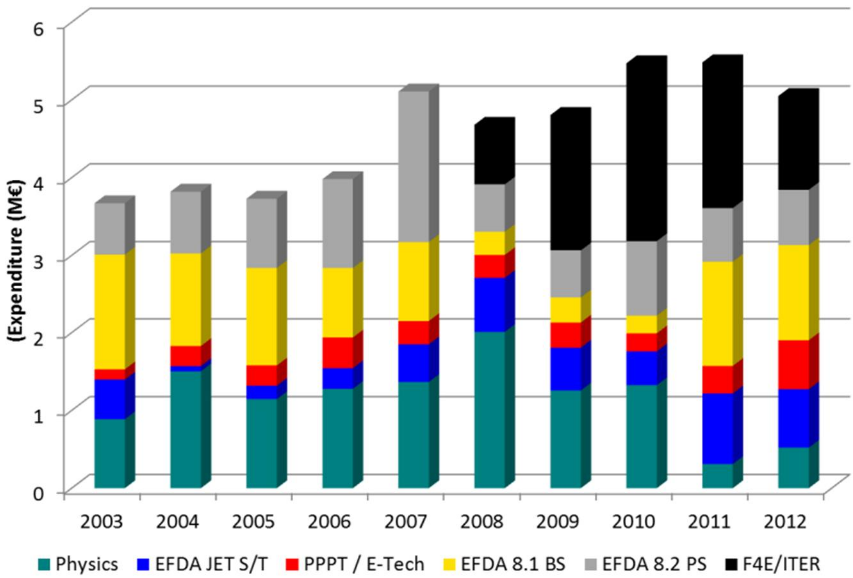

Figure 2.1. Expenditure (in Mio €) of the Association Euratom-Tekes for different physics and technology R&D activities in 2003–2012. The total expenditure was € 5.05 million. The EFDA 8.1 and 8.2 sections cover the participation in ITM, ITER physics and PWI Task Forces, Topical Groups and GOT as well as Staff Mobility.

3. EFDA Fusion Physics and Materials Research

Institute:	**VTT Technical Research Centre of Finland**
Research scientists:	Dr. Seppo Karttunen (Head of Research Unit until March 2012), Dr. Tuomas Tala (Head of Research Unit from April 2012), Dr. Leena Aho-Mantila, Dr. Markus Airila, Dr. Antti Hakola, Dr. Jukka Heikkinen (Project Manager), MSc. Seppo Koivuranta, Dr. Jari Likonen (Project Manager, Deputy TFL), Dr. Antti Salmi Students: Juuso Karhunen, Paula Sirén
Institute:	**Aalto University (AU) School of Science**
Research scientists:	Prof. Mathias Groth (Group leader, Deputy TFL), Prof. Rainer Salomaa (Head of Laboratory), Dr. Pertti Aarnio, MSc. Otto Asunta, MSc. Eero Hirvijoki, Lic.Sc (Tech.). Salomon Janhunen, MSc. Aaro Järvinen, Dr. Timo Kiviniemi, MSc. Tuomas Korpilo, MSc. Tuomas Koskela (JOC secondee), Dr. Taina Kurki-Suonio, Dr. Susan Leerink, Dr. Johnny Lönnroth (JOC/CSU Secondee), MSc. Toni Makkonen, MSc. Juho Miettunen, Dr. Marko Santala (JOC secondee), Dr. Seppo Sipilä, MSc. Antti Snicker, MSc. Simppa Äkäslompolo Students: Eetu Ahonen, Ville Lindholm, Tuuli Pyy, Ilmo Räisänen, Slawomir Simbierowicz
Institute:	**University of Helsinki (UH) Accelerator Laboratory**
Research scientists:	Prof. Juhani Keinonen (Head of Laboratory), Dr. Tommy Ahlgren, Dr. Carolina Björkas, Dr. Flyura Djurabekova, Dr. Kalle Heinola (JOC secondee), Dr. Krister Henriksson, MSc. Ane Lasa, MSc. Andrea Meinander, Dr. Lotta Mether, Prof. Kai Nordlund (Project Manager), Dr. Katharina Vörtler
Companies:	Diarc Technology

3.1 Introduction

VTT technical Research Centre of Finland, Aalto University School of Science and Helsinki University Department of Physics carried out the majority of fusion physics and materials research work in Association Euratom-Tekes. Major focus areas were the participation in the EFDA-JET and EFDA Workprogrammes. The year 2012 was marked by essential increase in the Association's manning in JET support positions: Three CCFE JOC positions and one CSU position were filled by Tekes scientists. In addition, two Task Force Leaders executed the experimental campaigns C29–30 and Fusion Technology programme, and 9 other researchers participated on-site in experimental or modelling work at JET. Further notification work related to the analysis of the 2011 campaign C28 and participation in the experimental programme 2012 of ASDEX Upgrade at IPP Garching was continued. Main research topics were plasma transport, exhaust and plasma-wall interactions, fast particle studies and diagnostics. The fusion plasma simulation groups at VTT, Aalto University and the University of Helsinki constitute an important modelling and support centre in fusion physics, code development & integration and plasma engineering for EFDA, F4E and ITER. In the field of plasma-wall interaction, the key competence is related to surface analyses of plasma-exposed samples and supporting computer modelling of erosion and material transport in the scrape-off-layer (SOL). Preparation of advanced coatings and wall diagnostics with smart tiles are carried out in collaboration with industry.

3.2 Energy and Particle Confinement and Transport

3.2.1 Momentum Transport Studies on JET, AUG and DIII-D

EFDA tasks:	WP12-IPH-A04-1-01, JET Orders and Notifications
Research scientists:	T. Tala, A. Salmi, VTT
Collaboration:	R. McDermott, C. Angioni, IPP Garching
	W. Solomon, PPPL

Recently, several tokamaks have shown that a significant inward momentum pinch exists. Numerous experimental results have been reported on individual devices – yet no dedicated multi-machine momentum transport experiments have been performed. Now we report on dedicated scans to study momentum transport that have been carried out on JET, DIII-D, AUG, NSTX and C-Mod within the International Tokamak Physics Activities (ITPA) framework. Quantifying the parametric dependence of the momentum and particle pinch on the density gradient length and collisionality υ^* (and possibly some other parameters as well) consolidates the extrapolation of the toroidal rotation for ITER.

The NBI modulation technique, which creates a periodic rotation perturbation, has been exploited on JET, DIII-D and AUG. The NBI modulation experiments have been carried out in different types of plasmas to study the parametric dependencies of momentum pinch and Prandtl numbers. Both in L-mode and H-mode plasmas with NBI modulation, ITGs are the dominant instability on JET, DIII-D and AUG. As the Prandtl number is defined as $Pr = \chi_\phi/\chi_i$, i.e. inversely proportional to the ion heat diffusivity, a comparison of the Prandtl number between different plasmas is unambiguous.

The standard method to carry out the dimensionless similarity experiment and to scan the collisionality was utilised in this experiment. The main idea is to vary collisionality while keeping the other dimensionless quantities, such as ρ^*, β_N, q and T_i/T_e, as constant as possible, i.e. by varying current, magnetic field and heating power in an adequate way. Within the 3-point scan both on JET and DIII-D, collisionality changes over almost a factor of 4 while the volume averaged ρ^* and β_N remain constant to about 10 % and 20 % accuracy, respectively. Both JET and DIII-D scans were performed in L-mode because the collisionality scan, while simultaneously keeping R/L_n constant, is not possible to carry out in H-mode plasmas due to the density peaking dependence on collisionality.

The averaged momentum pinch number (defined as $-R_0 v_{pinch}/\chi_\phi$) over $0.5 < \rho_{tor} < 0.8$ from the JET and DIII-D dimensionless collisionality scans after the detailed transport analysis does not depend on collisionality either on JET or on DIII-D. The pinch numbers are higher on JET than on DIII-D, most probably due to R/L_n being of the order 3 on JET and 2 on DIII-D in these pulses. This is an important result, both in view of extrapolating the magnitude of the pinch in ITER (ITER plasmas will have lower collisionalities than these experiments had) and in this study by excluding the effect of collisionality on momentum pinch number in any further analysis of the parametric dependences. Similarly, within this collisionality scan, the Prandtl number does not depend on υ^*. The dependence of the momentum pinch and Prandtl number on collisionality was also studied in linear gyro-kinetic simulations using the GS2 code. In JET, the simulations are fully consistent with the experimental results; neither momentum pinch nor the Prandtl number depends on collisionality.

The dependence of the pinch number on R/L_n obtained from JET, DIII-D and AUG NBI modulation shots is illustrated in Figure 3.1. The pinch number shows a clear dependence on R/L_n on each device separately and also as a joint database. In the right frame, a set of NSTX pulses with similar values of collisionality and q have been added with the points from the other tokamaks. Linear regression for the pinch number gives $-R_0 v_{pinch}/\chi_\phi \approx 1.2R/L_n$ both for JET and DIII-D, $-R_0 v_{pinch}/\chi_\phi \approx 1.5R/L_n$ for AUG and $-R_0 v_{pinch}/\chi_\phi \approx 0.6R/L_n$ for NSTX. The combined four tokamak dataset yields $-R_0 v_{pinch}/\chi_\phi = 1.1R/L_n + 1.0$ for the overall dependence. For the same set of data, it is evident that the Prandtl number does not depend on R/L_n as the scatter of the points from the three tokamaks is rather uniform.

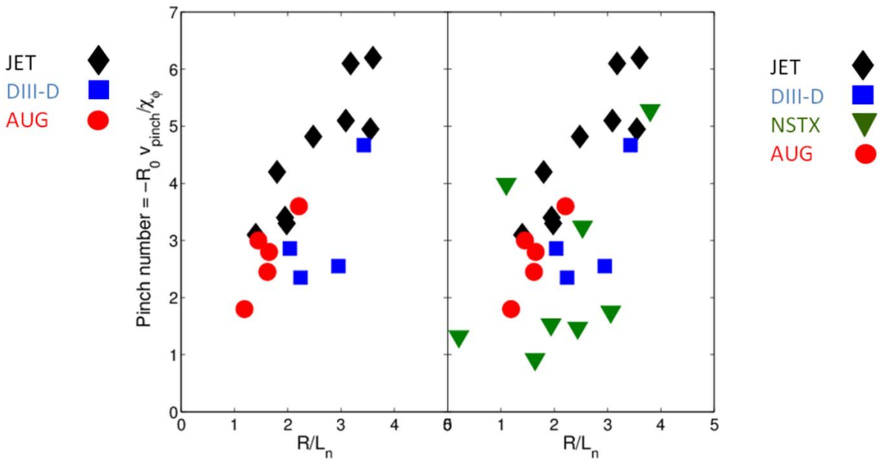

Figure 3.1. (Left frame) Pinch number as a function of R/L_n from JET (black diamonds), DIII-D (blue squares) AUG (red circles) from the NBI modulation shots. The data have been averaged between $0.4 < \rho_{tor} < 0.8$. (Right frame) As in left frame, but including data from NSTX (green inverted triangles) pulses with RMP coil perturbation.

The increase in the pinch number with increasing R/L_n is qualitatively consistent with theory and gyro-kinetic simulations, but quantitatively the simulations give roughly a factor of 2 weaker dependence than found in the experiments. The difference between the experiment and gyro-kinetic simulations is not fully understood. Momentum transport coefficients for all experiments in each device give quite similar dependences and trends, and therefore extrapolation to ITER seems fairly robust. The extrapolation of these results to ITER illustrates that with large enough R/L_n ($R/L_n > 2$) the pinch number becomes large enough (> 3–4) to make the rotation profile peaked provided that the edge rotation is non-zero. And this rotation peaking can be achieved with small or even with no core torque source.

3.2.2 Thermal ion influence on plasma rotation in Tore Supra and AUG

EFDA task:	WP12-IPH-A04-01-23
Research scientists:	A. Salmi, T. Tala, VTT
Collaboration:	C. Fenzi, CEA
	T. Pütterich, E. Viezzer, IPP Garching

There are several mechanisms how thermal ions are involved in generating torque into the plasma to make it rotate. Here two of them are studied.

Firstly, the 3D magnetic perturbation, TF ripple, which breaks the toroidal symmetry of the plasma, induces non-ambipolar radial transport of thermal ions. The torque arising from the non-ambipolar thermal ion radial on Tore Supra has been calculated with ASCOT for five discharges from a ripple scan (= plasma volume scan). Furthermore, fast ion torque from the 400 kW diagnostics NBI in presence of ripple has been calculated. The obtained counter current torque is found to increase both with the fast and the thermal ions and the total torque is seen to become negative at ripple levels exceeding 2 %. The observed monotonically decreasing plasma rotation with radius is consistent with the torque calculations: co-current torque from NBI in the core and counter-current torque near the edge due to ripple.

Secondly, thermal ion orbit losses cause an asymmetric velocity distribution near the separatrix and lead to finite toroidal rotation. ASCOT code is used to calculate the losses in realistic experimental magnetic configuration and with the measured plasma density and temperature profiles as well as the radial electric field. This is an ongoing work where a significant amount of the work has been used to set up the simulations to as realistic as possible and to validate the results in simple test cases. This has required implementing new particle initialisation methods and new diagnostics to resolve the poloidal variation in toroidal and poloidal boundary rotation. Initial collisionless simulations are qualitatively consistent with experimental observations in both the poloidal variation of the impurity density and poloidal and toroidal rotation. The work continues by adding collisions and enhanced phenomenological radial transport to set up quasi-steady state density profiles that remain as close to the experimental ones as possible.

3.2.3 Intrinsic torque studies on AUG and JET

EFDA tasks:	WP12-IPH-A04-1-03; WP12-IPH-A04-1-24
Research scientists:	T. Tala, A. Salmi, VTT
Collaboration:	R. McDermott, C. Angioni, IPP Garching
	W. Solomon, PPPL
	B. Duval, EFPL
	F. Nave, IST

The first ever set of intrinsic torque experiments were performed on AUG in 2012 by using the slow NBI modulation technique (2 Hz). The results showed that the compensated modulation (by varying the off-axis and on-axis NBI torque but keeping the total power constant) does not yield a rotation perturbation from which one can extract the intrinsic torque with small enough error bars. The uncompensated modulation at 2 Hz, on the other hand, does create a large enough perturbation.

A successful 3-point q-scan, a fair R/L_n scan, RMP test pulse and an ECRH scan were executed. Each shot included a phase with slow modulation for intrinsic torque part and a fast modulation for momentum transport part. Many shots had the noise level too high to be able to unambiguously determine the torque. Detailed analysis of existing data and the effect of measurement noise have given several concrete and feasible ways for optimising the experimental conditions, modulation waveforms, and diagnostics resolution to gain sufficient accuracy for future experiments. The initial analysis indicates that the intrinsic torque is mainly arising from the outer part of the plasma, and qualitatively ECRH seems to induce some torque in the plasma, most probably related to the change of ITG versus TEM micro-instability regime.

European intrinsic rotation database aims to collect toroidal rotation data from several European experimental devices to allow statistical study of the physical properties that control the rotation of the plasmas in the absence of external torque sources. The database will include also temperature and density data as profiles so that sources of free energy and momentum can be evaluated. The task reported here concerns putting best quality JET data into the database.

JET experimental database has been searched for discharges with no momentum input (NBI) but with rotation measurement, i.e. shots with only Ohmic/ICRH/LHCD heating applied but with NBI blips for rotation measurement. About 150 times of interest have been found (together with F. Nave) from about 50 different discharges. Rotation data from about one third of the shots have already been published while a large number of the rest are from F. Nave's parasitic experiments.

Scripts have been written to read the relevant profile and time trace data from the JET PPF system and to process the data into time averaged values/profiles over sensible time windows. EFIT has been rerun for all the times of interest to produce ≈ 150 g-eqdsk files containing the 2D magnetic equilibrium data. Most of the relevant data has been collected and processed to a state where it can be uploaded into the MDS+ tree once it is opened and its details have been released.

3.2.4 Poloidal rotation prediction

EFDA task: WP12-IPH-A04-1
Research scientist: J. Heikkinen, VTT

Large-scale mean **E** × **B** flows, fine-scale zonal flows and turbulent transport in ohmic discharges in the small Russian FT-2 tokamak have been investigated with the full-*f* particle-in-cell (PIC) code Elmfire. Direct measurements of transport phenomena in ohmic FT-2 discharges have been shown to be quantitatively reproduced by the Elmfire simulation predictions. A detailed agreement with mean equilibrium **E** × **B** flows, oscillating fine-scale zonal flows and turbulence spectra observed by a set of sophisticated microwave back-scattering techniques as well as a good fit of the thermal diffusivity data are demonstrated. The measured and simulated mean equilibrium **E** × **B** flows were validated against various analytical models where the effect of the T_e/T_i ratio, ion orbit loss current and impurities were investigated in more detail. It was found that the impurity ratio is modifying both the oscillating and background radial electric field significant while the effect of the ion orbit loss current diminished when turbulence was included in the simulations. Statistical and correlation analysis of the oscillating fine-scale zonal flow and density perturbations were compared to geodesic acoustic mode estimates.

3.2.5 Full-f gyrokinetic simulation of experimental H-mode conditions for middle-sized tokamaks

EFDA task: WP12-TRA-01-01
Research scientist: T. Kiviniemi, AU

Simulation of properties of GAMs for TEXTOR L-mode and H-mode plasmas has continued. In Figure 3.2a and b, the electric field oscillations as a function of time and radius are shown for L-Mode and H-mode data. Here, the values are normalized to mean value in each radius in order to illustrate the phase of the oscillatory behavior in each position. For L-mode case, clear GAM oscillation with phase shift of π over 2 cm is seen in figure which is in rough agreement the analytic theory [S.-I. Itoh et al., Plasma Phys. Controll. Fusion **49** (2007) L7] for which the radial mode is Airy function with characteristic scale of λ = 0.9 cm (the wave length is few times λ). For H-mode case the results are not that clear as GAM oscillation is much weaker and no clear radial eigenmode is seen.

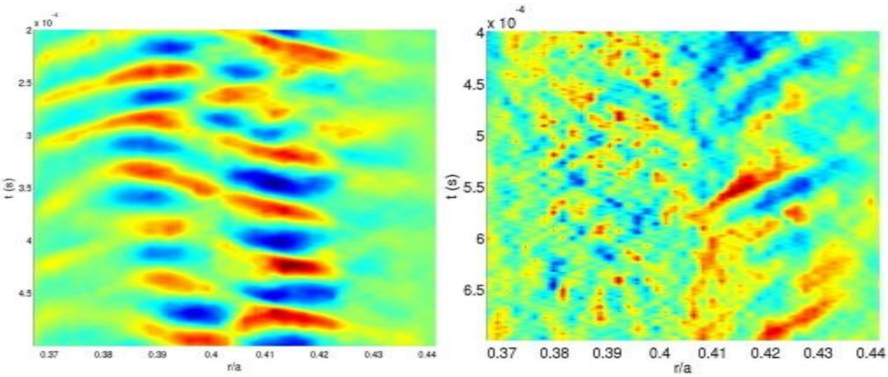

Figure 3.2. (a) Clear GAM oscillations in L-mode case are seen; (b) In H-mode case the temporal behavior of $\mathbf{E}_r$ is obscure.

As clear GAM oscillations are seen in L-mode case and also in some AUG experiments before L–H transition it is of interest to look at the **E × B** shear values due to radial eigenmode of the oscillation. In Figure 3.3, **E × B** values are shown to achieve values up to 10^6 s^{-1} which already exceeds the BDT-criterion for strong turbulence suppression for typical values. This occurs locally over range of typical radial decorrelation length of turbulence and over time which well exceeds the typical decorrelation time of turbulence. Thus, we may speculate if this shear due to phase shift has a role in triggering of L–H transition.

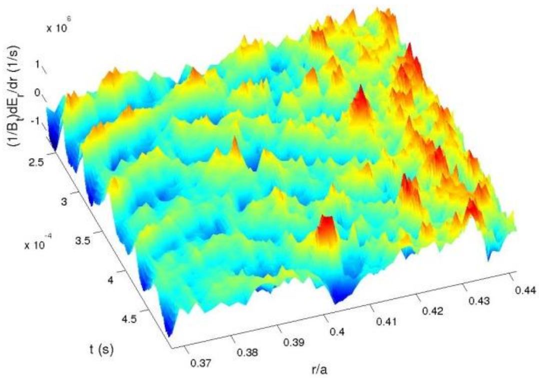

Figure 3.3. Locally high **E** × **B** values due to radial phase difference of GAM oscillations are observed in L-mode case.

3.2.6 JET and JT-60U current profile modelling with identity plasma experiments

EFDA task:	WP12-ITM-ISM-ACT2-02
Research scientists:	P. Sirén, T. Tala, A. Salmi, VTT
Collaboration:	X. Litaudon, CEA
	JET EFDA Contributors

Plasma current is the most important key to good confinement properties in tokamak-type fusion devices. Steady-state operation requires production of the plasma current primarily by external current drive methods such as neutral beam injection (NBI) and radio frequency waves, and especially utilizing the self-generated neoclassical bootstrap current originated from pressure gradients.

Retaining of the reverse shape of the *q* profile, i.e., the ratio of the toroidal and poloidal magnetic fields, and keeping the current out of the tokamak plasma centre, are connected to triggering an internal transport barrier (ITB) which decreases turbulence and improves confinement. The focus of this work is to analyze and clarify the plasma properties of identity shots in two large tokamak devices JET in UK and JT-60U in Japan on the basis of identity plasma experiments in advanced tokamak scenarios.

Plasma current density simulations of JET and JT-60U shots for identity plasma experiment in reverse-*q* advanced scenarios have been performed by continuation for the experimental analysis. The main differences between the discharges of JET and JT-60U were neutral beam current density (j_{nbi}), electron density (n_e) and *q*-profile. In JET, j_{nbi} is peaked on-axis whereas in JT-60U it is peaked off-axis (at $\rho = 0.5$) while the NBI fraction of the selected discharges is the same (22–24 %). A strong density ITB appeared (at $\rho = 0.5$) in JT-60U but not in JET. The reversed *q*-profile was obtained at the beginning of each discharge, and it was sustained in JT-60U while it became flat in JET towards the end of discharge.

The reasons for the different time evolution of the q-profile have been studied by predictive current simulations with the 1.5-dimensional transport code JETTO. The current diffusion model was validated against reverse-q discharges (JET #74740, JT-60U #49469), and simulations were performed with experimental profiles, j_{nbi} given by ASCOT and neoclassical resistivity and bootstrap current (j_{bs}) calculated by NCLASS. The simulations concentrate on sorting out the effects of the non-ohmic current components, in particular the significance of the electron density gradients in the bootstrap current fraction. The time evolution of the current components (ohmic, NBI, and bootstrap) has been studied and steady-state condition of the critical bootstrap current density has been used.

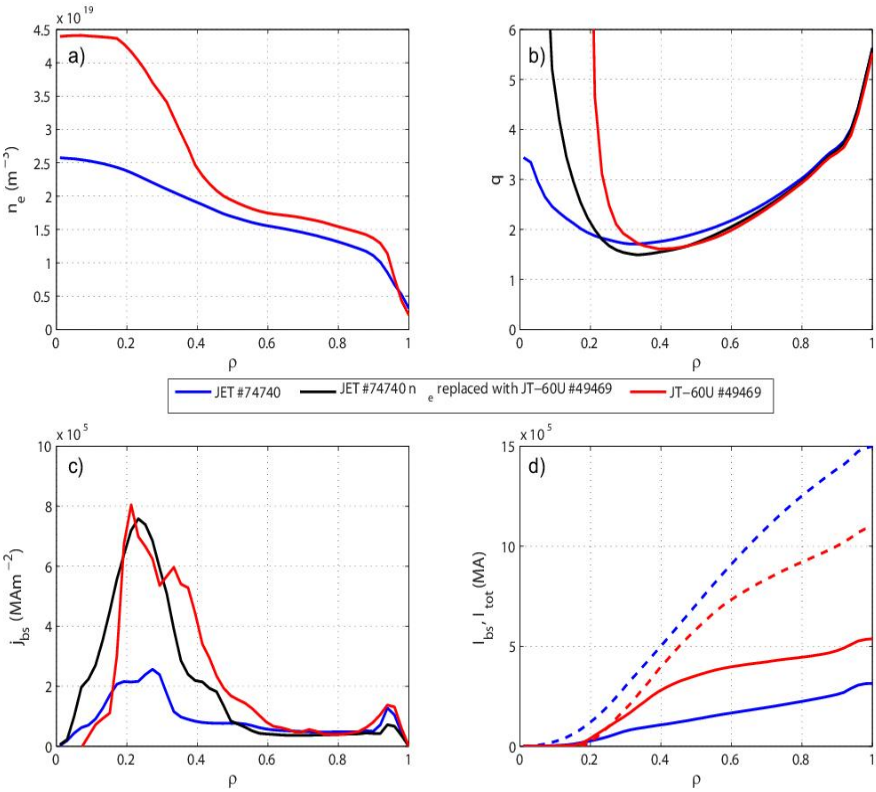

Figure 3.4. Electron density (a), q (b), bootstrap current density (c) bootstrap (solid) and total plasma current (dash) profiles (d) in experimental and simulated (electron density replaced) cases in the later phase (JET t = 6.0 s, JT-60U t = 6.5 s). Red: JT-60U #49469, Blue JET #74740, Black JET #74740 with replaced electron density from JT-60U.

The impact of different radial profile of j_{nbi} has been simulated by replacing the experimental profile in JET with a profile from JT-60U and vice versa. Based on the simulations, the influence of different j_{nbi} is negligible on the behaviour of the q-profile.

The effect of j_{bs} (driven by n_e gradients) or added external current source terms were also studied. In addition, the j_{bs} condition has been analysed with the experimental and simulated cases. Larger bootstrap fraction f_{bs} (in JET less than 30 % but in JT-60U 45–75 % which can be estimated in Figure 3.4d) and the different alignment of j_{bs} (in Figure 3.4c) have a more significant effect on the q-profile (in Figure 3.4b). In JT-60U the density gradient is 10 times larger than in JET in ITB region (profiles presented in Figure 3.4a). Replacing the JET n_e profile with the one from JT-60U leads to an increase of f_{bs} from 15 % to 30 %. Achieving higher j_{bs} and f_{bs} is easier to satisfy also with a smaller n_e gradient in JT-60U (the JT-60U n_e profile yields an f_{bs} between 23–33 % in JET, and in JT-60U f_{bs} = 25–40 % with the JET profile). The main difference between JET and JT-60U is the bootstrap fraction which causes a larger need for ohmic current in JET than in JT-60U (shown in Figure 3.4d). By studying the steady-state possibilities with 10–15 long-second simulations, stationary q profile (defined by stationary-located minimum q value and magnetic shear) is achieved in JT-60U but in JET the reverse shape disappears during the experimental pulse length.

3.2.7 Particle transport studies on JET

EFDA task:	JET Order
Research scientists:	T. Tala, A. Salmi, VTT
Collaboration:	A. Sirinelli, CCFE/JET

Fuelling and density peaking are one of the major concerns and uncertainties in ITER physics extrapolation in the area of core tokamak physics. There were two separate activities on the particle transport front in JET. More detailed analysis of the past L-mode data and a new test exploiting the gas puff modulation technique in H-mode plasma. The initial analysis of the dimensionless collisionality scan in L-mode plasma shows that the particle pinch does not depend on collisionality. This result is consistent with the previous result based on a database analysis of density peaking. The comparison of this work with the gyro-kinetic simulations is on-going.

The gas puff modulation technique was tested for the first time in H-mode plasma. The main goal was to see a proof-of-principle whether the gas puff modulation method is a feasible way to study edge particle transport in H-mode plasmas. This would be a very useful tool to study pedestal particle transport and neutral fuelling. On ITER, the default assumption is that the large pedestal optical thickness to neutrals precludes efficient fuelling, thus making a pellet injector essential for fuelling. However particle and impurity pinches have been identified in the core plasma hence there is enough ground to suspect non-convective inward transport other than neutral influx. The initial tests are promising and show that a density perturbation is created by the gas puff modulation and therefore, new experiment using this technique will be carried out on JET in autumn 2013.

3.3 Power and Particle Exhaust, Plasma-Wall Interactions

3.3.1 Overview

Research activities in 2012 in the field of power and particle exhaust and plasma-wall interaction had a strong focus on the exploitation of the ITER-like wall of JET. In addition, the participation in the ASDEX Upgrade experiments continued. The work consists of experiment planning, coordination and execution, surface analyses of plasma-exposed samples and computer modelling of the SOL as well as erosion, global and local material migration. Active code development (reported in section 3.6) supports the modelling work.

3.3.2 Material transport and erosion/deposition in the JET torus

3.3.2.1 Post mortem analysis and modelling of erosion/deposition on first-wall components

EFDA-JET task: JW12-FT-3.71

Research scientists: J. Likonen, P. Coad, A. Hakola, S. Koivuranta, M. Airila, VTT
J. Keinonen, K. Mizohata, UH
A. Widdowson, K. Heinola, JET-CCFE
J. Kolehmainen, T. Haikola, S. Tervakangas, DIARC-Technology

Background: Since 2001 an extensive analysis program has been going on under the JET Task Force Fusion Technology to investigate erosion, material transport and deposition in the JET torus using various surface analysis techniques. Several sets of divertor and wall tiles have been studied in three different divertor geometries: MkII-GB (Gas Box, 1998–2001), MkII-SRP (Septum Replacement Plate, 2001–2004) and MkII-HD (High Delta, 2005–2009). During these different configurations, JET has been operated with CFC as the plasma-facing material. Deposition in the divertor region has been highly asymmetric during each case, with heavy deposition at the inner divertor but just small net erosion at the outer divertor. Analyses of the tiles removed from the vessel during every shutdown form the basis of our knowledge on the plasma-wall interaction mechanisms at JET. The carbon wall was removed during the 2009–2011 shutdown and the CFC tiles were replaced with solid beryllium tiles in the main wall and with tungsten coated CFC tiles at the divertor.

Main results in 2012: In 2012, analysis of the remaining main wall carbon tiles has been completed and a set of inner wall guard limiter (IWGL), outer poloidal limiter (OPL), upper dump plate and ICRH antenna tiles removed in 2010, were characterized using Secondary Ion Mass Spectrometry (SIMS) and optical microscopy. In addition, investigation of local migration of ^{13}C in the Scrape-Off Layer (SOL) was finished.

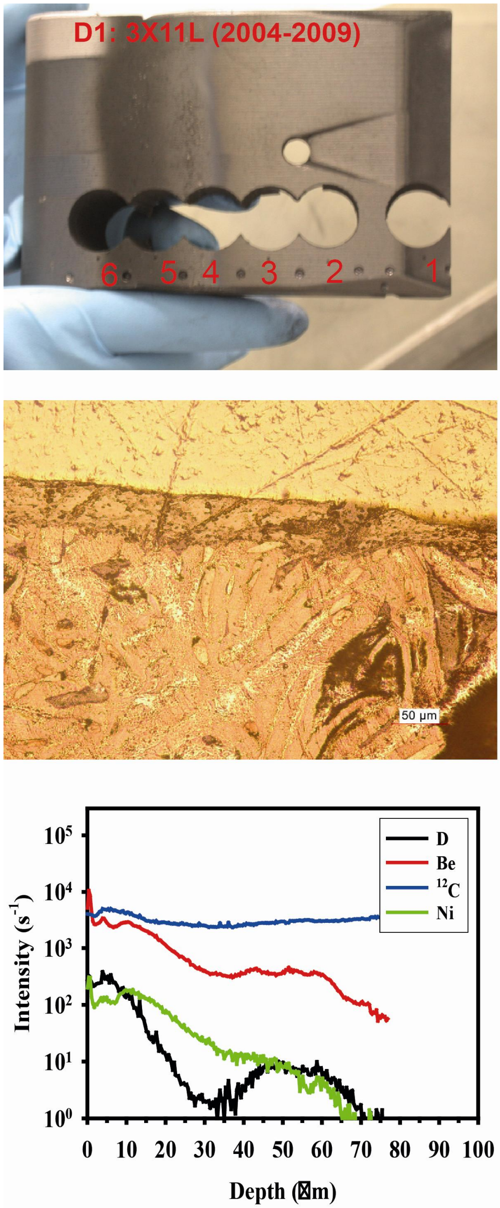

Figure 3.5. Photograph of IWGL tile 3X11L (top), optical microscope image (centre) and SIMS depth profiles (bottom).

Visual inspection of the Inner wall guard (IWGL) limiter (exposed in 2005–2009) shows that the general pattern of erosion/deposition is erosion on the left tile of the pair and deposition on the right tile at the top of the limiter, gradually changing to opposite at the bottom of the limiter. This general pattern has been shown previously for previous campaigns. Figure 3.5 shows a photo of IWGL tile 3X11L (located near the centre of the limiter), an optical micrograph from sample 5 and SIMS depth profiles from the same sample. The co-deposited layer with a thickness of ≈ 50 µm contains some D, Be and Ni as an impurity. Optical microscope data were also used for calibrating the tile profiler results.

The analysis of some limiter tiles surrounding the ICRH antenna clearly shows that for the ICRH tiles, there is a band of deposition on each side of the tile while the tile centre is relatively clean indicating erosion. The SIMS analysis confirmed that there is clearly Be deposition at each end, with low concentration in the middle of the tile. The D is at a reasonably low level, with no obvious peaking.

On the other hand, the tile profiling of upper dump plate tiles shows mainly erosion but in some areas SIMS results indicate that there is also a thin co-deposited layer (thickness < 5µm) which also contains D and Be (in addition to C).

Concerning the outer poloidal limiter (OPL) tiles, all of them have been cored and analysed but there is no clear-cut conclusion in terms of material migration and distribution. For most of the tiles there is a co-deposition zone at one end of the tile and an erosion zone in the centre containing D and Be, but this may vary depending on the location of the tile inside the vacuum vessel. For instance, contrary to the general observation, tile 8D1B from near the top of the limiter has a deposition zone both at the centre and at the ends. The plasma is never in contact with this tile; the maximum in deuterium probably arises from the centre of the tile being closer to the last closed flux surface (LCFS) and thus intercepting a higher impurity flux in the boundary region than the more distant ends of the tile.

Based on all the ion beam analysis and SIMS results, it was estimated that the deuterium retention by all divertor tiles during 2007–2009 is ≈ 2 %, which is the same as the D retention observed during 2001–2004. In fact, the total D retention during 2001–2004 (including limiters and remote areas) was estimated to be approximately 4 % with 2 % for the divertor region only. The main wall areas and remote areas for 2007–2009 will be evaluated in the follow-up task in 2013.

At the last day of the campaign C27 in 2009, an experiment was executed to provide specific information on material transport and SOL flows observed at JET. $^{13}CH_4$ was injected into the plasma boundary through 24 holes in a number of outer floor tiles 6 using one type of discharge only. ^{13}C deposition pattern was measured both with SIMS and Rutherford backscattering Spectroscopy (RBS). In 2012, data analysis of local ^{13}C migration was completed. A strong toroidal deposition band for ^{13}C was observed on each of the analysed four tiles 6. In addition, ^{13}C was also found on the vertical edge of tile 5 and at the bottom of tile 5 facing the puffing hole. Local ^{13}C migration near the injection location was modelled with ERO. In the simulation, plasma density had a marked effect on deposition, and best agreement with the experimental results was obtained with a uniform plasma density of 1×10^{18} m^{-3}, considered to be compatible with (but not well constrained by) the Langmuir probe data. Figure 3.6a shows an experimental 2D map of the ^{13}C distribution, to be compared to the deposition pattern obtained with ERO (Figure 3.6b–c).

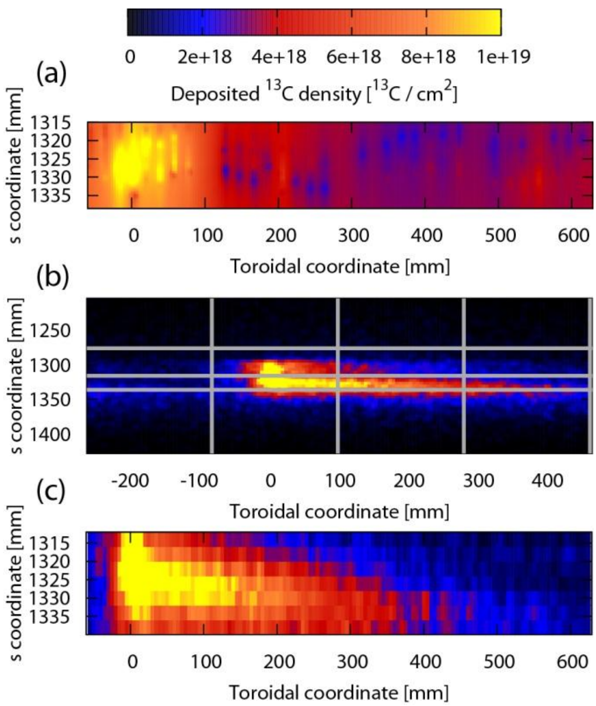

Figure 3.6. (a) Experimental deposition pattern for ^{13}C. The ^{13}C amount is in at/cm^2. Puffing hole is located at toroidal coordinate 0 mm and poloidal coordinate 1316 mm. (b) Deposition pattern of ^{13}C as simulated with ERO. Tile boundaries and edges are indicated with grey lines. The top row corresponds to the sloping part of tiles 5, the second row to the vertical part of tiles 5, the third row to the horizontal part of tiles 6, and the bottom row to the sloping part of tiles 6. Vertical lines indicate the tiles 6. (c) Magnified deposition pattern near the puffing hole.

3.3.2.2 Predictive ASCOT modelling of ^{10}Be transport in JET with the ITER-like wall

EFDA task:	JET Orders and Notifications
Research scientists:	J. Miettunen, M. Groth, T. Kurki-Suonio, S. Äkäslompolo, AU
	J. Likonen, VTT
Collaboration:	H. Bergsåker, KTH
	S. Marsen, IPP Greifswald
	C. Silva, IST

In 2011, JET started its operation in the ITER-like wall (ILW) materials configuration with beryllium in the main chamber and tungsten (W) in the divertor. One of the most important questions for investigation is how beryllium migrates within the main chamber, from the main chamber walls to the divertor and how the migration pattern compares to that of carbon. For studying beryllium migration, an isotopic marker experiment with ^{10}Be was carried out during the 2011–2012 experimental campaign on JET. Three adjacent central pieces of an inner wall guard limiter (IWGL) tile located poloidally above the inner midplane were enriched with ^{10}Be prior to their installation and, after shutdown, deposition of the eroded marker on selected plasma-facing components will be experimentally assessed using the accelerator mass spectrometry technique.

Simulations with the 3D orbit-following code ASCOT code were utilized to investigate the global migration pathways of ^{10}Be in plasma conditions representative of the beginning of the experimental campaign. In JET, plasma discharges are predominantly inner-wall limited during the start-up phase before the X-point formation, which in this study was assumed to be the dominant source of ^{10}Be erosion. Therefore, ^{10}Be migration was studied during a sequence of two plasma scenarios that represents transition from the start-up phase into flat-top operation.

The simulation was started in the limited scenario by following an ensemble of $^{10}Be+$ test particles that result from the ionization of neutrals being eroded uniformly from the enriched IWGL tile pieces containing the ^{10}Be marker. The ensemble represents ^{10}Be that is eroded during a time interval of 0.1 s at the end of the inner-wall limited phase and was followed until the ions were deposited or their maximum simulation time was reached.

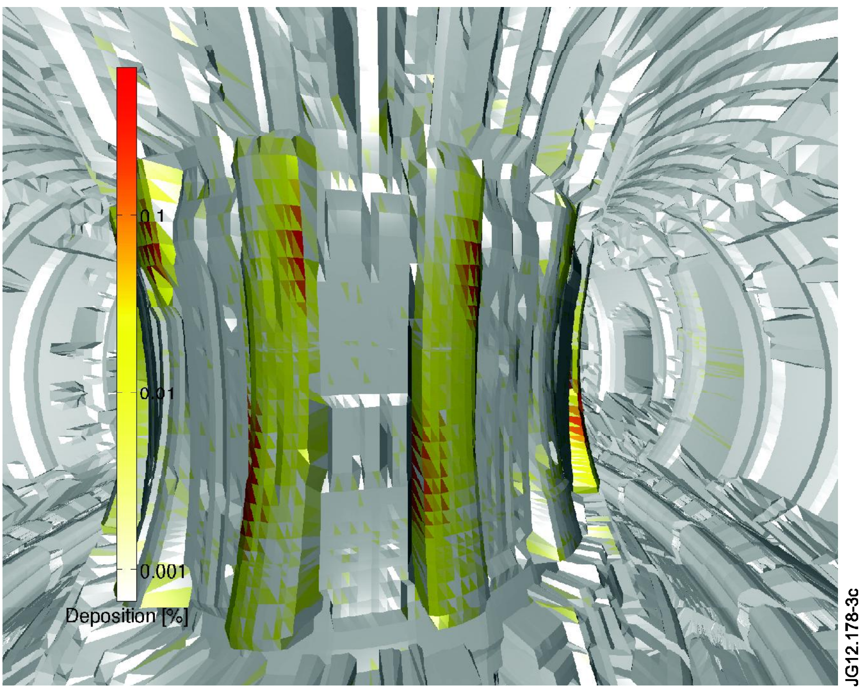

Figure 3.7. Visualization of ^{10}Be deposition during the inner-wall limited plasma phase. Localized deposition can be observed on the lower left and upper right edges of the inner wall guard limiters.

After the limited scenario, the simulation sequence was continued in the diverted scenario using the final state of the first simulation as the initial test particle ensemble. Particles that were deposited in the limited scenario were considered being eroded and all of the test particles were followed until their deposition.

In the limited scenario, the SOL plasma near the inner midplane is extremely thin and, consequently, most of the sputtered ^{10}Be neutrals were observed to be ionized in the core plasma. For the particles that diffuse out of the confined core, the simulation showed strong transport back towards the inner wall. On the IWGLs, ^{10}Be deposition was observed to be localized around two locations on most of the IWGLs, i.e., on the lower left and the upper right edges, as seen in Figure 3.7. The result bears resemblance to observations from experimental post-mortem studies of PFCs in JET during previous campaigns. On analyzed IWGL tiles, the same locations as indicated by the simulation have been observed to be areas of net deposition.

Particles that meet their maximum simulation time before deposition (27 %) were observed to remain scattered in the core plasma. Therefore, when considering ^{10}Be migration during the diverted scenario, it is noticeable that a significant fraction of the eroded ^{10}Be can exist in the core plasma before X-point formation.

When the simulation was continued in the diverted scenario, the particles that were considered being eroded from their deposition locations on the IWGL tiles were mainly either locally re-deposited at the inner wall or being transported by the background plasma flow towards the inner divertor leading to strong deposition there. For particles initialized in the core plasma, it is important to notice that due to, e.g., trapped orbits, their cross-field diffusion into the SOL is strongest in the low-field side. There, the followed ^{10}Be particles were predominantly deposited on the outer poloidal limiters and other protruding wall structures and on the outer divertor.

The identified migration pathways indicate two competing mechanisms that lead to ^{10}Be deposition in the high-field and low-field sides, respectively: plasma flow driving particles most strongly towards the inner divertor, and transport in the core plasma which effectively produces a particle outflux to the low-field side SOL.

3.3.2.3 Migration of beryllium from the main chamber onto the inner divertor

After the installation of the ITER-like wall at JET, it was anticipated that eroded beryllium from the main wall is transported to the tungsten divertor and form mixed-material deposits as soon as plasma operation commenced. To investigate this process, the operation with the ITER-like wall was initiated with a long series of identical Ohmic discharges. The migration was followed up in monitoring discharges which had an Ohmic phase in identical plasma shape and plasma conditions [S. Brezinsek et al., J. Nucl. Mater., accepted; J.W. Coenen et al., Proc 24th IAEA FEC 2012]. This allows determining the characteristic time constants for the formation of a stationary equilibrium of wall sources. The characteristic times were found to be comparable to those in pre-ILW experiments using heavy Be evaporation [K. Krieger et al., J. Nucl. Mater., accepted].

In 2012, Be erosion from the main wall, Be migration into the divertor and its deposition on W in the initial operation phase are modelled with the 3D Monte Carlo impurity transport code ERO. The simulation covers the inner wall and the inner divertor. To generate the plasma background for MC tracing of impurity particles we used the OSM code and a wall-conforming grid, which allows reproducing closely the measured plasma conditions close to material surfaces ($T_{e,IT}$ ≈ 5–10 eV, $n_{e,IT}$ ≈ 2–4 × 10^{19} m^{-3}). The formation of potentially significant mixed materials, in particular Be_2W, was investigated by applying for the first time the upgraded surface model of ERO with plasma-surface interaction data for Be/W compounds in addition to pure elements. Initial results indicate that compound formation changes the gross erosion and deposition but the net effect remains small. We will continue the investigations by comparing the modelled impurity densities in the plasma and their temporal evolution to the spectroscopic BeII line (527 nm) and Z_{eff} measurements. The strength of the main chamber erosion source and the resulting plasma beryllium content are the key parameters that define the Be divertor deposition, resulting from Be impurity transport in the edge and divertor plasma.

3.3.2.4 Simulations of tungsten transport in the edge of JET ELMy H-mode plasmas using EDGE2D/EIRENE and DIVIMP

EFDA task: JET Orders and Notifications

Research scientists: A. Järvinen, M. Groth, J. Lönnroth, AU

Collaboration: S. Wiesen, M. Lehnen, JET/FZ Jülich
M. Beurskens, G. Corrigan, C. Giroud, E. Havlickova, JET/CCFE
D. Moulton, CEA
D. Tskhakaya, University of Innsbruck
T. Eich, IPP Garching
J. Strachan, PPPL
P. Belo, IPFN Lisbon
S. Jachmich, ERM Brussels

Introduction: Tungsten plasma facing components (PFCs) are foreseen in the divertor of ITER during the activated operational phase due to low fuel retention in the bulk material and absence of co-deposition. While tungsten is resilient against sputtering in semi-detached plasma conditions, edge-localized modes (ELMs) and plasma impurities may lead to considerable tungsten erosion and contamination in the plasma centre, and, therefore, reduction of the plasma performance. Therefore, it is vital to understand tungsten erosion and transport processes in ELMy H-mode plasmas in order to reach the optimal performance in future fusion reactors.

This study numerically investigates tungsten erosion and scrape-off layer transport in JET type-I ELMy H-mode plasmas with the Monte-Carlo code DIVIMP on background plasmas dynamically evolved with the 2-D multi-fluid code EDGE2D/EIRENE for one of the highly shaped JET ITER-like wall reference plasmas: JET pulse number 76666, $B_\phi = 2.7$ T, $I_p = 2.5$ MA, $P_{in} \approx 16$ MW, $n_e \approx 0.8n_{GW}$, high triangularity $\delta \approx 0.4$, $f_{GW} \approx 0.8$, $f_{ELM} \approx 20$ Hz, $\Delta W_{ELM} \approx 200–300$ kJ. Based on a steady state EDGE2D/EIRENE solution, ELMs were modelled *ad hoc* by enhancing the cross-field transport for a short duration around the outer mid-plane. The model was adjusted to reproduce the experimentally measured drop in the confined energy of the plasma, as well as the ratio of the convective and conductive ELM losses. Two ELM durations were considered: 0.2 ms, and 1 ms. Based on the obtained plasma solutions, tungsten erosion and transport were modelled with DIVIMP, assuming erosion due to deuterium and 1 % C^{4+} contamination. The carbon contamination represents the presence of light impurities, such as carbon, beryllium, nitrogen, and neon, in the plasma. This work was presented at the 2012 PSI conference in Aachen in Germany, and the work was published in the Journal of Nuclear Materials in January 2013.

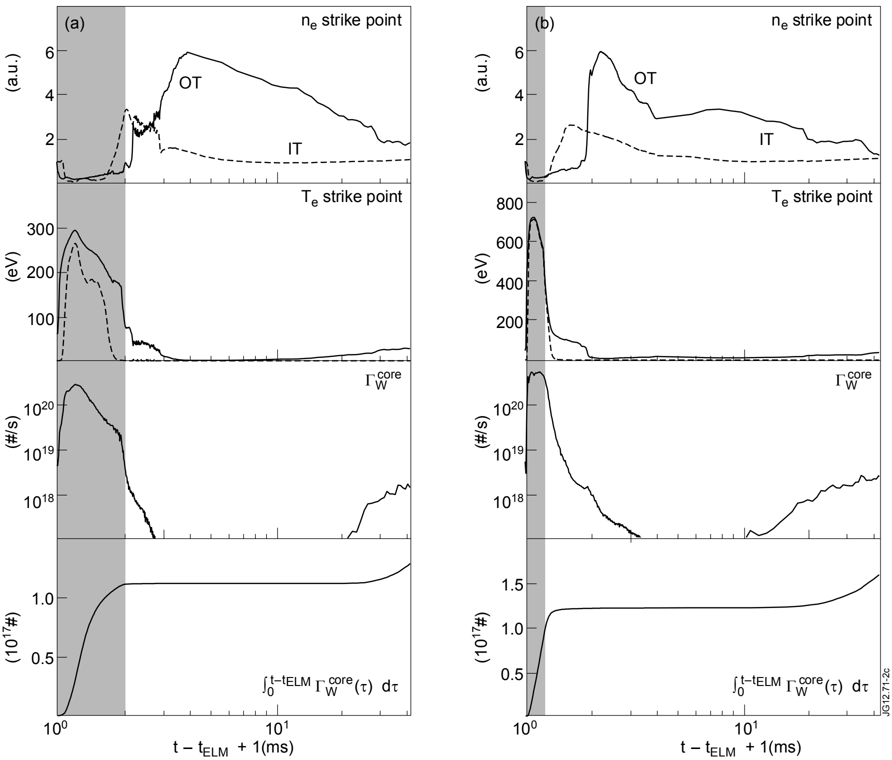

Figure 3.8. Time-traces of target electron densities and temperatures, as well as of tungsten influxes to the core plasma and the integrated tungsten influxes to the core plasma. In the target electron density and temperature figures, the solid lines stand for the outer target values (OT) and the dashed lines for the inner target values (IT). The a-column represents the simulated 1 ms ELM, and the b-column represents the 0.2 ms ELM. The ELM onset time slices are illustrated with the grey background shadings.

Main results: The simulations show that the integrated tungsten core contamination over an ELM cycle is strongly dominated by the ELM onset (Figure 3.8). Figure 3.8 represents time-traces of target electron densities and temperatures, core tungsten influxes, and the integrated tungsten influxes to the core over the two simulated ELM cycles. The a-column represents the simulated 1 ms ELM, and the b-column the simulated 0.2 ms ELM. The simulated ELMs lead to transient sheath-limited scrape-off layer plasma during the first few 100 μs after the ELM onset with target temperatures in excess of a few 100 eV, and densities approximately 5 times lower than the pre-ELM values (Figure 3.8). This sheath-limited phase leads to a significant increase of tungsten erosion and to a considerable drop of tungsten divertor retention, therefore, causing a dramatic increase in the tungsten influx to the core plasma. The sheath-limited phase is followed by a high recycling one approximately 1–2 ms after the ELM onset, leading to target densities up to 5 times the pre-ELM values and target temperatures below 20 eV. The high recycling phase extends up to 10–20 ms after the ELM onset. As the high-recycling phase begins, tungsten erosion is significantly suppressed and the divertor retention of tungsten is considerably increased. Accordingly, in the model, the tungsten core influx appears to be strongly dominated by the sheath-limited ELM onset phase, while only a negligible tungsten influx to core occurs in between subsequent ELMs (Figure 3.8). It was also observed that, since most of the tungsten core contamination occurs during ELMs, approximately 50 % of the tungsten contaminating the core plasma was sputtered by deuterium. Therefore, according to the model here, achieving plasmas without light impurities would reduce the tungsten core influx only by a factor of 2. Assuming confinement times of tungsten of the order of 60 ms, core electron density of 7×10^{19} m^{-3} and volume 100 m^3, the resulting core concentration in both of the simulations was estimated to be of the order of 10^{-5}, which is only marginally acceptable in reactor relevant plasmas.

3.3.3 Impact of Carbon and Tungsten as Divertor Materials on the Scrape-off Layer Conditions in JET

EFDA task:	JET Orders and Notifications
Research scientists:	M. Groth, A. Järvinen, AU
Collaboration:	S. Brezinsek, J.W. Coenen, M. Clever, D. Harting, A. Huber, M. Lehnen, S. Wiesen, FZ Jülich
	M. Brix, G. Corrigan, K. Lawson, A.G. Meigs, M.F. Stamp, CCFE
	T. Eich, C. Maggi, S. Marsen, B. Sieglin, IPP
	P. Belo, C. Silva, IST
	G. van Rooij, DIFFER
	EFDA-JET Contributors

Radiation from impurities in the scrape-off layer (SOL) of tokamaks critically affects the SOL power balance and thus the power conducted to the divertor target plates. Carbon, in particular, strongly radiates in the temperature range characteristic of the divertor SOL (i.e., 10 to 50 eV), favourable for the reduction of power conducted to the divertor target plates. When changing the plasma facing components (PFCs) from all-carbon to metals in JET (JET-C and JET-ILW, respectively) in 2009/10 in one single shutdown, a significant loss of carbon radiation was anticipated, which in turn, was predicted to result in higher divertor heat loads. Sets of reference plasmas in low-confinement mode (L-mode) with moderate auxiliary power of up to 3 MW were performed in both the JET-C and JET-ILW materials configurations to systematically characterise the materials effect on the SOL conditions These plasmas were analysed for their radiative losses in the SOL, the particle and heat fluxes to the divertor targets, and the plasmas conditions (electron temperature, T_e) at the divertor plates, and compared to predictions obtained with the fluid edge code package EDGE2D/EIRENE.

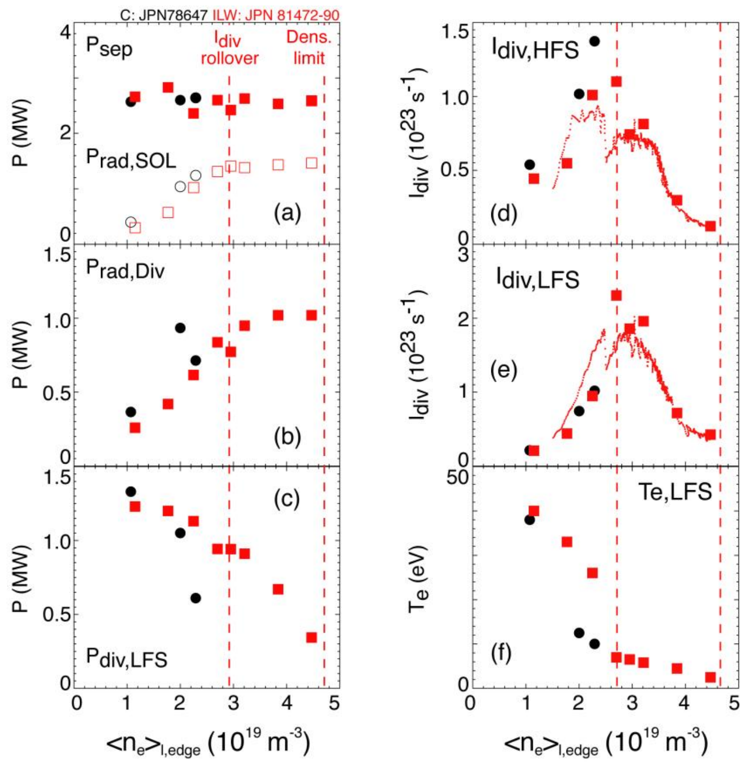

Figure 3.9. Total power across separatrix and radiated power in the SOL (a), radiated power in the divertor (b), total conducted power to the LFS plate (c), total ion currents to the HFS (d) and LFS (e) plates, and peak electron temperature at the LFS plate (f) as function of line-averaged edge density. Black symbols refer to JET-C, the red symbols to JET-ILW.

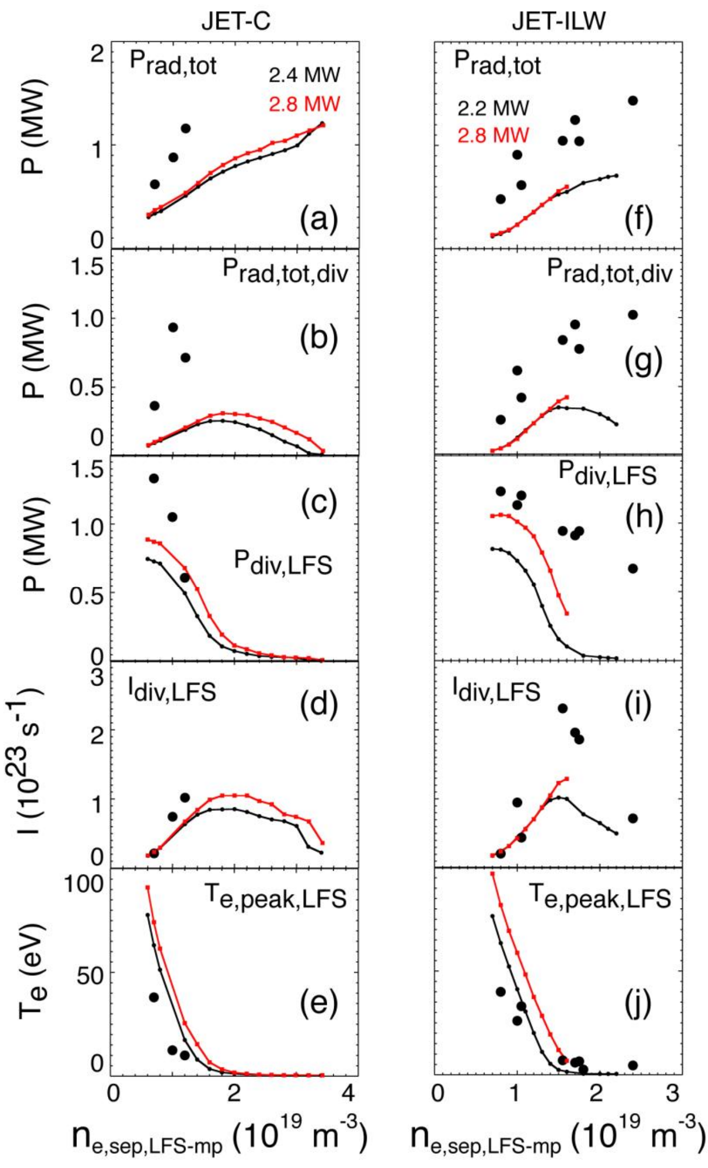

Figure 3.10. Comparison of the measured (symbols) and predicted (lines) total radiated power in the SOL (a, f), total radiated power in the divertor (b, g), conducted power to the LFS plate (c, h), total ion currents to the LFS plates (d, i), and peak electron temperature (e, j) for the C wall (left column) and ILW (right column) L-mode plasmas in horizontal configuration. The simulated curves in black and right indicate the lower and upper bounds of the assumed power across the grid core boundary.

Principal results in 2012: For high-recycling conditions, replacing the carbon (JET-C) wall with a Be/W (JET-ILW) wall in JET reduced the radiated power in the divertor by 30 %, and correspondingly increased the power conducted to the plate and electron temperature by up to a factor of 2 (Figure 3.9b and c). The reduction in radiated power is consistent with the measured, approximately ten times lower carbon content in the plasma in the JET-ILW. In low-recycling conditions the SOL plasmas are nearly identical between the two materials configurations [S. Brezinsek et al., PSI2012 conference]. The rollover of the divertor ion currents as well as the density limit occurred at approximately 30 % higher upstream density in the JET-ILW. Stable detached divertor plasmas with a significantly larger operational window in upstream density space were obtained in JET-ILW: beyond partial detachment, $I_{div,LFS}$ steadily decreased with upstream density and was reduced by a factor of 2 compared to its peak value at rollover; in JET-C a 25 % reduction of $I_{div,LFS}$ only was obtained. Rather remarkably, the rollover of $I_{div,HFS}$ and $I_{div,LFS}$ occurred at the same upstream densities for both materials configurations. Nearly identical Balmer-α emissions in the LFS divertor plasmas and subdivertor pressures indicate that the neutral behaviour did not significantly differ between the two materials configurations. Electron temperatures of the order 5 eV were obtained at upstream densities distinctly lower (≈ 30 %) than those at rollover of $I_{div,LFS}$; they are reduced further to 1 eV, and likely below, when the LFS divertor plasma was fully detached.

For otherwise identical setups, simulations with the edge code package EDGE2D/EIRENE predict a 50 % reduction of the radiated power in the SOL, qualitatively consistent with the measurements (Fig. 2). For both wall materials the simulations show the rollover of the divertor ion current at intermediate densities and steady decrease when increasing the upstream density beyond that: the rollover is less pronounced in JET-C as observed experimentally (Fig. 2d and i). Key to obtaining these results is the inclusion of additional reaction rates relating to deuterium molecules and molecular ions. However, the simulations underestimate the radiated power in the SOL, and in particular the radiated power in the divertor, independent of the materials configuration (Figure 3.10b and g). The predicted power conducted to the LFS plate is, however, within the uncertainties and limitations of the measurements (Figure 3.10c and h). For a corresponding vertical configuration and the same upstream conditions as in a horizontal configuration, the simulations predict up to an order of magnitude lower electron temperature at the separatrix on the LFS plate, as observed in previous calculations [A. Loarte, Plasma Phys. Controll. Fusion **43** (2001) R183 and references therein].

3.3.4 Material transport and erosion/deposition in ASDEX Upgrade

3.3.4.1 Gross and net erosion in the divertor and main chamber of AUG

EFDA task:	WP12-IPH-A01-1-06
Research scientists:	M. Airila, A. Hakola, J. Karhunen, S. Koivuranta, J. Likonen, VTT
Collaboration:	A. Herrmann, K. Krieger, M. Mayer, H.W. Müller, V. Rohde, K. Sugiyama, IPP Garching
	T. Haikola, J. Kolehmainen, S. Tervakangas, DIARC-Technology

Erosion of different plasma-facing materials in ASDEX Upgrade (AUG) is an important joint research topic of Tekes and IPP. For these investigations, DIARC-Technology Inc. has produced special marker tiles and probes to be exposed during the experimental campaigns of AUG since 2002. For the 2010/11 campaign, DIARC-Technology coated a number of outer strike-point tiles with 2–4 μm thick poloidal marker stripes of W, Mo, Cr, Al, and W+5%Ta. In the case of W and Mo, the stripes also showed different surface roughnesses; the original R_a roughness values of the stripes ranged from 0.4 μm to 6 μm.

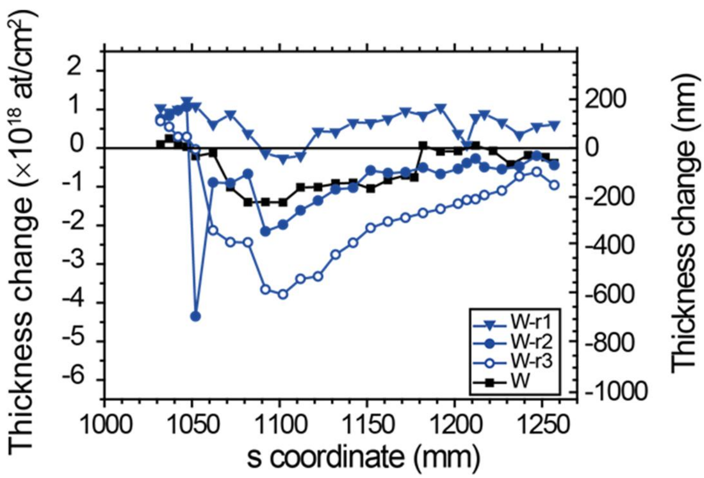

Figure 3.11. Poloidal erosion profiles of W stripes with different surface roughness. The original roughnesses of the stripes (in terms of their Ra values) were 5.5 μm (W-r1), 0.8 μm (W-r2), and 0.4 μm (W-r3). The black curve labeled W has been extracted from the tile with W, Mo, Cr, and Al markers and serves as a reference here.

In 2012, the campaign-integrated erosion profiles of the markers discussed above were determined by Rutherford Backscattering Spectroscopy (RBS), while Secondary Ion Mass Spectrometry (SIMS) was applied to investigate the depth profiles of different elements in the surface layers. Our results indicate that the net erosion rates of rough coatings are 4–8 times smaller than those of smooth layers (see Figure 3.11). We attribute this noticeable difference both to significant re-deposition in valleys shadowed by protruding surface features and to the protective effect of thick co-deposited layers on the rough surfaces; the rough markers contain 5–10 times more boron, carbon, and deuterium than the smooth ones.

The comparison between the different plasma-facing materials revealed that the erosion rate increases with the decreasing charge number *Z* of the PFC material. Compared to the maximum erosion rate of W, about 0.03 nm/s, Mo had been eroded approximately 2–3 times faster and Cr, simulating here steel, some 3–4 times faster. The whole Al layer had been damaged because of its low melting point, and the results obtained from it cannot thus be used as representative values for the erosion yield of beryllium.

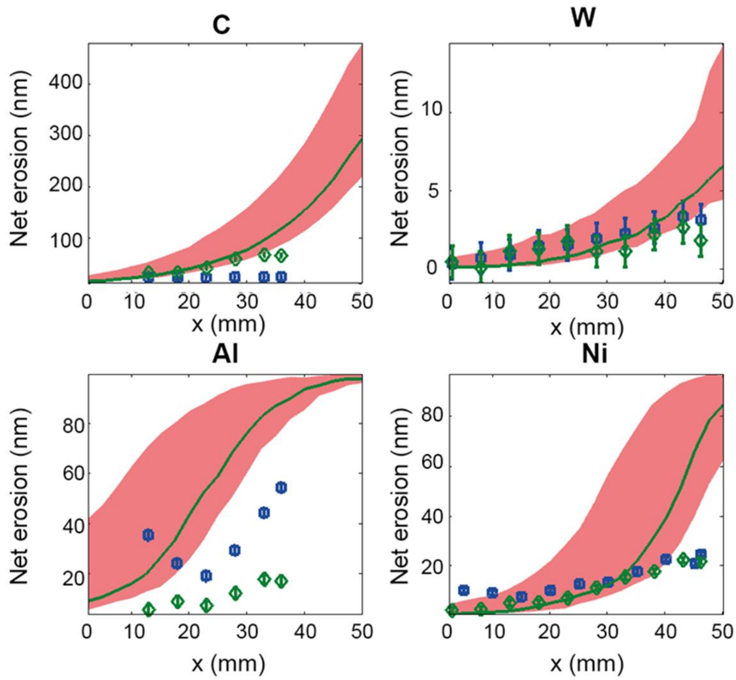

Figure 3.12. Erosion profiles of the different marker stripes as a function of distance along the surface in the case of the L-mode probe experiment. Here, the fit for T_{e0} = 60 eV and λ_{Te} = 30 mm is shown (solid line). The x coordinate increases towards the plasma, the separatrix being at x = 85 mm. The red area represents the range of simulated net erosion that was covered by varying T_e and T_i and their decay lengths. Experimental results are denoted by blue (RBS with protons) and green (RBS with ^{4}He ions) symbols.

In addition to the marker tiles, erosion processes have been investigated in AUG by exposing probes with marker stripes to a pre-determined number of plasma discharges and comparing the experimentally determined erosion profiles of the stripes to predictions by the ERO code. In this front, the work in 2012 concentrated on modelling two experiments [J. Karhunen, et al., EPS Conf. on Plasma Physics 2012], where graphite probes with W, Al, Ni, and C markers (thickness 50–100 nm) were exposed to different plasmas in 2011. One probe was exposed to four L-mode shots (exposure time 15 s), the other one to a single, high-power H-mode shot (exposure time 1 s) at the outer midplane of AUG.

In the L-mode case, the best match with ERO simulations and the experimental results was obtained at low electron temperatures and with long decay lengths for n_e, T_e, and T_i; T_e was observed to have a larger effect on erosion than T_i. Especially, the erosion of W, C, and Ni could be reproduced while due to experimental uncertainties, the simulated erosion was strongly overestimated in the case of Al. The results are presented in Figure 3.12.

In the H-mode case, only the erosion profile of W could be matched to some degree due to uncertainties in the RBS method and the lack of proper n_e, T_e, and T_i data. According to the simulations, only the total duration of ELMs affected the results independently of the duration and frequency of ELMs, which suggests that re-deposition was insignificant; with noticeable re-deposition, changes in surface composition during long inter-ELM phases would have led to larger erosion of deposited layers during ELMs than with shorter ELM cycles. With realistic values for the inter- and intra-ELM periods, the inter-ELM periods were observed to yield larger erosion than ELMs. For W, ELMs began dominating erosion only after their duration was more than 20 % of the duration of the ELM cycle.

3.3.4.2 Global migration of ^{13}C in the divertor and main-chamber regions of AUG

EFDA task:	WP12-IPH-A01-1-13
Rersearch scientists:	A. Hakola, S. Koivuranta, J. Likonen, VTT M. Groth, T. Kurki-Suonio, V. Lindholm, J. Miettunen, T. Makkonen, AU
Collaboration:	A. Herrmann, K. Krieger, M. Mayer, H.W. Müller, V. Rohde, K. Sugiyama, IPP Garching P. Petersson, VR T. Haikola, J. Kolehmainen, S. Tervakangas, DIARC-Technology

Studying global migration of impurities in AUG and modelling the experiments with the edge codes ASCOT, DIVIMP, ERO, and SOLPS are the second main form of collaboration between Tekes and IPP. To meet these goals, tracer gases have been deliberately injected into the AUG vessel during a number of identical plasma discharges at the end of an experimental campaign and a set of tiles has been removed from the vessel immediately after the experiment for post mortem surface analyses. The deposition profiles of the tracer elements, typically ^{13}C, on the tiles have been determined using SIMS.

The latest injection experiment, consisting of 11 high-density, lower single-null discharges in L mode, was carried out in July 2011, and in 2012 the deposition profiles of ^{13}C on some 40 first-wall tiles of AUG were determined. The tiles originated from the divertor, the limiter structures at the outer midplane, the inner heat shield, and the top parts of the AUG vessel.

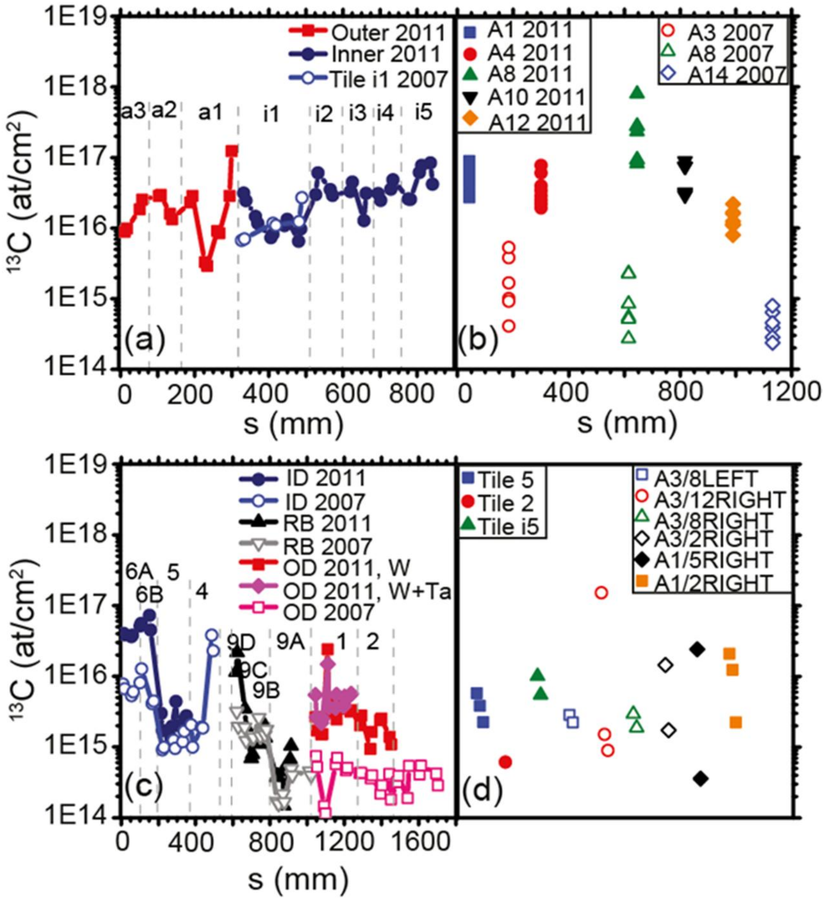

Figure 3.13. Poloidal deposition profiles of ^{13}C in the (a) upper divertor, (b) central heat shield, (c) lower divertor, and (d) tile gaps in 2007 and in 2011 in AUG. The s coordinate denotes the poloidal distance along the tile surfaces. Here, ID = inner divertor, OD = outer divertor, and RB = roof baffle. In part (b), the set of data points for each analysed tile correspond to different toroidal locations on them.

Our results [A. Hakola et al., J. Nucl. Mat., accepted] show that the main chamber of AUG is the most prominent sink for carbon in the investigated L-mode discharges: some 35 % of the injected atoms have ended up in different regions there. In addition, gaps between tiles are significant deposition regions for ^{13}C with surface densities comparable to those on the plasma-facing surfaces. Differences between the deposition profiles in 2007 and 2011 were observed at the heat-shield and outer-divertor regions, and these are expected to be due to the different magnetic configurations and SOL flow profiles of the two experiments. It is also worth noticing that the deposition profiles reported here are different from the long-term ones observed in AUG. This could be due to several erosion and re-deposition steps that finally determine the deposition behaviour of carbon. The poloidal deposition profiles of ^{13}C in the different regions of the AUG vessel can be found in Figure 3.13.

In the simulation front, SOLPS provided a range of background plasmas and predictions of the poloidal flow profiles. However, ASCOT simulations with the SOLPS solution indicated dominant deposition at the outer divertor, which was not the case experimentally. Therefore, an imposed flow profile was used, and it shifted the strongest deposition peak to the inner divertor, but also predicted localized deposition on the limiter and ICRH structures near the injection location as one can observe in Figure 3.14. This shows that the assumption of toroidally symmetric deposition in the torus is not valid as we have also experimentally observed. A notable feature is the prediction of high deposition at the top of the vessel while the observed deposition peak at the heat shield could not be reproduced and the prediction for the deposition at the inner divertor was far too large. All this we attribute to the effect of the double-null configuration on the poloidal flow, which will be the topic of future studies.

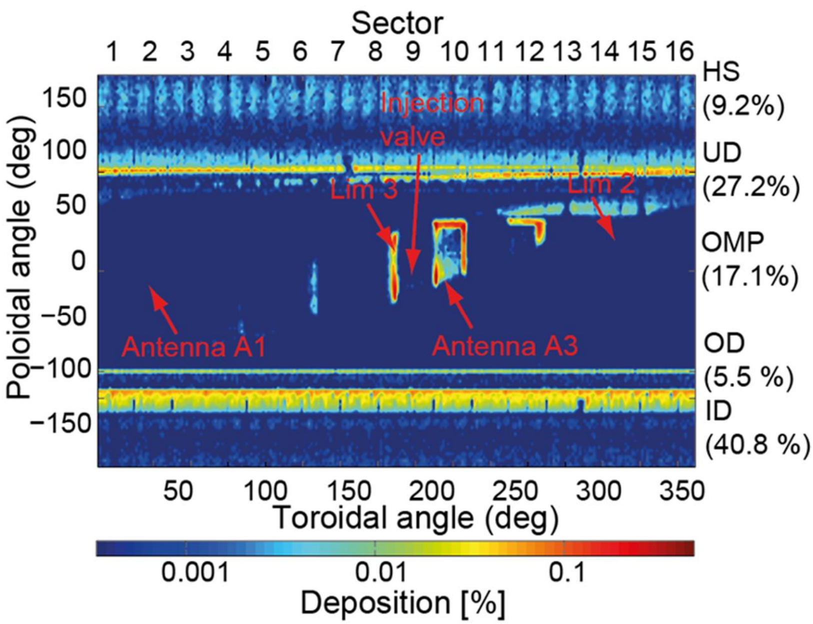

Figure 3.14. ASCOT results for the ^{13}C deposition (as percentages of total deposition) in the entire torus. Here, HS = heat shield, OMP = outer midplane, and UD = upper divertor. Different limiter structures at the OMP from which tiles had been removed for analyses are marked in the figure.

3.3.4.3 Flow measurements in the high-field side SOL in AUG

EFDA task:	WP12-IPH-A01-01-15
Research scientists:	T. Makkonen, M. Groth, T. Kurki-Suonio, AU M. Airila, VTT
Collaboration:	R. Dux, A. Janzer, T. Lunt, H.W. Müller, T. Puetterich, E. Viezzer, IPP-Garching

The high-field side (HFS) scrape-off layer (SOL) flow profile has been studied in 2011 and 2012. Methane was injected into the HFS SOL and the ensuing emission plume was followed with a fast video camera (green pyramid in Figure 3.15a–b) equipped with appropriate filters for CII and CIII and a spectrometer. The spectrometer has 8 lines of sight crossing the plane of the injection from R = 1.0856 m to R = 1.1681 m (blue lines in Figure 3.15a–b) providing a radial profile for the Doppler shift of CII and CIII.

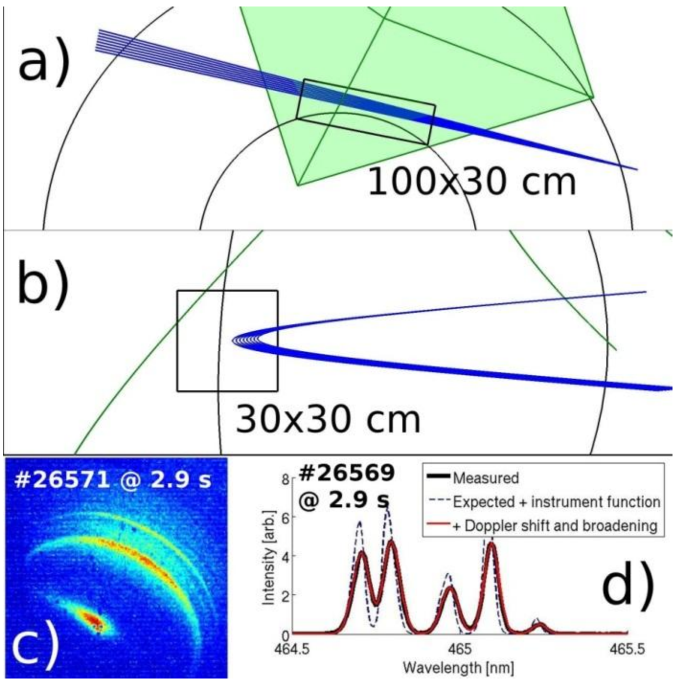

Figure 3.15. (a–b) The experimental setup and the ERO simulation box. (c) Example of camera data. The emission plume is visible bottom left. (d) Example of spectrometer data.

In 2012, the CIII flow profiles were studied in L-mode and H-mode for varying densities. The results are shown in Figure 3.16. where the positive direction is towards the lower inner divertor. The time 2.3 s corresponds to the line-averaged density of 3.3 × 10^{19} 1/m^3 for L-mode and 3.6 × 10^{19} 1/m^3 for H-mode. This is referred to as the low density case. The medium density case is at 3.1 s with 5.2 × 10^{19} 1/m^3 for L-mode and 7.8 × 10^{19} 1/m^3 for H-mode. The high density case at 3.9 s has 7.6 × 10^{19} 1/m^3 and 9.3 × 10^{19} 1/m^3, respectively. Lower densities indicate more of the injected carbon is transported towards the top of the machine while higher densities indicate transport towards the lower inner divertor. These results, together with 2011 data and ERO simulations, where published at the PSI 2012 conference and in [T. Makkonen et al., J. Nucl. Mater., accepted].

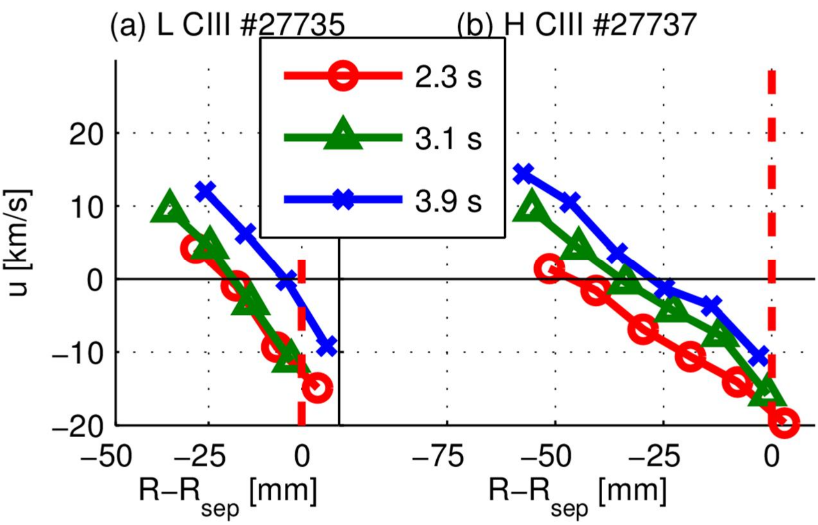

Figure 3.16. (a) L-mode flow profiles and (b) H-mode flow profiles for low (2.3 s), medium (3.1 s) and high density (3.9 s).

The observed CII and CIII flow profiles serve as a proxy for impurity migration but does not reveal the exact background flow velocity as the injected carbon is not fully equilibrated. Therefore, ERO simulations were used to shed light on the coupling between the background and carbon flows. Figure 3.15a–b shows the ERO simulation area. This required code development reported in section 3.7.2.

For this method to be used a routine diagnostics, further understanding of the coupling between the carbon and background flows is required. This work has been started and is reported in section 3.7.2.

3.3.4.4 Retention of plasma fuel in the divertor and main-chamber regions of AUG and related MD simulations

EFDA task:	WP12-IPH-A03-1-02
Research scientists:	A. Hakola, S. Koivuranta, J. Likonen, VTT K. Heinola, UH
Collaboration:	A. Herrmann, K. Krieger, M. Mayer, H.W. Müller, V. Rohde, K. Sugiyama, IPP Garching T. Haikola, J. Kolehmainen, S. Tervakangas, DIARC-Technology

In addition to erosion and material migration, retention of plasma fuel in the first-wall structures of AUG has been studied with the help of special marker tiles since 2002. The tiles have been produced by DIARC-Technology Inc. and they have been exposed to plasma during a whole experimental campaign. The amount of deuterium on them has been determined using the ion-beam techniques Nuclear Reaction Analysis (NRA) and SIMS.

In 2012, the retention studies focused on marker tiles, exposed to plasma during the 2010/11 experimental campaign of AUG. These tiles originated from the outer strike-point region and their specifications have been listed in section 3.3.4.1.

The data from the W roughness tiles (Figure 3.17a) indicates that the strongest retention has taken place in and around the actual strike-point zone. A smaller retention peak can also be seen in the private flux region, most likely as a result of co-deposition of D with boron. Of the three stripes, the rough ones show 3–10 times larger retention than the smoother ones. This is not totally surprising: The rougher the surface, the more deposition is expected to take place in microscopic valleys protected from further plasma contact by the hilly features on the surface.

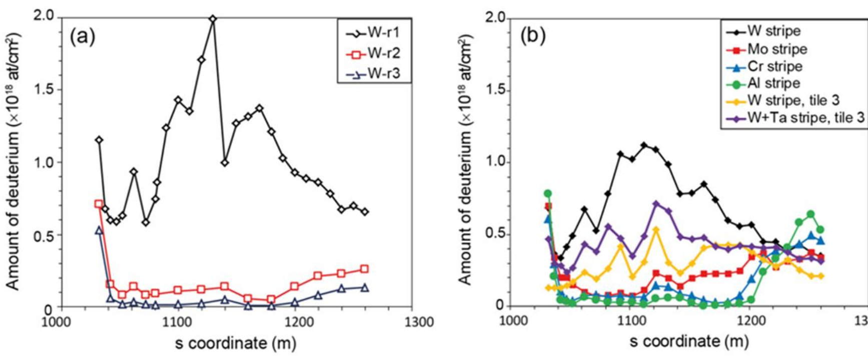

Figure 3.17. (a) Retention of deuterium in W stripes with different surface roughness. The data has been extracted from the same tile analysed in Figure 3.11. (b) Retention of deuterium in different marker stripes (W, Mo, Cr, Al from one of the marker tiles, W and W+Ta stripes from another marker tile).

No noticeable differences can be observed between the retention in W and W+Ta markers or between the Mo, Cr, and Al stripes (see Figure 3.17b). In contrast, the different W stripes and the W+Ta stripe show retention profiles that are comparable to that extracted for the W-r1 stripe in Figure 3.17a – while retention in Mo, Cr, and Al is similar to the situation for the W-r2 and W-r3 stripes in the same figure. This may be explained by larger net erosion of smooth W coatings as well as the other marker materials: larger erosion leads also to the removal of deuterium accumulated in the materials.

Hydrogen (H) retention to bulk W containing grain boundaries and varying amounts of C, O and Ar impurities was studied computationally [K. Heinola and T. Ahlgren, J. Nucl. Mater., accepted]. The retention and detrapping was monitored during and after a low-fluence, low-energy hydrogen pulse of 20 secs. The method used solves numerically set of rate theory equations (RE) describing all the dynamic events occurring in the bulk and on the sample surface. Equations were parametrised with (i) first-principles calculations using electron density functional theory (DFT), (ii) the intrinsic W point defects and extended defect properties were modelled with molecular dynamic (MD) simulations and (iii) binary collision approximation (BCA) calculations were used in hydrogen pulse calculation.

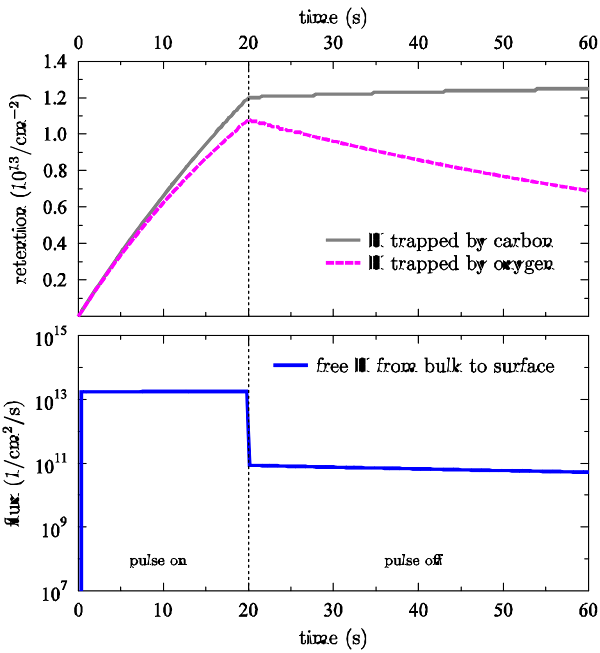

Figure 3.18. Top: Exemplary RE calculation results for H retention in W at 500 K. The C and O impurity concentrations were 5×10^{18} cm^{-3} each. After the pulse, detrapping of H from O increases the retention to C. Bottom: Resulted flux of mobile H from bulk to the surface. Flux is not terminated rapidly after the pulse due to the inventory of mobile H in the bulk.

The results show that C acts as an effective trapping site for H at 500 K whereas H was found to be trapped only to grain boundaries at 800 K. At lower temperature also O impurity has an impact to the H retention, but the effect of Ar was found to be negligible. After the pulse the H flux from bulk to surface did not effectively drop to zero at 500 K, but instead was found to slowly decrease in the end of the monitoring time 60 secs (Figure 3.18). This implies strongly that H will be released from W up to several minutes after the pulse. This prolonged out-diffusion is due to the H reserves at C impurities and grain boundaries which slowly release H at lower temperatures. Future work will contain simulations where H pulse will be combined with simultaneous Be bombardment. For this study, the necessary parameters for describing Be interactions will be determined with DFT and MD.

3.3.5 Modelling of detachment and density limit in AUG using SOLPS

In 2012, density scans based on two ^{13}C migration experiments performed in 2007 and 2011 have been modelled. The experiments were not identical, so efforts were concentrated on the 2011 experiment, which has better data. Using this case, SOLPS was used to simulate a density scan of a slightly simplified version of the experiment, with plans for more detailed simulations at a later date. Results are compared with data, and special attention is given to the differences between H and D plasma solutions (H was used in 2011, D in 2007).

The free parameter in the simulations is the electron density at the outer midplane separatrix, $n_{e,sep}$. In general, it was easy to match the OMP experimental data. However, OMP and target conditions did not match the data at the same time in any of the cases. Then again, it is a known limitation that SOLPS rarely produces solutions that match the data everywhere in the simulated domain. Furthermore, the experimental data may well be shifted a few cm radially, since there is an uncertainty as to where the separatrix is exactly.

In general, the hydrogen solutions were cooler at the targets than deuterium, while being denser at the outer midplane (inside the separatrix). Aside from effects that are expected from changing the plasma particle mass, no qualitative difference was found between H and D plasmas.

Neutral penetration was also studied. At low densities, both H and D plasmas have a total neutral flux across the separatrix of 2.5×10^{22} 1/s, while at higher densities the value is 3.5×10^{23} 1/s for H and 1.75×10^{23} 1/s for D, a difference of a factor of two. This quantity also exhibits some fairly strong fluctuations for higher H densities, suggesting that the cases may not be completely converged. An increase in the number of test particles in EIRENE might improve statistical fluctuations.

3.3.6 Validity of the 2-point model in varying L-mode SOL conditions

The validity of the 2-point model was assessed for a set of L-mode plasmas by comparing results from the model to experimental results and the more sophisticated Onion-skin model (OSM). Experiments performed in the JET ILW-configuration produced eight cases of varying density. The target Langmuir probe (LP) data from these eight cases was used as input to the models, and the model predictions were compared to the measured upstream densities and temperatures from high-resolution Thomson scattering (HRTS), lithum beam, and reciprocating probe (RCP).

Analysis on the experimental data revealed that increasing the average electron density of the plasma from $n_e = 1.8 \times 10^{19}$ m^{-3} to $n_e = 3.5 \times 10^{19}$ m^{-3} changed the SOL regime from sheath-limited to high-recycling. This resulted in greatly reduced target temperatures. Increasing the density further from $n_e = 4.0 \times 10^{19}$ m^{-3} resulted in even lower target temperatures and detached SOL regimes were obtained.

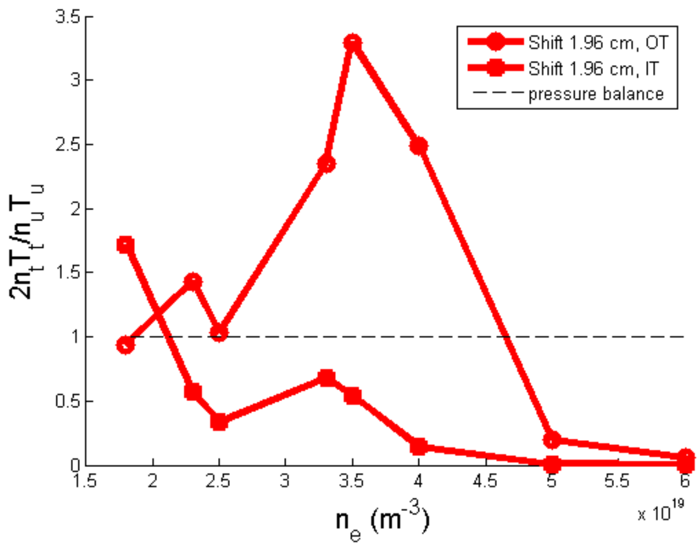

Figure 3.19. The ratio of downstream (outer and inner target, OT and IT, respectively) and upstream pressures for three different density cases. Upstream data was shifted so that, based on outer target data, $(2n_tT_t)/(n_uT_u) = 1$ for the lowest density case ($n_e = 1.8 \times 10^{19}$ m^{-3}).

To achieve pressure balance between upstream and downstream SOL for the low density sheath-limited case, the upstream profiles from the Li beam and RCP had to be shifted 1.96 cm radially outwards when assuming $T_i = T_e$ upstream and 1.5 cm outwards when assuming $T_i = 2T_e$ upstream. The pressure ratio between upstream and outer target and between upstream and inner target behaved qualitatively similarly (see Figure 3.19). Using a shift of 1.96 cm the upstream pressure was lower than the outer target pressure and higher than the inner target pressure for higher upstream densities.

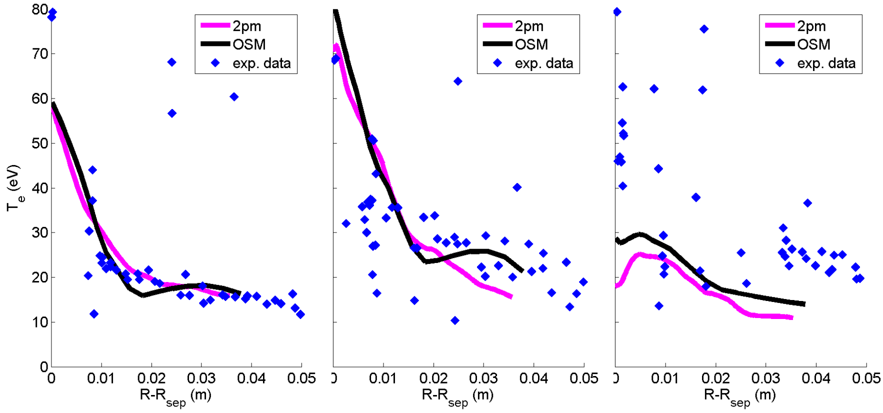

Figure 3.20. Radial electron temperature profiles from outer midplane for (from left to right) low ($n_e = 1.8 \times 10^{19}$ m^{-3}), medium ($n_e = 3.5 \times 10^{19}$ m^{-3}) and high ($n_e = 6.0 \times 10^{19}$ m^{-3}) average density.

The 2-point model and OSM were used to estimate the radial temperature and density profiles at outer midplane based on radial target profiles. For electron temperature, the 2-point model and OSM gave similar results (see Figure 3.20). The agreement with experiments was good in sheat-limited regime and high-recycling regime, but broke down when the divertor plasma detached at high densities. For density profiles, the 2-point model was generally 2 times higher than the OSM-profile (see Figure 3.21). Here, too, the agreement was good in the sheath-limited regime, but started to break down already in high-recycling regime. Especially the 2-point model overestimated the density profile greatly in high-recycling regime. This difference in density between the two models stems from the quasi-neutrality and the ion temperature difference between OSM and the 2-point model. According to OSM-modelling, for all upstream densities and SOL regimes the total pressure is conserved, including upstream and downstream total pressures being equal, which is in accordance with the assumption made when deriving the 2-point model. However, the assumption of equal ion and electron temperature upstream is clearly not justified.

The studies show that the basic 2-point model is a sufficient model for predicting upstream densities from the target LP profiles only at low upstream densities when the SOL is in sheath-limited regime. However, the 2-point model predicts temperature reasonably well for both low and high-recycling regimes. This implies that the pressure balance as assumed in the 2-point model is not warrant, but that the power balances hold reasonably well. In the future, the pressure balance in the 2-point model should be re-assessed and compared to predictions from fluid codes, such as EDGE2D/EIRENE and SOLPS.

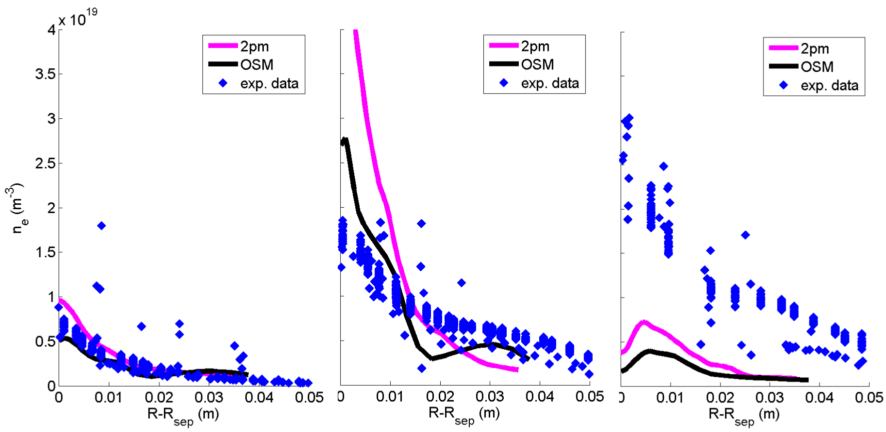

Figure 3.21. Radial density profiles from outer midplane for low (1.8×10^{19} m^{-3}), medium (3.5×10^{19} m^{-3}) and high (6.0×10^{19} m^{-3}) average density.

3.3.7 Fuel retention in mixed beryllium containing materials

EFDA task:	WP12-IPH-A01-3-11
Research scientists:	A. Hakola, J. Karhunen, VTT
	M. Laan, A. Lissovski, P. Paris, UT
Collaboration:	C. Lungu, MedC
	K. Sugiyama, IPP Garching

In ITER, the interaction between plasma and the first wall of the device will give rise to various mixed layers of beryllium and tungsten that are deposited on the plasma-facing surfaces and may also contain significant amounts of radioactive tritium. Laser-induced breakdown spectroscopy (LIBS) is a promising *in situ* tool for determining the composition of such layers. In LIBS, intense laser pulses remove material from the surface of the studied samples, and the ejected particles form a plasma plume whose emission spectrum is measured and analysed.

In 2012, several ITER-relevant Be-W samples, produced by MEdC, were studied by LIBS to investigate primarily the ablation properties of Be and W. In addition, to elucidate retention mechanisms in the materials, some of the samples were doped with D during deposition or implanted with 200-eV D ions.

Two pairs of intense beryllium lines (atomic and ionic lines at 313 nm and 332 nm and at 457 nm and 467 nm) were identified, and they were clearly distinguishable from the background in all the experiments. With optimal settings, narrow lines with a width down to 0.5 nm could be recorded as indicated in Figure 3.22. The most intense atomic tungsten lines at 401 nm and 407 nm were also detectable, but they were much weaker than those of beryllium; this we attribute to the low fluence values (< 4 J/cm^2) used in the experiments. The deuterium line at 656 nm was visible for some samples, but only with the first laser pulse.

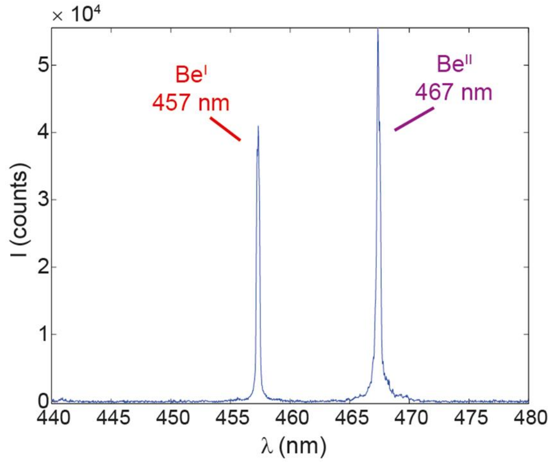

Figure 3.22. Examples of atomic (BeI at 457 nm) and ionic (BeII at 467 nm) spectral lines of beryllium when using optimized settings for their detection.

The ablation rates of the samples ranged in 20–30 nm/shot, slightly increasing with the thickness of the layer as well as with the W content of the mixed Be-W alloy, possibly due to the inferior quality of these coatings. In addition, it was generally easier to drill through deuterium-implanted samples than through undoped samples, which we attribute to lattice defects caused by D bombardment.

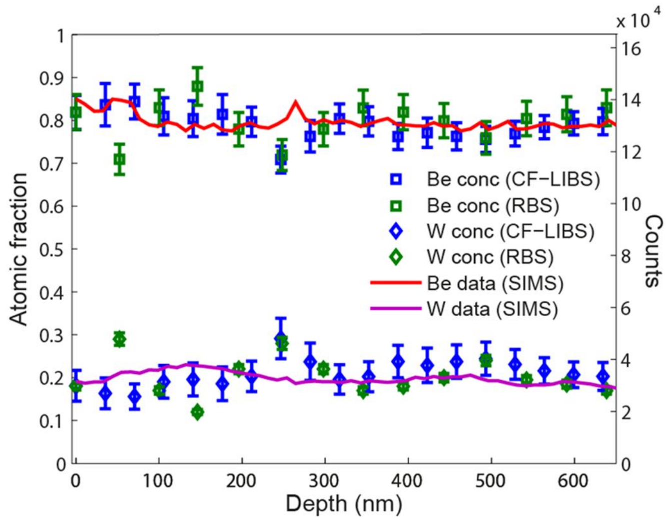

Figure 3.23. Atomic fractions of Be and W as a function of depth in a Be-W sample. The blue symbols denote the results given by CF-LIBS while the green symbols represent the RBS data. The solid lines are SIMS depth profiles.

The compositions of the samples were determined calibration-free LIBS (CF-LIBS). The CF-LIBS results for a Be-W sample are shown in Figure 3.23, and they nicely match with the RBS and SIMS results extracted from the same samples. This validates the capability of CF-LIBS to resolve the quantitative composition of an unknown sample with better than 5 % accuracy.

Fuel retention in the samples was further investigated using SIMS. SIMS revealed that the amount of deuterium in the doped samples was very small, which partly explains the non-detectability of the deuterium line in the LIBS spectra. However, deuterium was present in the implanted samples: In the pure beryllium coatings, deuterium lies within the topmost 300 nm, whereas the implantation profile extends through the whole layer in the case of the beryllium-tungsten mixtures.

3.3.8 Fuel retention in mixed material samples exposed to Pilot-PSI plasmas

EFDA task:	WP12-IPH-A03-1-06
Research scientists:	A. Hakola, J. Likonen, VTT
	M. Laan, A. Lissovski, P. Paris, K. Piip, UT
Collaboration:	T. Haikola, J. Kolehmainen, S. Tervakangas, DIARC-Technology
	K. Bystrov, G. de Temmerman, DIFFER

VTT and University of Tartu have collaborated with the DIFFER Institute in the field of plasma-surface interactions since 2008. The main research theme is studying erosion of ITER-relevant materials when exposed to plasma in the linear devices Pilot-PSI and Magnum-PSI. For the experiments, test samples consisting of a few μm thick coatings have been produced by DIARC-Technology Inc.

In 2012, the work concentrated on the analyses of D-doped W-Al samples (up to 4 μm thick coatings on Mo) that had been exposed to plasma discharges in Pilot-PSI in late 2011. In the experiments, H_2 plasmas with neon to enhance erosion had been used. The main experimental parameters were: $n_e = 2–3 \times 10^{20}$ m^{-3}, $T_e \approx 1$ eV, flux $10^{23}–10^{24}$ m^{-2}s^{-1}, $B = 0.4$ T, ion energy 40 eV, and exposure time 260–520 s. The maximum surface temperature was kept at 500–600°C. The determined mass loss of each sample varied from 0.1 mg to 0.2 mg.

The erosion of the samples as well as retention of fuel in them were determined using SIMS and LIBS. In addition, the surface morphology was studied using SEM and X-ray diffraction. Typically, the surface contained a thickish re-deposited layer and had been largely modified close to the center of the plasma spot, with a large number of crystallites in the otherwise amorphous film matrix, especially when the ion energy was > 50 eV. Due to these modifications, the sputtering rates of different elements in especially LIBS were much smaller in exposed than in unexposed regions of the samples. A more thorough discussion on the analyses can be found in section 4.1.

Based on SIMS analyses, deuterium had completely vanished from the plasma-exposed region of the samples (down to 1 μm). Instead, more hydrogen could be detected close to the center of the plasma spot than further away but in both cases hydrogen was homogeneously distributed all the way down to the substrate as Figure 3.24 indicates.

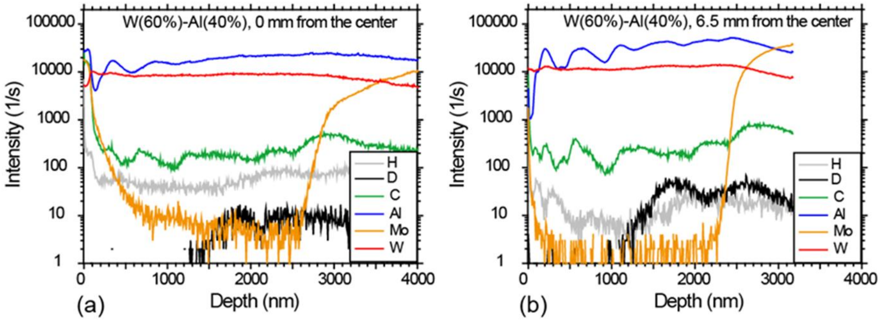

Figure 3.24. SIMS depth profiles measured from a W(60%)-Al(40%) sample at (a) 0 mm and (b) 6.5 mm from the centre of the plasma spot. The original thickness of the coatings was around 4 μm.

3.3.9 Simulating W fuzz formation using MD

EFDA task: WP12-IPH-A11-1-09
Research scientists: A. Lasa, UH

The experimentally observed W fuzz formation during the long-term He plasma exposure is a highly worry some issue for ITER, as this unexpected effect could lead to the re-evaluation of W as a divertor material. Hence, it is important to quickly understand the fuzz formation mechanisms and how the conditions affect this formation. Therefore, we attempted to understand the fuzz formation onset by simulating high doses He irradiation on tungsten. The results will be compared with other MD simulations and linked to Kinetic Monte Carlo simulations for studying the long-term evolution of the system.

We performed Molecular Dynamic simulations of helium irradiation on (100) W surfaces, at normal incidence, up to 105 impacts. The following parameters were used in this first attempt: 30eV He ions, 3000 W atoms in the initial cell (31 × 31 × 37 $Å^3$), 5 ps between consecutive impacts (flux 3 × 10^{27} m^{-2} s^{-1}) and two different EAM potentials for the W-W and W-He interaction: one by Henriksson (2005) and an improved version of it by Juslin (unpublished). Both potentials gave very similar results, confirming what already was known: He bubbles develop dynamically under the W surface. The pressure on the bubble increases with the number of He atoms in it until it breaks the W surface and the bubble desorbs. Due to the low ion energy, and thus low ion range, the He bubbles are formed under only few (4–5) W atomic desorbing while being still small (< 40 atoms). Therefore, no new conclusions could be drawn despite the very high dose ($\approx 10^{22}$ m^{-2}).

Aiming to overcome this small bubble formation limit, we increased the W cell size to 12,800 atoms (63 × 63 × 37 Å) and He impact energy to 60 eV, matching with the experimental value (Baldwin et al., 2008). Aiming to study the effect of impurities and temperature on the fuzz formation onset, we simulated 4 cases: at room or experimental temperature (300K or ≈1120K, respectively), and with or without impurities (90 % He plus 10 % C using a Tersoff potential by Juslin or 100 % He with the latest EAM potential by Juslin, respectively). The C-containing simulations are still ongoing, but the fluences are large enough (up to 2.5×10^4 impacts) to draw some important conclusions.

Our MD simulations (Figure 3.25) reproduce the experimentally found $t^{1/2}$ dependence of the fuzz layer thickness growth, but the pre-factor differs by 4 orders of magnitude possibly due to the very high MD flux. The bubble formation, consequent loop punching and surface growth, and bubble rupture are the key events in this fuzz formation onset: the balance between these two processes – bubble formation and rupture – leads to this particular time dependence. Furthermore, this bubble dynamics damages the W crystal, leaving holes that partially recrystallize. Also the C impurities cause damage in the W matrix, amorphizing it. In the other hand, the presence of C favours the formation of many small bubbles over few large ones. The high temperature enhances the bubble formation and desorption activity too, preventing the formation of few large bubbles. Also the recrystallization of the damaged areas is more effective at high temperature, especially in the C containing cases. Moreover, we found that the He atomic density decreases with increasing the number of He atoms in the cell.

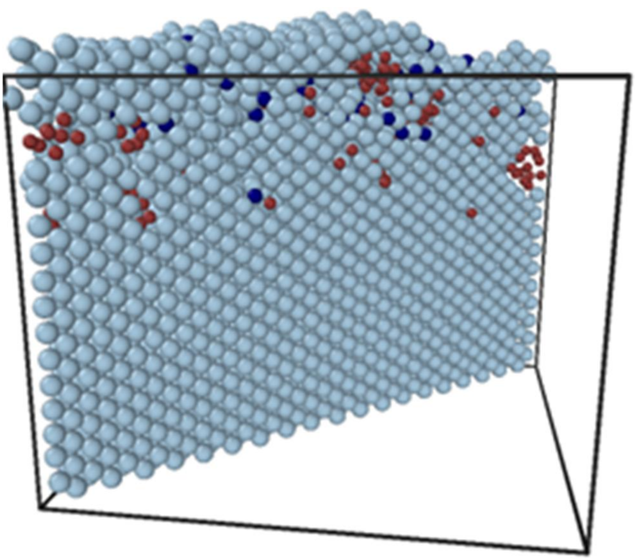

Figure 3.25. A diagonal 'cut' of the large W cell, showing its inside, after 1.7×10^4 cumulative He plus C impacts, at 910K. W atoms are shown in gray, He in red and C in blue. The black lines draw the original cell boundaries, showing the surface growth due to the He-bubble induced loop-punching.

3.4 Energetic Particle Physics

3.4.1 Power loads to ITER first wall structures due to fusion alphas in non-axisymmetric magnetic field including the presence of MHD modes

EFDA task: WP12-IPH-A09-1-03
Research scientists: A. Snicker, E. Hirvijoki, T. Koskela, O. Asunta, S. Äkäslompolo, T. Kurki-Suonio, AU
Collaboration: P. Lauber, IPP Garching

3.4.1.1 Introduction

One of the most important issues on the way to fusion reactors is to understand and control the behavior of energetic particles. The energetic particles play a significant role in providing heating and current drive in reactor scale tokamak plasmas, but they can also excite a multitude of magnetohydrodynamical (MHD) instabilities such as Alfvén Eigenmodes (AEs). These instabilities act back on the energetic particles, potentially redistributing them. This can lead to a deterioration of fast ion confinement, which translates into decreased plasma heating and increased power loads on the plasma-facing components (PFCs). Because in future reactors there will be plenty of fast particles from both fusion reactions and external heating, the wall power loads should be investigated in detail in the presence of relevant MHD activity.

The 5D Monte Carlo orbit-following code ASCOT has already been used to study the fast ion power loads in a variety of ITER plasmas, including the effect of various magnetic perturbations such as toroidal ripple and field aberrations due to ferritic inserts and TBMs (Test Blanket Modules for tritium breeding). The simulations indicated that the wall power loads remain at tolerable level in all scenarios and for all particle species. However, these favorable results were obtained under the assumption that the fast ion transport is dominated by neoclassical mechanisms (i.e. Coulomb collisions). The predictions are expected to change in the presence of a process that transports fast ions from the core to the edge, e.g., various MHD modes.

In 2012 we extended the ASCOT code for simulations of MHD modes, in particular neoclassical tearing modes and toroidal Alfvén eigenmodes [E. Hirvijoki et al., Computer Phys. Commun. **183** (2012) 2589]; see also section 3.6.3. The first results were presented at the 24th IAEA FEC, and a full paper has been submitted for publication in Nuclear Fusion.

3.4.1.2 Effect of neoclassical tearing modes

ITER is prone to neoclassical tearing modes (NTMs) that can expedite radial excursions of fast ions, possibly leading to increased fast ion population at the edge, where transport due to various field aberrations can lead to unacceptably high peak power loads on some first wall components.

We have now used ASCOT, refurbished with the recently developed MHD model that allows an arbitrary coordinate system, to calculate the power loads on ITER first wall in the presence of NTM modes. The modes included in the study are (2,1) and (3,2), assumed to be most relevant for the losses. The 15 MA H-mode plasma was chosen because this scenario has the highest fusion power production which, combined with the wider birth profile, suggests that NTMs could be more detrimental to the first wall in this scenario. The simulations were carried out including the effect of ferritic inserts, neutral beam ports and TBMs, and using the most recent wall geometry with 18 poloidal limiters. The perturbation amplitudes of the NTM modes were scanned to find if a critical island size for the wall loads could be determined.

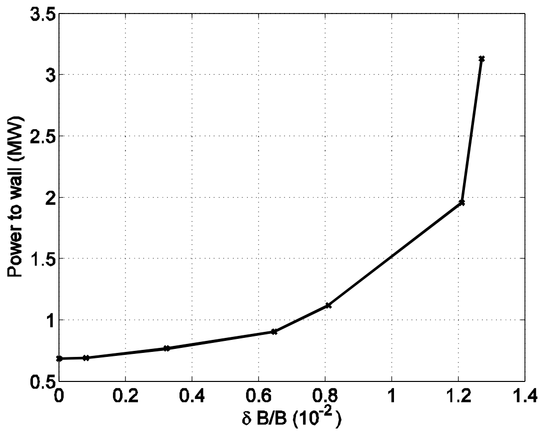

Figure 3.26. The total alpha particle wall power load vs. perturbation amplitude for the (3,2) NTM.

The simulation results (see Figure 3.26) suggest that, in the case of NTMs, the total power load to the wall strongly depends on the NTM perturbation amplitude. However, even with very high amplitudes the wall power loads remain below the design limits of the wall materials. It was also shown that the NTMs do not cause additional hot spots on the wall, but will rather increase the wall load uniformly.

3.4.1.3 Effect of toroidal Alfvén eigenmodes

In fusion reactors, energetic particles play a significant role in providing heating and current drive, but they can also excite a multitude of magnetohydrodynamical (MHD) instabilities like Alfvén eigenmodes (AEs). These instabilities act back on the energetic particles, potentially redistributing them. This can lead to a deterioration of fast ion confinement, which translates into decreased plasma heating and increased power loads on the plasma-facing components (PFCs). Because in future reactors there will be plenty of fast particles from fusion reactions and external heating, the wall power loads should be investigated in detail in the presence of these modes, most notably toroidal Alfvén eigenmodes (TAEs). In the past, the effect of TAEs on energetic particles could be studied inside the separatrix and for axisymmetric plasmas only, because the models were restricted to field-aligned coordinates. We have now advanced the models so that an arbitrary coordinate system can be adopted, allowing for 3D magnetic geometries and simulations extending all the way to the PFCs. This model has been implemented in ASCOT, and we have investigated the behaviour of fusion alphas in the ITER 9 MA scenario. This is because, in earlier studies, the effect of TAEs on fast particles was found modest in the ITER hybrid scenario, but stronger in the 9 MA advanced scenario. The simulations included the effects due to toroidal ripple, ferritic inserts, neutral beam ports and TBMs, and the most recent wall geometry with 18 poloidal limiters was adopted. The eigenfunctions for the most unstable TAEs (n = 5), were given by the LIGKA code (Philipp Lauber, IPP Garching).

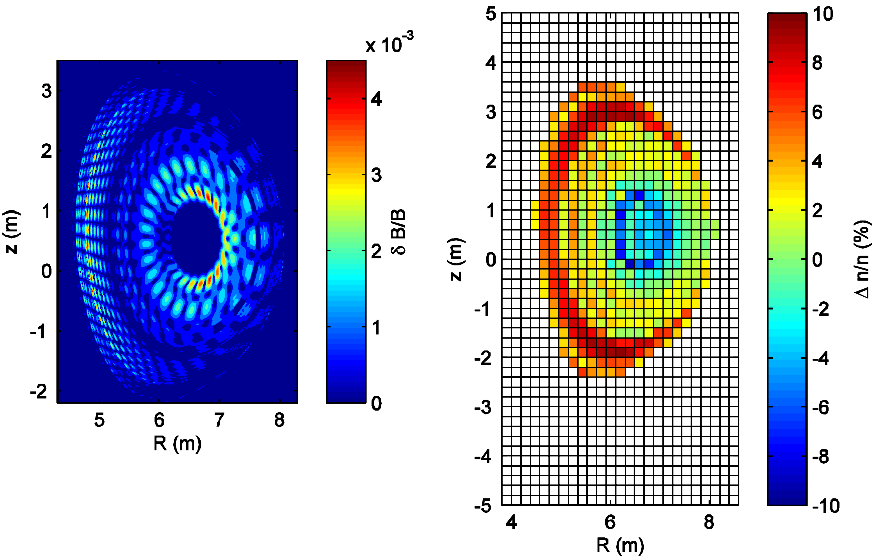

Figure 3.27. (Left) A 2D map of the magnetic perturbation (caused by the TAEs) strength given as a fraction of the background magnetic field. (Right) The relative change in the simulated alpha particle density brought about by the n = 5 TAE modes. A clear correlation is observed.

The simulation results are illustrated in Figure 3.27, indicating that the alpha particle wall power load will stay at the MHD-quiescent level. However, a quite strong redistribution of alpha particles in the core plasma was observed. The redistribution of alphas also affects the alpha heating profile, causing changes of up to 10 %.

For more precise investigations, self-consistent simulations would be required, as the change in the power deposition will change the temperature profile and also the TAE spectrum.

3.4.1.4 ITER ELM control coils: effect on fast ion losses and edge confinement properties

Type I ELMs, characteristic of high-performance H-modes, are foreseen to be a serious threat to the operation of ITER. Various ways of mitigating or eliminating ELMs have been considered over the years and, at the moment, the most promising method appears to be the generation of error fields with in-vessel coils. Efficient and reliable ELM control with such coils has been achieved at AUG and DIII-D tokamaks. The magnetic perturbations due to in-vessel coils, foreseen to mitigate ELMs also in ITER, could also compromise the confinement of energetic ions. Indeed, early on it was reported that over 20 % of the NBI power could be lost in the presence of the ECCs. Such losses would render the ECCs useless and, therefore, the physics of the losses has to be carefully investigated and understood.

We have now used ASCOT to simulate the losses of fusion alpha particles and NBI-generated fast ions in ITER under the influence of the 3D perturbations caused by toroidal Field coils, Ferritic Inserts (FIs), Test Blanket Modules (TBMs) and ELM Control Coils (ECCs). The 3D perturbations are calculated in the vacuum approximation and added to the axisymmetric equilibria. This corresponds to assuming the plasma response to the perturbations to be negligibly small and, thus, probably leads to over-estimating the perturbation.

The ECCs were found to make the magnetic field stochastic deep inside the pedestal in the 15 MA inductive reference operating scenario. Such a field is found insufficient to confine not only the fast but also the thermal ion population, leading to a strongly reduced fast ion source in the edge. Therefore, even with a stochastic edge, high fast ion power loads are not expected. However, the plasma response has not yet been included in the calculation of ITER magnetic background data, and it is probable that the perturbation is currently overestimated.

We have thus shown that in cases where excessive losses are obtained, the magnetic background would not be able to support the edge plasma profiles assumed in the simulations and, thus, the edge fast ion source is overestimated. Furthermore, we point out a generic problem with the magnetic backgrounds calculated by combining a 2D equilibrium with a 3D vacuum field that contains all the external perturbations: in this manner, including the ELM mitigation coils can lead to NBI power loss of 3 % or 30 %, depending on which of the equilibria available for ITER is chosen. This artefact is expected to disappear if 3D equilibrium construction were available. Thus, more emphasis has to be given to the equilibrium construction.

This work has been published in Plasma Physics and Controlled Fusion **54**, 105008 (2012).

3.4.2 DIII-D TBM mock-up

Research scientist: T. Koskela, AU

The effect of error fields generated by Test Blanket Modules on fast ion confinement, among other things, has been studied in two sets of experiments on DIII-D in 2009 and 2011. In these experiments the effect of the ferritic material contained in a TBM has been simulated by a set of coils that produces a similar magnetic perturbation. In the 2011 experiments an infrared camera was used to monitor the heat footprint on the wall tiles covering the TBM mock-up module. This provided a good opportunity to benchmark fast ion orbit-following codes on the infrared measurements.

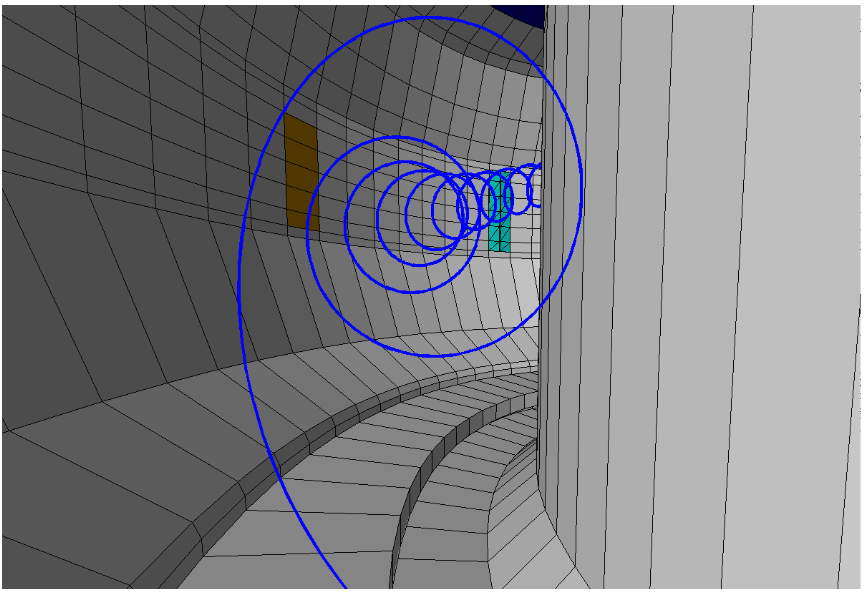

Figure 3.28. The Larmor orbit of a 1.01 MeV DD fusion product tritium ion in DIII-D, calculated by ASCOT. The large ratio of the Larmor orbit to the machine size requires full orbit following to capture the physics accurately.

An ASCOT simulation was made with full orbit following (see Figure 3.28), to benchmark to IR camera measurements, and the simulation results were compared with the OFMC and SPIRAL codes. A good agreement was found between the codes and the measurements. The agreement between orbit calculations and measurements validates the analysis of ASCOT fast ion loss calculations made for ITER.

The results were published at the 24th IAEA FEC by G. Kramer and have been submitted for publication in Nuclear Fusion.

3.4.3 The effect of JET upgrades on the behaviour of NBI ions

EFDA task: JET Orders and Notifications
Research scientist: T. Koskela, AU

JET has recently upgraded both its first wall to an ITER-like materials mix, and its neutral beam system to increase maximum power, pulse duration and reliability. There has been some concern over the possible connection of these upgrades to an observed decrease in plasma performance. ASCOT simulations have been performed to evaluate the impact of the change in neutral beams and plasma impurities on fast ion losses and NBI heating profiles.

Fast ion losses in the presence of toroidal field ripple were simulated, in preparation for possible future ripple operation. As shown in Figure 3.29, with 1 % ripple on the outer midplane separatrix, the losses from the upgraded beams are slightly smaller than the losses from the old beams when injected into a similar plasma. The plasma heating profiles were found to decrease slightly at plasma mid-radius and shift towards the axis and the edge.

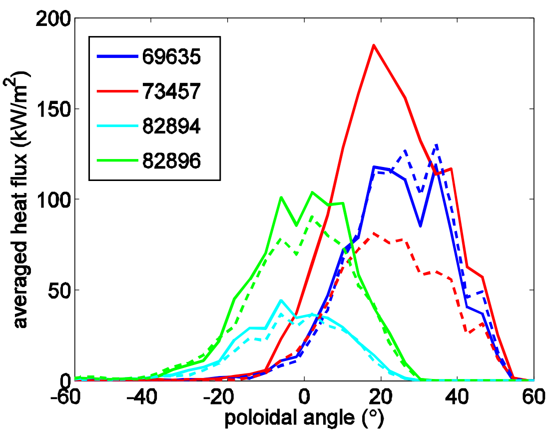

Figure 3.29. Toroidally averaged power load from losses of NBI ions in four JET discharges with 1 % ripple at outer midplane. Solid lines are beams before the EP2 upgrade and dashed lines are beams after the upgrade. We see that, especially for discharges with the ILW #82894 and #82896, the upgraded beams create slightly lower losses.

The effect of tungsten impurity on beam power deposition was found to be very small, when an experimentally observed, radially constant, Z_{eff} was assumed, and the impurity density was assumed constant on flux surfaces. However, there is experimental evidence that the centrifugal force of plasma rotation may cause the impurity density to become asymmetric with strong peaking on the low-field side. Incorporating this effect to the analysis is in progress.

3.5 Theory and Modelling for ITER and DEMO

3.5.1 Gyrokinetic global SOL/edge code development

EFDA task: WP11-TRA-03-01
Research scientists: T. Kiviniemi, T. Korpilo, AU
J. Heikkinen, VTT

Elmfire code domain decomposition in 1D (in toroidal dimension) was finished and together with Åbo Akademi University – Department of Information Technologies scientists its 3D Domain Decomposition was initiated, in order to improve the memory usage of the code. The latter effort belongs also to the CRESTA EU project and will help the Community to enable the Exascale computing environment. The more efficient memory usage and improved scaling with respect to the number of cores by the combined effect of Domain Decomposition and openMP memory sharing features is believed to help Elmfire to be run at JET configuration. The code global features were improved by extending the calculation region to the magnetic axis as illustrated in Figure 3.30. At the same time, the calculation grid was exchanged from quasi-ballooning coordinates to Boozer coordinates and modified to support a user-defined non-uniform grid spacing both in radial and poloidal directions. The code has been also newly structured, and the adaptation of the code to the plasma-wall interface has been further developed. The new features have been successfully validated against the results obtained with the older versions of the code.

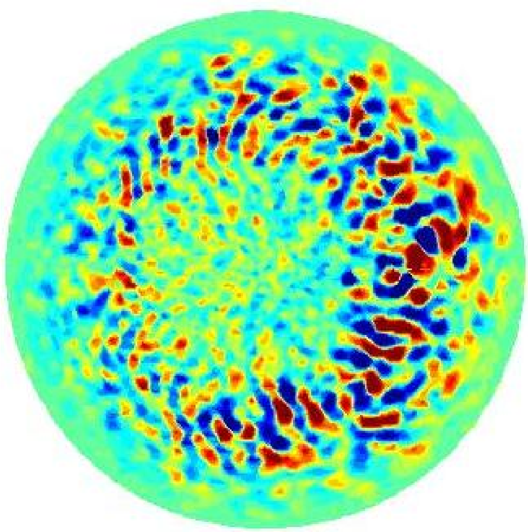

Figure 3.30. Density fluctuations from the magnetic axis to the separatrix in a Elmfire simulation.

3.5.2 Benchmarking of SOL turbulence code

Before the ITM code camp in Risø current interpolation from a given set of radial points was implemented to be used optionally to the original analytic magnetic background model. This was much more efficient than using Lagrangian interpolations directly. The simulations were performed on HPC-FF, which was the only machine that had the ITM FORTRAN workflow available for ELMFIRE at the time.

We find it important to note that the Cyclone benchmark case has now been successfully run to convergence, meaning that with sufficient care the code reaches marginal stability after turbulence has eaten away the gradients (for $R/L_T = 6.9$). Higher gradients need more particles.

The status of the code is that the ITM workflow is implemented up to the level of outputs, which are still in the form of text file outputs. Based on preliminary results we need greater resources from IFERC-CSC to be able to run this benchmark case realistically with good resolution. The runs did not conserve momentum well enough, which suggests that they were under-resolved. We estimate that about 1 million node hours are needed. The V12 version of the code was been ported to the Helios machine as well. Extra Helios resources were applied for the ITM benchmarking work, but only 0.1M node-hours were awarded. Therefore most work has been done on HPC-FF and SuperMUC.

3.5.3 First principle based core/edge transport simulations using HPC resources

The Elmfire project has been awarded with 30M core-h on a PRACE tier-0 machine (SuperMUC) and some issues had to be solved while the code was ported there. HPC-FF on the other hand works very well for the code. The code version V12 (domain decomposition) has developed substantially. It now incorporates most of the features that were present in the earlier V11 version that was used in production runs on HPC-FF. Based on experience on the LRZ supercomputer SuperMUC, production runs may be run now with 16k cores, while usually 8k is preferred (due to machine instability).

Recently the code results were compared to Doppler reflectometry measurements on the FT-2 tokamak. The difference between this case and the Cyclone results (see section 3.5.2) is the collisional regime: the FT-2 parameters are strongly collisional, while still exhibiting interesting TEM turbulence with strong fluctuations. The required particle numbers were therefore much lower, while it was quickly found that the high shear in FT-2 required the use of a radially dense grid, especially near the outer boundary where the experimental diagnostic was located. Code development has relaxed this condition slightly.

We have presented these results in the 24th IAEA Fusion Energy Conference as a talk and two posters.

3.5.4 Modelling of material mixing for extrapolation to ITER conditions

EFDA taskS: WP11-PWI-05-05; WP12-IPH-A01-2
Research scientists: A. Meinander, C. Björkas, K. Nordlund, UH
M. Airila, VTT

Introduction: Current fusion reactor designs focus on the use of multiple materials for the plasma-facing components. The initially clean surfaces will, through erosion and redeposition, quickly form mixed material surfaces [Ch. Linsmeier et al., Phys. Scripta **T111** (2004) 86]. While the properties of pure materials are fairly well known, the behaviour of mixed materials is less known, and can have a large impact on such performance parameters as erosion characteristics and hydrogen isotope retention. Chemical effects can be expected to give a significant contribution to material erosion from incident ions with kinetic energies of the order of 1-100 eV, since the energies involved are comparable to, or only slightly higher than, the strengths of chemical bonds. This issue is particularly important due to the ongoing development of the ITER fusion reactor, and JET's current ITER-Like-Wall, where carbon impurities will affect the interaction of the beryllium first wall with plasma particles in this energy range.

Multiscale simulations can aid in the extrapolation of current experimental results to ITER relevant conditions, by providing insight and understanding of the complex interplay between factors such as re-deposition probability, incident particle energy, and plasma impurity content. For this purpose, detailed results of effects such as sputtering and reflection gained through molecular dynamics (MD) simulations in this work will be used as input for the plasma transport code ERO, in order to refine the results pertaining to surface evolution when mixed materials come into play.

Methods and analysis: The Brenner hydrocarbon potential [D.W. Brenner, Phys. Rev. B **42** (1990) 9458] was originally designed to model chemical vapor deposition of diamond films, and as such is well suited to modeling surface interactions in energy regimes where chemical effects are significant, and where carbon and hydrogen (or deuterium, which is chemically equivalent to hydrogen and thus described by the same potential) are key elements. It is based on Tersoff's formulation of a bond-order potential [J. Tersoff, Phys. Rev. B **37** (1988) 6991], but adds certain correction terms to prevent over-binding of radicals, and to describe conjugation of C-C bonds. The Tersoff-type analytical bond-order potential (ABOP) has been shown to be suitable for describing both metallic and covalent bonds [K. Albe, K. Nordlund, R.S. Averback, Phys. Rev. B **65** (2002) 195124], and is used in these simulations for the ternary Be-C-D system. We have added the Brenner correction terms to the Be-C-D ABOP in such a way that the corrections are calculated only for C-C bonds, but Be neighbors are counted when determining the coordination of the C atoms involved. The resulting potential retains the properties of the ternary Be-C-D system, including the stability of the Be_2C crystalline structure, while at the same time providing the chemical hydrocarbon behavior predicted by the Brenner potential.

Simulations of impinging D ions on mixed Be-C surfaces were performed using the combined potential, for ion energies between 10 and 100 eV. Versions of the classical molecular dynamics code PARCAS were used for all simulations. Simulation cells with a mixed Be_2C/C surface were created with regions of crystalline anitfluorite Be_2C and amorphous C. A surface was chosen so that the surface was composed approximately half and half of Be_2C and C areas.

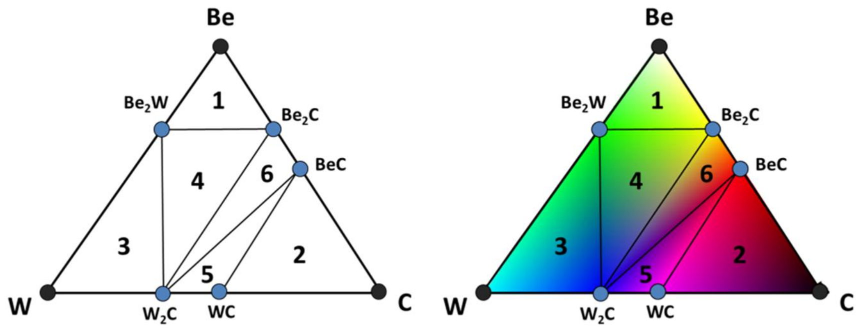

Figure 3.31. Division of the Be-C-W ternary phase diagram into six sub-triangles for sputtering data interpolation. The division is based on available data (shown compounds and mixtures) and is not unique. The colours illustrate the used linear interpolation.

Finally, we implemented the MD generated sputtering data in the Monte Carlo impurity transport code ERO. The data set covers D bombardment of BeC, Be_2C, Be_2W, W_2C and WC that are potentially formed on divertor targets in machines operating with an ITER-like wall. A linear interpolation method is proposed for the evaluation of the sputtering behaviour of any ternary Be/C/W composition. We have simplified the problem by dividing the (unknown) ternary phase diagram into six sub-triangles as shown in Figure 3.31. In each of these sub-triangles there are unique proportions of the three materials that combine to the given Be, C and W concentrations inside this triangle[1]. Results from first test simulations with this new surface model are reported in section 3.3.2.3.

Results and discussion: The predictions of the unmodified Be-C-H potential were directly compared to those of the Brenner potential in the case of sputtering from an amorphous C surface. The sputtering yield as well as the surface composition and structure were seen to differ substantially. Only the Brenner potential predicted the formation of a broken surface of carbon chains decorated with D atoms, including terminating methyl groups which are the precursors to sputtered

[1] Note, however, that we have selected only one of several possible ways to construct the sub-triangles. The present solution is not completely satisfactory – in particular regions 5 and 6 – and will be improved as soon as we obtain data for a ternary vertex inside the triangle.

C atoms. In contrast, the ABOP potential showed very little breaking up of the surface, with all carbon chains securely bound to the surface at both ends, and very few D atoms attached to these.

Sputtering simulations from mixed surfaces using the full combined potential show markedly different behavior in the case of low energy 10–20 eV ion impacts. At energies below 50 eV preferential C sputtering is predicted, while preferential Be sputtering is predicted for energies above 50 eV. This is in stark contrast to predictions without the bond-conjugation terms, which showed no C sputtering below 50 eV, as shown in Figure 3.32.

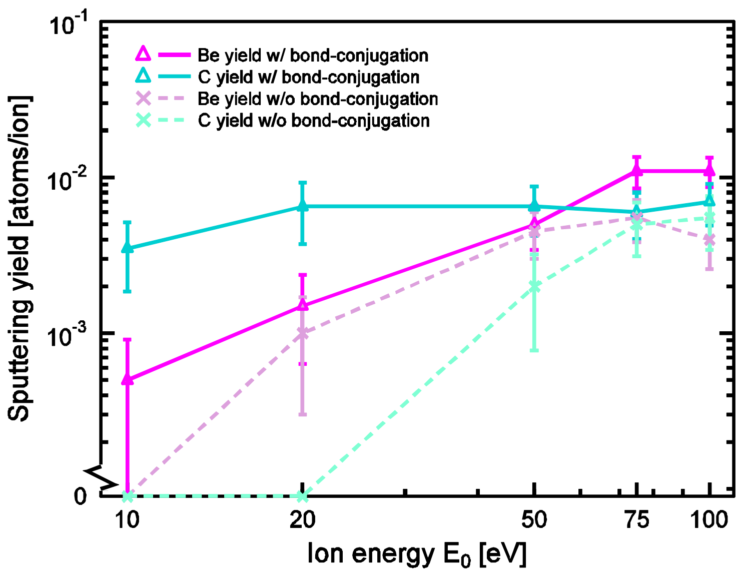

Figure 3.32. Results for sputtering yields from a mixed surface from simulations with and without the Brenner bond conjugation terms.

Conclusions: We have shown the importance of chemical effects for sputtering of mixed material Be-C systems at low incident ion energies. Comparison of MD simulations employing two different formalisms clearly show that terms correcting for hydrocarbon chemical bonding behavior are a necessary component in an empirical potential when describing low energy ion-surface interactions with both H and C present.

Simulations using the Brenner bond conjugation terms together with the ABOP potential for Be-C-H show the expected behavior of the C-H subsystem, allowing investigation of the effect of carbon chemistry on the complete ternary system.

3.5.5 Monte Carlo method for the collisional guiding-center kinetic equation

Research scientists: E. Hirvijoki, A. Snicker, AU
Collaboration: A. Brizard, St. Michael's College, Vermont

Understanding and analyzing the behaviour of energetic particles, be it run-away electrons, fusion alphas or MeV-range ions from external heating, in the complicated magnetic field of a tokamak requires orbit-following simulations in a non-uniform magnetic field. Following the accurate orbit of the particle is numerically a very laborous taks. To make the task less demanding, Lie-transform methods were adopted to eliminate fast gyromotion from single particle Hamilton equations, the result revealing the guiding-center motion. Brizard has since taken a step forward and utilized the Lie-transformations to obtain guiding-center equivalents for collisional kinetic equation and Fokker-Planck collision term. Orbit-following implementations, however, tend to use Monte Carlo operators suited for particle phase-space, not for guiding-centers.

The work of Brizard has now been applied to yield a Monte Carlo method consistent with the guiding-center phase-space. We constructed simple guiding-center operators and showed that the standard operators are recovered in the limit of homogenous magnetic field. The Lie-transform formalism also directly reveals connection between spatial and velocity space diffusion. Thus, applying a collision operator, consistent with the guiding-center formalism, leads to changes not only in the particle's momentum but in its position as well. The significance of the spatial shift will depend on the application.

We also reformulated the guiding-center kinetic equation to point out its connection to stochastic differential equations. The resulting form explicitly sets the corrections terms in the collision operator, introduced only within the guiding-center formalism, to same order as the drift velocities in the guiding-center equation of motion. This observation calls for treating both the collisional part and equations of motion with similar accuracy, contrary with the general convention where high-level integrators are used for orbit following while when evaluating the collisional effects, only crude methods are applied to both the deterministic and stochastic parts.

This work will be submitted to Physics of Plasmas and has been partially funded by the Academy of Finland.

3.6 Code Development and Integration

3.6.1 Code implementation, integration, verification and validation

3.6.1.1 ITM work related to fast ions

EFDA tasks:	WP12-ITM-IMP5-ACT1; WP12-ITM-IMP5-ACT2; WP12-ITM-IMP5-ACT4; WP12-ITM-EDRG-ACT1; WP12-ITM-EDRG-ACT3
Resesearch scientists:	O. Asunta, E. Hirvijoki, T. Koskela, T. Kurki-Suonio, J. Miettunen, A. Sipilä, A. Snicker, S. Äkäslompolo, AU

Work towards a highly standardized and sophisticated computing environment has been continued within the EFDA-Integrated Tokamak Modelling (ITM) Task Force. The main emphasis at Aalto University has been on writing new components to the European Transport Solver (ETS). These include a fast ion sources from NBI (BBNBI), a module for calculating local fusion reaction source rates (AFSI), some synthetic diagnostics, and making ASCOT compatible with the Kepler workflow environment. An ASCOT Kepler actor has been developed, as well as various helper actors to fill the relevant data structures, Consistent Physical Objects (CPO). These actors were all adapted to data structure version 4.09b, and most of them updated to version 4.10a. They were successfully tested on at least Fortran workflows, and some of them in actual Kepler workflows. In addition, work on appropriately defeaturing 3D walls for simulation purposes has been continued. Such a wall has been created using the data of the new JET ITER-like wall.

All these efforts are briefly described below.

ASCOT works in Fortran workflows in data structure 4.10a, and an ASCOT Kepler actor that sends a parallel job to HPC-FF has been created. At the time of writing, the CPO input data are not conveyed to HPC-FF properly, leading to failure of the simulation on HPC-FF. On Gateway, the CPO data are correct and a local ASCOT simulation executes without problems.

BBNBI (Beamlet-Based Neutral Beam Injector) calculates the ionization distribution of injected neutral particles by tracking neutrals all the way from the injector until they get ionized inside the device. This ionization distribution then works as input for codes modelling fast ion behaviour. BBNBI has now been extensively tested in Kepler in data structure 4.10a with both 'test' data and real JET data, and is ready for integration to IMP5HCD.

AFSI (Afsi Fusion Source Integrator) calculates the fusion rate from a non-Maxwellian fast ion distribution described by a 4D density distribution of the reactants: $n(R, z, v_{\parallel}, v_{\perp})$. Such an integrator requires external routines to produce the Maxwellian part of the distribution. The Maxwellian distribution is integrated as an analytic component that is summed to the 4D density distribution. The parameters for the Maxwellian are read from a CPO providing T_i and n_i.

The development of synthetic fast ion diagnostics requires an understanding of the fluxes (gamma-ray, neutron, ion, fast CX neutral) that arise from a particular fast ion distribution. These are given as a 4D (energy, pitch and coordinates in poloidal plane) distribution by ASCOT simulations. Since the geometry of an NPA is nearly identical to a simple neutron or gamma diagnostics, we have implemented an NPA model for ITM use. Only the source terms and signal attenuation terms need to be calculated differently for the different diagnostics. We have also implemented an advanced 3D collimator geometry end constructed the necessary CPO I/O structure for the NPA.

Realistic PWI simulations require a surface mesh for the entire first wall, including details such as ports, and requiring gas-tightness. Using the CAD data describing the JET ITER-like wall, a dense set of rays suitable for the JET geometry was created and ray-tracing was performed using a code developed for the purpose. To account for numerical inaccuracy and excessive detail, defeaturing was done by fitting a smoothing spline to the output in Matlab. The method developed can now be applied to obtain the wall mesh for any tokamak. This particular defeatured wall was also used in ASCOT simulations of beryllium transport in JET, as described elsewhere in this report.

3.6.1.2 Integration of the ERO code into the ITM environment

EFDA task: WP12-ITM-IMP3-ACT2
Resesarch scientist: M. Airila, VTT

During 2012 the 3D Monte Carlo impurity transport code ERO was interfaced with the ITM database by developing pre- and post-processors using the f90 high-level interface. The pre-processor reads an edge CPO from the database, performs necessary transformations and interpolation for the fluid quantities and writes an ERO-readable plasma background ASCII file. Upon completion of a simulation time step, ERO writes 3D impurity density data into a temporary ASCII file that is then written into an edge CPO by the post-processor. The use has been demonstrated in specific JET cases (see Figure 3.33). The pre-processor will need an upgrade when fluid plasma data storage is implemented beyond dataversion 4.09a. While CPO output was presently implemented only for impurity densities in plasma, also surface quantities can be included in the output when the wall CPO is released. ERO is now practically ready to be converted into a Kepler actor and included into an edge workflow.

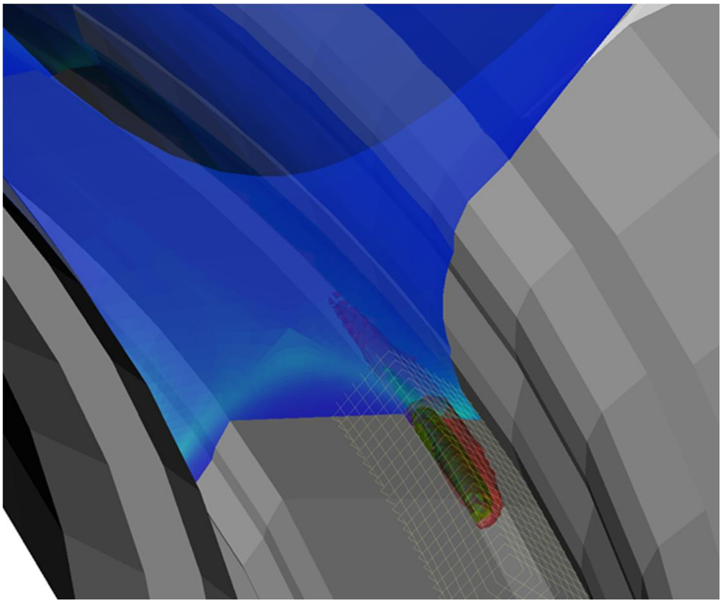

Figure 3.33. 3D ERO solution for C^{2+} density (from an ERO simulation of a tracer injection experiment) plotted together with 2D SOLPS plasma solution and JET wall.

3.6.2 Development of ICRH capability for ASCOT

EFDA tasks:	WP12-ITM-IMP5-01-02; WP12-ITM-IMP5-03-01
Research scientist:	A. Salmi, VTT
Collaboration:	T. Johnsson, KTH

The use of orbit following codes such as ASCOT to simulate ion cyclotron resonance heating (ICRH) requires several sophisticated functionalities in addition to the usual orbit tracing capability. The most important ingredient of course being the ICRH physics implemented as a Monte Carlo operator which can be applied during the orbit tracing. Other requirements are more related to the efficiency and structure of the code as ICRH modelling is typically very CPU intensive due to the large number of resonant ions that need to be followed.

ITM provides a library called RFOF in which the ICRH physics is implemented into a form that allows orbit following codes to use it for modelling the power absorption from the radio frequency (RF) waves. The aim of the project being reported here is to modify ASCOT such that it can use RFOF for the RF heating and to implement and test the schemes that speed up the code such that it can be used for realistic ICRH scenarios without overwhelming CPU burden.

The current status of the ASCOT enhancements is illustrated in Figure 3.34: ASCOT is able to simulate realistic ICRH scenarios with MPI to produce qualitatively sensible results.

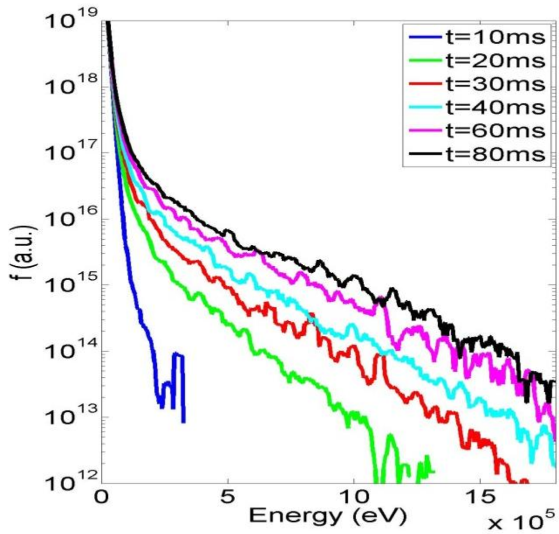

Figure 3.34. Energy distribution for 3 MW 1H(D) heating.

The ASCOT enhancements for ICRH that started in 2011 have been continued through 2012. The main focus has been on improving and testing the new code put in place earlier. In particular the particle weighting scheme has been discretised also in radial direction, refined and made to work dynamically to ensure that the high energy tail of the resonant ion distribution has sufficiently many ions for good statistics while the low energy end of the distribution uses as few ions as possible to minimise the CPU consumption. It has been tested to conserve energy and to produce identical results both in serial and in parallel environment.

The work will continue by testing and tuning the scheme for the acceleration of time scales after which the code should be sufficiently fast to allow benchmarking against theory and against other ICRH codes.

3.6.3 Alfvén Eigenmodes and Neoclassical Tearing Modes for orbit-following implementations

EFDA task:	WP12-IPH-A09-1-03
Research scientists:	A. Snicker, E. Hirvijoki, T. Koskela, O. Asunta, S. Äkäslompolo, T. Kurki-Suonio, AU
Collaboration:	P. Lauber, IPP Garching

The fast ion power loads on PFCs have typically been studied using orbit-following codes, which so far have not been able to realistically accommodate MHD phenomena. Until recently, there have been two ways of including MHD modes in fast ion loss studies: in the first approach, the modes are included as perturbative terms in the equations of motion, and the guiding-centers are followed in straight-field-line coordinates that assume axisymmetry and are defined only inside the separatrix. Since in ITER the axisymmetry of the magnetic field will be severely compromised by the toroidal field ripple as well as by perturbations caused by the tritium breeding modules (TBMs) and ELM-mitigation coils, there is a clear need for a simulation tool that allows a study of the behavior of energetic particles in strongly non-axisymmetric magnetic field, together with some unavoidable MHD phenomena. In the second approach to include MHD modes, the parameterized perturbations are calculated in advance and incorporated in the background magnetic field, making the model inherently static. Since ITER plasmas are likely to exhibit rapidly rotating Alfvén eigenmodes that redistribute energetic ions, there is a need for a model that allows the inclusion of time-dependent MHD modes in the simulations of non-axisymmetric plasmas.

We have developed a method that facilitates combining time-dependent MHD modes and realistic 3D magnetic field, at the same time allowing orbit-following up to the first wall in either guiding-center or full-orbit formalism. We adopted the models already developed for NTMs and AEs, but instead of relying on the straight-field-line coordinates in orbit-following we expressed the equations of motion, necessary for implementing the MHD perturbation fields, in general Cartesian or curvilinear coordinates. The resulting equations were also written in the straight field-line coordinates for a closer comparison to previous approaches, and the emerging differences were discussed. We also verified the method numerically: the effect of NTM perturbations was calculated with both the previous and present methods, and a benchmark against HAGIS was done in the presence of an AE perturbation, yielding a good agreement.

A suitable choice of the coordinate system for non-axisymmetric tokamak plasmas, such as in ITER, is e.g., cylindrical coordinates. Although the integration of the equations of motion in cylindrical coordinates is not quite as fast as in the field-line coordinates, the increase in CPU consumption is less than a factor of two.

3.6.4 ASCOT4 – remodelled race track for fast ions

Research scientists: O. Asunta, E. Hirvijoki, T. Koskela, T. Kurki-Suonio, J. Miettunen, S. Sipilä, A. Snicker, S. Äkäslompolo, AU
A. Salmi, VTT

Collaboration: J. Westerholm, Åbo Akademi University
CSC – IT Centre for Science

The ASCOT code was originally written in the early 90's, with primary interest in the runaway electrons related to current ramp-up and RF heating. Today, ASCOT is the most complete simulation tool in the world for studying energetic ions in full 3D geometries, including features such as beamlet-based NBI source, theory-based model for turbulent transport, new model for MHD activity (NTMs, TAEs) relevant for redistribution of fast ions, as well as a realistic first wall model consisting of a surface mesh of triangles. In parallel to these developments, ASCOT has also been enhanced to serve the needs of fusion research in the opposite end of the tokamak particle spectrum, so to speak: in order to help understand the behaviour of impurities and the resulting tritium retention in full 3D tokamak geometry, ASCOT has been refurbished with models for effective ionization and recombination for tracing impurities with multiple charge states, as well as a collision operator applicable in rotating plasmas.

The enhancements described above have been carried out by a multitude of different developers and, consequently, over the past 20 years ASCOT has undergone a kind of organic growth, with new models and features added by many code developers. Such a situation makes the scientific work vulnerable, because unintended crosstalk between bits of added code may easily go unnoticed unless the results are grossly off.

Simultaneously, the vast increase in computing resources with new superclusters available around the world has forced the code out of the modest parallel computing era, with tens or hundreds of parallel processes, to accommodate up to tens of thousands of processes. This opens new possibilities as the larger number of processes can accommodate a larger number of test particles to reveal the effects of the more detailed input data, e.g., in wall power load calculations in the presence of magnetic perturbations. However, the increased detail of the input means larger files, and tens of thousands of processes accessing these files simultaneously may exert an excessive load on the cluster's file system. To prevent the possible failure of the file system, the input should be read by only one process and passed on via MPI or other means to the rest of the processes.

For these reasons, the ASCOT group undertook the effort of rewriting the code from scratch, using most modern programming standards. In this work, the SimITER consortium of the LASTU research programme, funded by the Academy of Finland, including both CSC and Åbo Akademi University's high-power computing group led by Prof. Jan Westerholm, provided the ideal network. The new simulation tool is dubbed ASCOT4, to help identify possible differences in simulation results with older versions of ASCOT.

The main features of ASCOT4 are

- Possibility of choosing between the accurate full orbit following (a modified leapfrog method) or the time-saving guiding-center following (a fourth-order Runge-Kutta with fifth-order error estimation), depending on the application. A hybrid method, where full orbit following is adopted only in places where it can be expected to have a significant effect on the results, is also available without sacrificing the integrity of the orbits.
- Arbitrary full 3D magnetic fields, extending all the way to the plasma-facing components, can be used in the simulations. These fields can now even be produced locally from given coil currents and ferritic structures, as explained section 6.4.

- Ab initio test particle sources for energetic ions include fusion alphas, ions from neutral beam injection (NBI) and ICRH-generated ions.
- A realistic 3D wall structure, constructed from triangular and planar quadrangular elements, can be used for simulations where it is important to know the distribution of test particles arriving at the plasma-facing components. We have also provided the fusion community appropriately defeatured 3D walls, as explained in section 3.6.1.1.
- To model particle-wall collisions, ASCOT uses an efficient ray-polygon collision detection algorithm, originally developed for computer graphics applications.
- Like all the other fast ion codes in the world, ASCOT uses the Monte Carlo operators derived by Boozer and Kuo-Petravic to model the neo-classical effects. These operators act only in velocity space. However, they are not consistent with the guiding-center approach and, consequently, in collaboration with Dr. Brizard, we have now formulated new, consistent operators, as explained in section 3.5.5.
- Since tokamak confinement is not dictated by neoclassical transport only, it is important to have an operator also for anomalous spatial diffusion across the magnetic flux surfaces. In ASCOT, the diffusion coefficient D can have either a given constant value or a theory-based expression calculated from the plasma properties.
- The confinement and radial distribution of energetic ions can be affected by various MHD events. ASCOT now includes a model for both stationary neo-classical tearing modes (NTM) and rotating Alfvén Eigenmodes (AE). The development of this model is described in section 3.6.3.
- Diagnostic data is gathered during simulation into multidimensional histograms, called distributions. Distributions for the following physical quantities have been implemented:
  - density of particles,
  - density of energy,
  - parallel fast particle current density,
  - toroidal fast particle current density,
  - toroidal current density,
  - collisional power deposition to the plasma,
  - toroidal **j × B** torque to the plasma
  - toroidal collisional torque to the plasma, and
  - internal code-diagnosis distributions such as acceleration and time step length.

In addition, the density distribution is available in the four phase-space dimensions (R, z, $v_{\parallel}$, $v_{\perp}$) or (R, z, ξ, E). Distributions that depend on collisions are stored also as a function of background plasma species. Furthermore, all distributions are stored as a function of test particle species, which allows for multiple species of test particles or, say, particles from different neutral beams to be diagnosed separately in one simulation.

- Synthetic diagnostics: to facilitate a straightforward comparison to experiments, ASCOT is being refurbished with a host of synthetic diagnostics. Modules for FILD (Fast Ion Loss Detector) and activation probe as well as NPA (Neutral Particle Analyzer) already exist. The 4D density distributions have been used as inputs for Collective Thompson Scattering (CTS) forward modelling as well as sawtooth control studies.

When applying ASCOT to modelling impurity transport, several important differences to fast ion studies have to be taken into account. First and foremost, impurities mostly reside in the scrape-off layer (SOL), where the flow velocities can reach Mach numbers in the range 0.5–1, and they have typically very low energies (of the order of 1–100 eV). Due to the low energy, impurities are more strongly affected by the properties of the background plasma, such as its flow velocity. Additionally, the charge state of impurity particles can vary significantly as a result of their high Z number which further affects their transport. Therefore, a few additional features are needed:

- The standard Coulomb collision operators assume the background plasma to have a purely Maxwellian distribution which neglects plasma flow. In ASCOT, the effect of background plasma flow on Coulomb collisions can be modelled by using a frame of reference moving with the local parallel flow velocity of the background plasma.
- During a single time step, test particles can experience several different atomic reactions such as impact ionization when interacting with the background plasma. ASCOT features a probabilistic model for effective ionization and recombination.

A reference paper on ASCOT4 is under preparation. This work has been partially funded by the Academy of Finland.

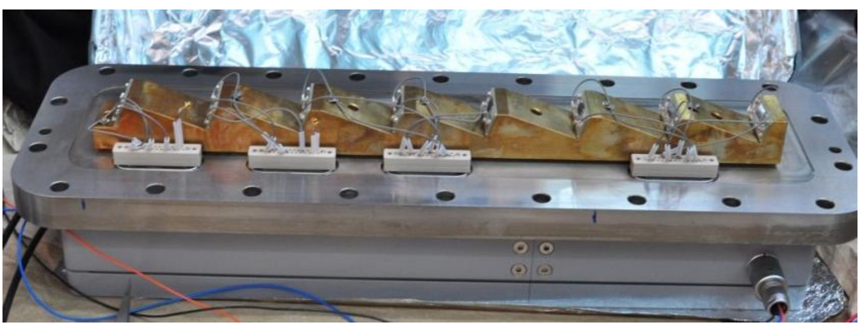

Figure 3.35. Completed diagnostic flange undergoing testing at JET. The vacuum side with detectors mounted on monolithic detector support is shown. The grey box on the air-side of the flange houses the new preamplifier electronics.

3.7 Plasma Diagnostics

3.7.1 Commissioning of JET NPA diagnostics upgrade

EFDA tasks:	JW6-OEP-TEKE-13; JW6-NEP-TEKE-17
Research scientist:	M. Santala, AU
Collaboration:	CCFE
	VTT Microelectronics
	Ioffe Institute, St. Petersburg

Neutral particle analysers (NPAs) detect atoms (i.e., neutralised ions) which escape plasma. As neutral atoms are not bound by the magnetic field they may escape the plasma and give information on the ion population even deep inside plasma. The NPAs measure the escaping atom flux in terms of atom species and energy as function of time. There are two NPAs at JET. The high energy NPA (GEMMA-2M, diagnostic ID: KF1) is installed on top of the JET machine and has a vertical line-of-sight. It can be configured to measure one ion species on eight energy channels with energy of 250–1 600 keV for hydrogen isotopes and up to 3 500 keV for He. The low energy NPA (ISEP, diagnostic ID: KR2) has a horizontal, radial line-of-sight through plasma centre. It measures simultaneously all three hydrogen isotopes on a total of 32 channels. The energy range can be configured from 5 keV to 750 keV (for H) by varying the electric and magnetic fields within the diagnostic. The original diagnostic hardware as well as all data collection electronics has been supplied to JET by Ioffe Institute, St. Petersburg.

During 2012, the commissioning of the new detector flange (Figure 3.35) with thin silicon detectors for the KF1 diagnostic has been completed and the performance has been demonstrated. The old detector flange with CsI(Tl) detectors had been replaced by a new flange with new, thin silicon detectors in 2011, and the commissioning as well as demonstration of performance continued throughout the 2012 campaigns. In addition to the detector flange, the entire data acquisition electronics had been replaced. The software for analyzing raw rata (1.5 GB per pulse) was developed and taken into use during spring 2012 campaigns.

The noise issues which were discovered upon installation continued to affect the acquired data until grounding arrangements at the preamplifiers were modified. The noise issues were also combated by implementing robust filtering algorithms in the data processing code. Eventually the noise could be reduced to a level where it does not impair the diagnostic performance.

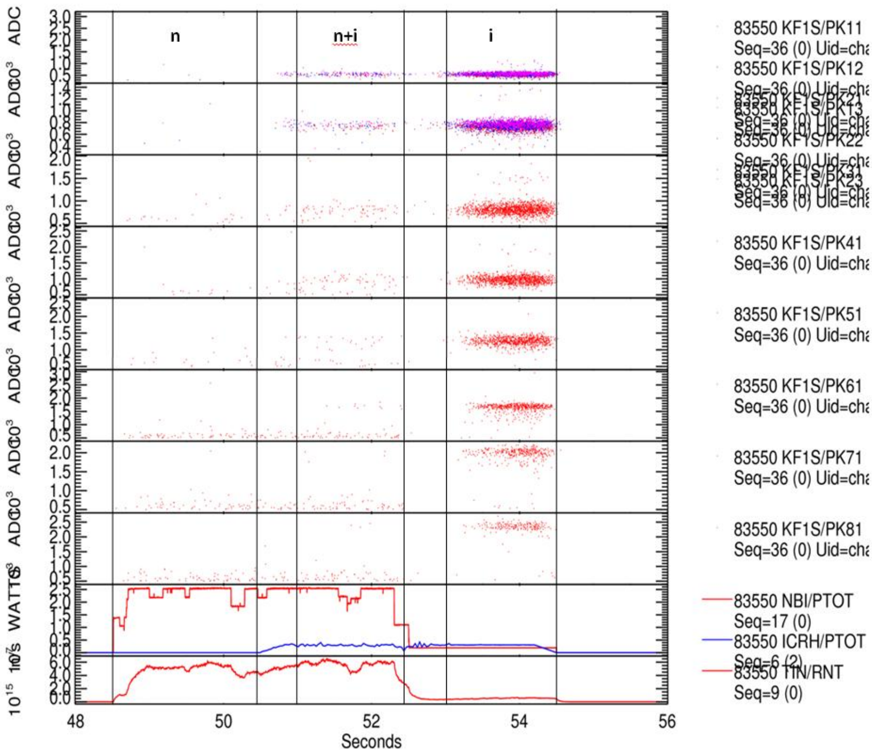

Figure 3.36. Overview of the pulse 83550 analysed for the pulse height spectra. The vertical axis shows pulse height and each dot represents one detected ion or other event. Initially there was a phase (48.5–50.5 s) with NBI only and no fast ions (n). After this some RF was applied and a slight ion tail developed (n+i, 51.0–52.5 s). Even later (53.0–54.5 s), NBI was reduced, and a strong ion tail developed (i). During high power a few small pulses were detected due to neutron background, however, these are well separate from large ion event detected during RF heating.

The performance demonstration in plasmas was completed during spring 2012 campaigns, despite the very limited production of high-energy ions in plasmas. Essentially all the goals initially laid out were achieved. Figure 3.36 shows an interesting pulse with periods of high neutron background as well as intense high-energy tail. It is evident that there are not very many neutron events (despite nearly maximum NBI power into plasma), and they are generally well separate from ion events during RF heating. Figure 3.37 further demonstrates the background immunity of the new detectors. It shows the background counts integrated over 2.8×10^{17} neutrons in 35 pulses by the different detectors. Especially striking is the performance of the two thin detectors which show almost no response at all. It is believed that the background is not caused neutrons directly but is due to neutron-induced gamma background in the JET torus all.

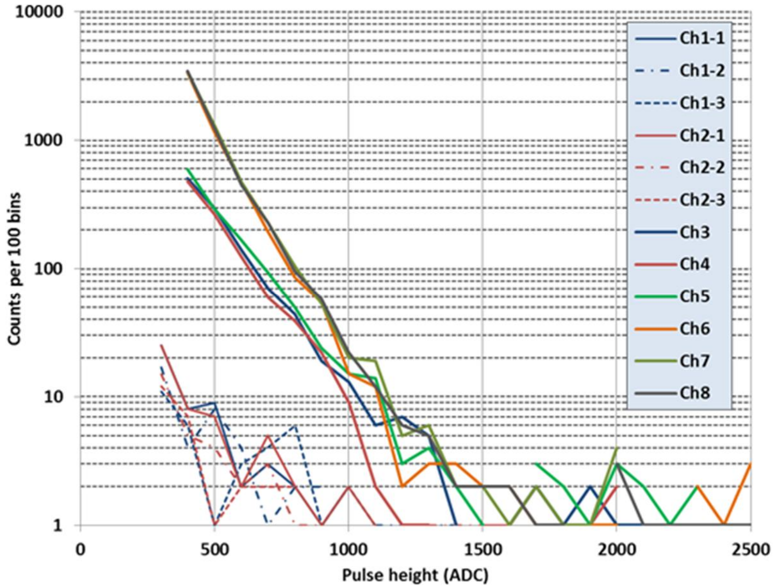

Figure 3.37. Neutron-induced background. Sum of 35 pulses with 2.8×10^{17} neutrons and 2.0 GJ of NBI energy. The response of the thin detectors (Ch1 and Ch2) is still almost negligible. The thick detectors do show some response, which may interfere with Ch3 ions in some cases.

As the final stages of the project, the new results were presented to the JET DVCM meeting in October. The new, processed data was approved to be produced as chain1 data. This is an improvement over the prior practice as the high-energy NPA has previously produced only so-called private data, i.e. data which is publically available but not advertised. Finally, the final project board was held in December and the upgrade was handed over to JET operator.

3.7.2 Development of new diagnostic for SOL flow measurements in the high-field side SOL of AUG

EFDA task: WP12-IPH-A01-1-15
Research scientists: T. Makkonen, M. Groth, T. Kurki-Suonio, AU
M.I. Airila, VTT
Collaboration: R. Dux, A. Janzer, T. Lunt, H.W. Müller, T. Puetterich, E. Viezzer, IPP Garching

The parallel flow profiles of injected CII and CIII have been measured in 2011 and 2012 using a spectrometer (reported in task 3.3.4.3). The injected carbon is not necessarily equilibrated with the background flow and there are 3D effects due to the toroidal curvature and radial transport of impurities. In order to understand the measured CII and CIII flow profiles, ERO simulations were carried out. Furthermore, synthetic diagnostics for replicating the actual spectrometer and video camera diagnostics were implemented in 2011 and 2012 and are reported in [T. Makkonen et al., Computer Phys. Comm., submitted]. Figure 3.38 shows a comparison between the synthetic ERO and actual camera diagnostics.

Besides allowing interpretative simulations of actual experiments, the ERO code with these diagnostics can be used to investigate the reliability of measuring the flow by methane injection. Simply put, one can perform a sensitivity study by injecting methane in ERO under various SOL conditions (density, temperature, and flow profile) and see what kind of CII and CIII flow profile should be observed. This work was started in 2012 and is ongoing.

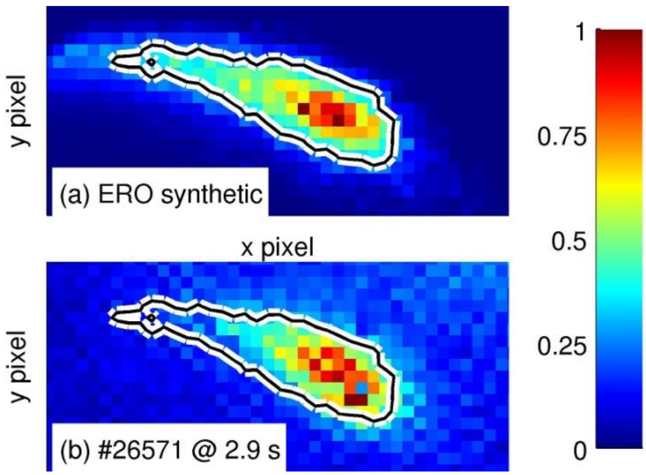

Figure 3.38. Comparison between the synthetic ERO and the actual camera diagnostics for carbon emission.

3.7.3 Fast particle probe measurements at ASDEX Upgrade

EFDA task:	WP12-IPH-A09-2-07
Research scientists:	S. Äkäslompolo, S. Sipilä, AU
Collaboration:	G. Bonheure, M. García-Muñoz, IPP Garching

Aalto University's ASCOT group members have a well established collaboration with ASDEX Upgrade fast ion measurement team. The main role of the ASCOT group is to perform fast particle simulations, but participation in the experiments is sometimes called for. In spring 2012, S. Äkäslompolo participated in the fast ion measurement campaign. He collaborated with Dr. Manuel García-Muñoz in setting up the FILD probe and data analysis software. Later ASCOT simulations of the measurements were performed. S. Äkäslompolo also collaborated with Dr. Georges Bonheure to prepare activation probe measurements. Äkäslompolo’s main contribution was to perform preparatory simulations of fusion product fluxes to the probe with the ASCOT code (see Figure 3.39). S. Äkäslompolo and S. Sipilä expanded the ASCOT suite of programs and routines to effectively use the fast ion distributions produced by ASCOT to calculate neutron fluxes and other particle fluxes.

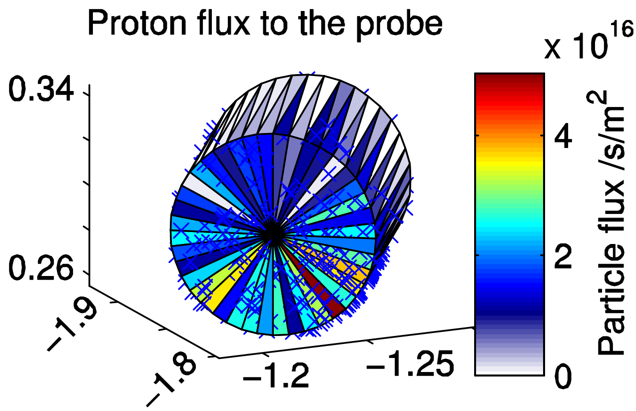

Figure 3.39. Particle encounters with the activation probe for a preparatory simulation calculated for a discharge similar to the actual experiments.

3.8 Emerging Technology and Power Plant Physics & Technology

3.8.1 Modelling of radiation effects in FeCr, tungsten and tungsten alloys

EFDA task: WP12-MAT-01-IREMEV
Research scientists: K. Nordlund, T. Ahlgren, L. Bukonte, K. Heinola, UH

Cementite and chromium carbide precipitates have been found to be present in most kinds of steels. How the presence of these precipitates will affect the mechanical properties of the steel is not yet fully known. In this study the interaction between different dislocations and the precipitates is investigated on atomic-level computer simulations. The results from this nanoscale investigation will be used as parameters for another kind of computer simulation methods that can simulate macroscopical effects and long time scales.

The first objective was to generate the simulation cell needed for our investigation. We have been able to generate such a box with an edgedislocation inside. In this simulation cell an arbitrary amount of chromium can be added randomly, which is a good approximation for a Cr-concentration below 10 %. Also different sized voids can be added to the system at different heights compared to the dislocation core. The interaction with a void is already a known phenomenon, but it is important to compare our results, from the new potential, with old results. Another reason for the void generation is that it can be filled with precipitates of different kinds and orientations, which is one of the main goals.

We have done a set of simulations with different void sizes and different potentials, to be able to see qualitatively the differences. The next step is to calculate the stresses to get data that can be compared with experiments. The implementation of the stress calculation is underway. When this is implemented, our results can be compared to earlier to see how they agree. When our new potential is validated the simulation of the dislocation movement and interaction with different precipitates can begin. Always when new data is available the results will be used in the other simulations methods.

The results we have got this far is a qualitative comparison between an Embedded Atom Model, EAM, potential and our Tersoff potential. The figures show how the dislocation will interact with a void in both potentials. A clear difference can be seen, in the EAM potential the dislocation core is more symmetrical than in the Tersoff potential. The phenomenon can be explained with different glide planes in our simulation cell and the difference between the types of interaction potential. From the qualitative study we see that the dislocation is pinned harder in the Tersoff potential than in the EAM potential (Figure 3.40).

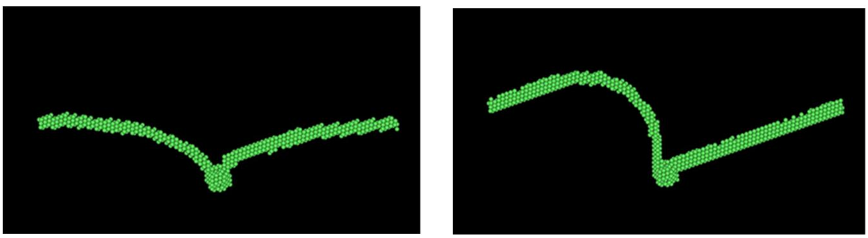

Figure 3.40. Comparison of typical dislocation geometries in simulations using the EAM potential (left) or the Tersoff potential (right).

3.8.2 Defect calculations in tungsten

EFDA task: WP12-IPH-A11-1-09
Research scientists: K. Nordlund, T. Ahlgren, L. Bukonte, K. Heinola, UH

The high flux of H isotopes from fusion plasma has been experimentally seen to introduce vacancy type defects in tungsten, which are the main reason for tritium retention in fusion reactor materials. It is crucial to understand and explain the experimentally observed vacancy formation and how it affects the plasma parameters. The present research objective is to identify the mechanisms how these H isotope trapping vacancy type defects are created and their mobility in W. This work is performed computationally using Molecular Dynamics (MD) simulations at different temperatures and H concentrations. The obtained results from MD simulations are compared with experiments and Density Functional Theory (DFT) results. The vacancy formation energy close to the surface is calculated to be 3.5 eV, which is in good agreement with DFT results. This energy decreases with increasing H concentration in W lattice as:

$$E_{\mathrm{vac}}^{\mathrm{fs}} = \left[E_{\mathrm{vac}+n\mathrm{H}^{\mathrm{O}}} + \frac{N+1}{N} E_0\right] - \left[E_{n\mathrm{H}^{\mathrm{T}}} + E_0\right], \quad (1)$$

where N is the number of atoms in the cell without defects, $E_{vac+nHO}$ is the cell with n hydrogen atoms in a W monovacancy in octahedral position, E_{nHT} the total energy of the system with n hydrogen atoms in tetrahedral interstitial positions close to each other, and E_0 the total energy of the system without defects. Table 3.1 shows how the vacancy formation energy close to surface decreases with increasing H atoms present. In Figure 3.41 is presented the time and temperature dependence of vacancy concentration with two different H concentrations simulated by MD.

Table 3.1. Vacancy formation energy close to surface as a function of H.

nH	0H	1H	2H	3H
E_{vac}^{fs}	3.5	1.48	-0.52	- 2.42

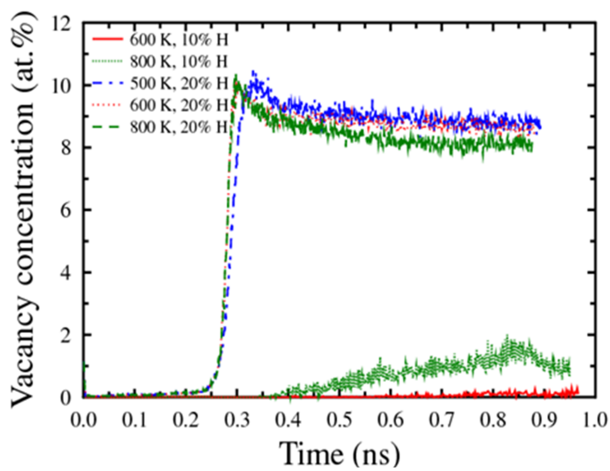

Figure 3.41. Vacancy formation close to the surface at 500, 600, and 800K at 10 and 20 % of H from MD simulations.

It is experimentally seen that under certain conditions vacancies form not only close to the surface, but also in bulk tungsten, therefore vacancy formation mechanism is studied in bulk W under supersaturation of H. The vacancy formation energy was calculated with MD for different size self-interstitial atom (SIA) clusters and H concentrations in W. The energy needed for one W atom to leave its lattice site, forming a vacancy and increase SIA cluster size by one W atom, can be calculated from:

$$E_{\text{vac}}^{\text{fb}} = \left[E_{\text{vac}+n\text{H}^{\text{O}}} + E_{m\text{SIA}}\right] - \left[E_{n\text{H}^{\text{T}}} + E_{(m-1)\text{SIA}}\right], \quad (2)$$

where $E_{vac}+n_{HO}$ is the total energy of the cell with n hydrogen atoms in W monovacancy in octahedral position, E_{nH}^{T} is the total energy of the system with n hydrogen atoms in tetrahedral interstitial positions close to each other, and E_{mSIA} and $E_{(m-1)SIA}$ are total energies of the system with *m* and (*m* - *1*) sized self-interstitial atom clusters, respectively.

Table 3.2. Vacancy formation energies in bulk W – the energy needed for one W atom surrounded by n H atoms to leave its lattice site, forming a vacancy and increase SIA cluster size by one W atom.

nH / $(m-1)$SIA to mSIA	0H	1H	2H	3H
1 SIA to 2 SIA	10.2	8.2	6.2	4.3
2 SIA to 3 SIA	9.7	7.6	5.6	3.7
3 SIA to 4 SIA	7.1	5.1	3.1	1.2
4 SIA to 5 SIA	5.6	3.5	1.5	-0.4

The presence of H in tungsten lattice lowers the potential energy of W atoms surrounded by H, thus the energy needed to form a vacancy decreases with increasing H concentration. To minimize the energy of the system, SIA atoms tend to form larger SIA loops. The results are summarized in Table 3.2.

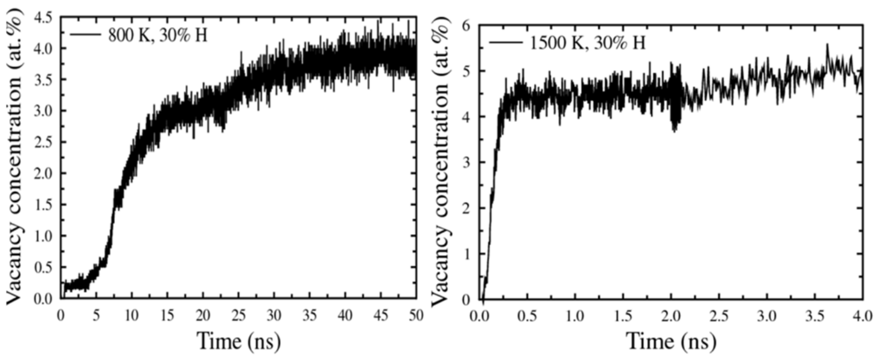

Figure 3.42. Vacancy formation in bulk at 800K and 1500K at 30 % of H.

The vacancy formation close to W surface and in the bulk (Figure 3.41 and Figure 3.42) is seen to be mainly driven by the H concentration rather than temperature, whereas the rate at which the vacancy equilibrium concentration is achieved, is temperature dependent.

Migration of vacancies in W is studied at different temperatures from 1 300 K to 3 200 K (Table 3.3). Monovacancy diffusion pre-exponential factor and activation energies are calculated. Results show the occurrence of long vacancy jumps at high temperatures, which increases diffusion coefficient and thus might explain the upward curvature of Arrhenius plot for tungsten self-diffusion.

Table 3.3. Monovacancy diffusion jumps. At high temperatures long monovacancy jumps are observed in <111> direction.

Temperature \ Nr. of jumps	1	2	3	4	5 – 15
1300K	100 %	–	–	–	–
2500K	99.7 %	0.28 %	0.004 %	–	–
3200K	98.5 %	1.35 %	0.044 %	0.003 %	0.103 %

3.8.3 Power plant power exhaust studies

EFDA task: WP12-PEX-01
Research scientists: L. Aho-Mantila, M. Airila, VTT
Collaboration: C. Lowry, EFDA CSU Culham
M. Wischmeier, IPP Garching
X. Bonnin, LSPM – CNRS
C. Björkas, D. Borodin, A. Kirschner, FZ Jülich
ASDEX Upgrade Team, JET-EFDA Contributors

Introduction: Given the inability to obtain complete DEMO edge regimes in present experiments, numerical modelling is required to predict power exhaust in future fusion reactors. It is essential that the models used in the extrapolation agree with the edge regimes achieved in present-day devices. In 2012, efforts were made to characterize edge regimes of impurity-seeded discharges in ASDEX Upgrade and JET, in order to benchmark the state-of the art plasma modelling for conditions with significant radiative power exhaust.

Main results in 2012: Low-density L-mode experiments with various levels of N impurity seeding were conducted at both ASDEX Upgrade and JET. The JET experiment was conducted with an open, horizontal outer target configuration. Steady conditions were obtained in each discharge with N seeding. At all seeding rates, most of the radiation was measured in the SOL plasma, increasing rapidly as a function of seeding rate until the total radiated power was 60 % of the total input power. Consequently, the divertor cooled down, leading to significant reductions in target heat loads and a roll-over in the tungsten sputtering yield with increasing seeding level. Further increases in seeding rate did not lead to higher radiated power fractions, within the investigated seeding levels.

In ASDEX Upgrade, both unseeded and seeded discharges were characterized in closed vertical target geometry. At the lowest seeding rates, radiation was measured mainly in the divertor plasma. At the highest seeding rates, radiation concentrated at the X-point location where it increased rapidly at a constant seeding level, leading to a disruption. Hence, an upper limit of steady-state radiated power fraction was observed.

SOLPS5.0 simulations have been prepared to describe these experiments, using the highest level of physics description available in the code package, namely multiple impurity species, kinetic neutral description and activated drift and current terms. Extensive scans of the incremental effects of seeded impurities have yielded radiation patterns and in-out asymmetries qualitatively similar to those observed in the experiments. To prepare for modelling of the erosion of divertor targets, a pre-processor was developed for transferring the SOLPS plasma solutions into the ERO code. The work in 2013 will focus on addressing the features of strong X-point radiation and divertor geometry.

3.8.4 Arc-discharge cleaning of surfaces at atmospheric pressures

EFDA tasks:	WP11-ETS-DTM-01-01; WP11-ETS-DTM-01-02
Research scientists:	A. Hakola, J. Karhunen, J. Likonen, VTT M. Aints, M. Laan, A. Lissovski, P. Paris, UT
Collaboration:	J. Kolehmainen, M. Koskinen, S. Tervakangas, DIARC-Technology

Arc-discharge-based techniques are potential candidates for cleaning the main-chamber tiles of ITER from co-deposited layers. In these approaches, arc discharges are ignited on the surface to be cleaned, which results in the ejection of material normal to the surface. After a certain material-dependent number of arc pulses, the topmost layer is completely removed and the cleaning device can be moved to a new location.

The work in 2012 concentrated on the design and construction of an arc-discharge device such that the device would work at atmospheric pressures of nitrogen in the ITER vessel. In addition, a spectroscopic system was designed and implemented to determine when the surface is clean enough for the arc-discharge device to move on to the next uncleaned spot on the surface. The present design allows cleaning samples with areas of 200 × 200 mm^2 and thicknesses up to 90 mm. During the actual cleaning phase, argon flow is switched on to reach the pre-determined operational pressure of the device; argon is used as the process gas to prevent the formation of nitrides and oxides.

For the cleaning experiments, a set of pure Al as well as mixed Al-W, C-W, and W-Al-C samples, all having a 1-μm thick coating on stainless steel were produced using the vacuum-arc deposition systems at DIARC-Technology Inc. The best cleaning results were obtained at 2.0 mbar of Ar. By visual inspection, the cleaned surface is rather homogeneous and only at single spots shows signs of local melting of the substrate (see Figure 3.43 for an example). The cleaning rate is estimated to be 2×10^{-10} m^3/s but this can be further increased by using different power supplies and higher repetition rates for the arc pulses.

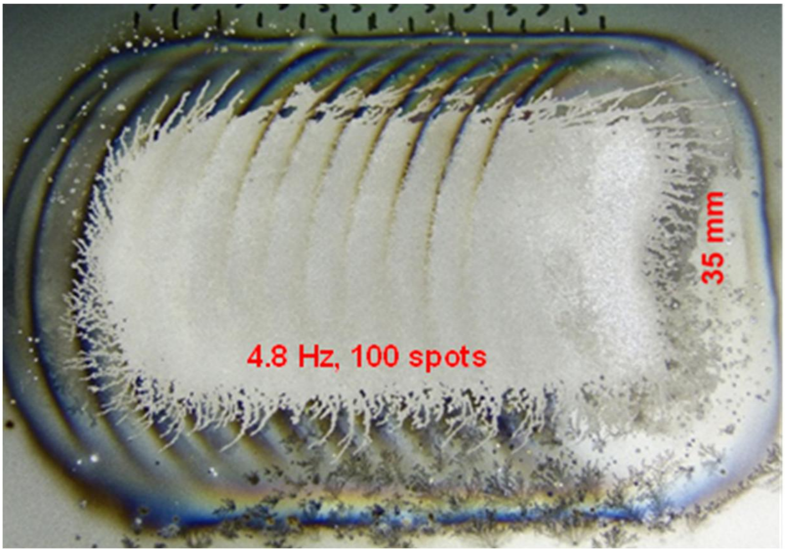

Figure 3.43. Photograph of the cleaning patterns formed on the surface of a C(90%)-W(10%) sample at 2.0 mbar of Ar. Here, the head of the arc-discharge device has been moved 13 times at 5 mm steps on the surface.

Considering the spectroscopic detection system, it made use of two observation windows through which the emitted light could be recorded. All the elemental lines of interest were visible, even though some of them (mainly those from carbon and tungsten) were rather weak and mostly overlapped by argon, iron, or chromium lines. One should take into account that the arcs do not stay at the same spot all the time, which results in the spectra being relatively noisy and showing large changes in the intensity levels of the different spectral lines. In addition, the spectra fluctuated between “coating-like” and “substrate-like” because every now and then the arcs jumped from the surface to the steel parts of the vacuum chamber – which was at the same potential as the sample surface.

Despite these complications, we were able to extract, e.g., the Al/Fe ratio of the pure Al coatings and C/Ar ratio of the mixed C-W coatings. Both these ratios, illustrated in Figure 3.44, demonstrated that as the number of arc pulses increases, the coating became thinner and the substrate signal became more dominant. Therefore, we can spectroscopically determine when the surface is clean from the deposited layers.

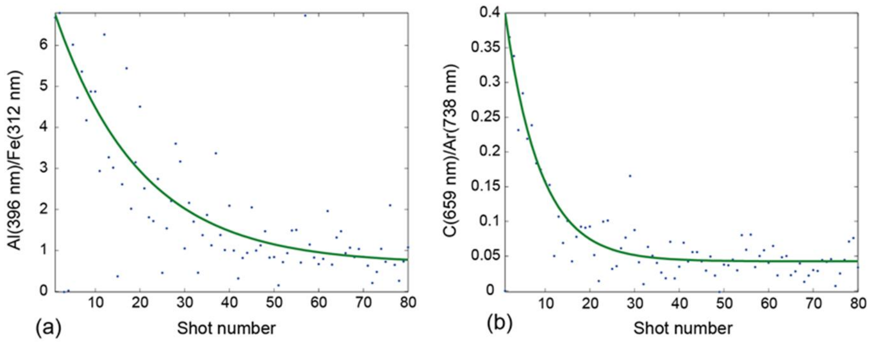

Figure 3.44. (a) Ratio of the AlI (396 nm) and the FeI (312 nm) lines (dots) as a function of arc pulses and an exponential fit (green solid line) for a pure Al sample, (b) corresponding ratio of the CI (659 nm) and the ArI (738 nm) lines for a C(90%)-W(10%).

3.8.5 Remote handling studies for DEMO

EFDA task: WP12-DAS-06-T04
Research scientists: M. Siuko, J. Järvenpää, VTT

In DEMO design, one important consideration is availability. The availability is greatly affected by the efficiency of reactor maintenance. In this research the latest studies of DEMO divertor maintenance were done.

DEMO reactor design is proposed to have 16 toroidal field coils. Between each coil is a port, which makes totally 16 ports. It is assumed that each port can be used for divertor maintenance as reactor access port.

By designing divertor to consist of 48 cassettes, it makes 3 cassettes per each of the 16 ports. Through each port, one cassette can be handled straight to the port, one at left and one at right. By this arrangement, there is no need for separate in-vessel cassette carrier. When comparing to ITER, much simpler maintenance procedure and logistics can be achieved.

The divertor ports are inclined 45 degrees downwards (Figure 3.45). Due to the inclination and the cassette load, ITER-like rack-and-pinion drive is not suitable for mover drive. However, ITER second cassette end-effector can be used as example when developing end-effector to handle the three DEMO cassettes through one port. For carrying the end-effector through the radial tunnel, a telescopic boom seems feasible solution. To carry part of the cassette weight, the supporting rails on the tunnel walls are necessary.

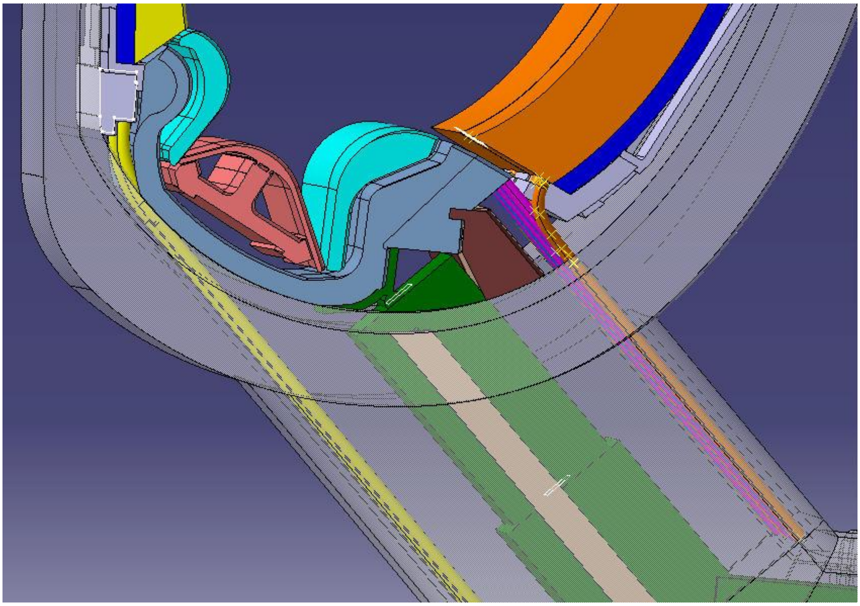

Figure 3.45. Cross section of the DEMO Divertor maintenance port.

Like in ITER, the mover (in this case radial telescopic boom) is operating from the transportation cask. Due to the tunnel inclination and therefore high forces, the high loads need to be considered in the cask docking system.

The lower end of the radial tunnel has docking interface for the transportation cask. The interface is vertical and planar to provide easy interface for the cask to align.

Each of the cassettes is equipped with two cooling fluid pipes, inlet and outlet. The pipes are 125 mm outer diameter with wall thickness of 15 mm. The most suitable arrangement is that the pipes of the three cassettes are going through the same port than the cassettes are transported. During the cassette removal process, first the cooling pipes are removed and carried out from the tunnel, then the cassettes.

Each of the blankets has also cooling system drain pipe down at the divertor area. Those pipes can go through the reactor wall, or they may also be guided through the maintenance tunnel.

The cassette-reactor connection has to support DEMO high magnetic forces and to provide simple, robust operation after DEMO harsh conditions. The ITER-like cassette inboard locking can be used, as well as the cassette preloading to avoid the cassette locking system clearance which could cause the cassette “shaking” under magnetic fields. The cassette outboard locking mechanism has to be designed such a way that it generates the preloading with simple mechanism. The design proposal is under work. The work for DEMO divertor maintenance continues in 2013.

3.8.6 RAMI tools for DEMO

EFDA task: WP12-DTM-02
Research scientists: R. Tuominen, T. Ahonen, VTT
Collaboration: CCFE (UK), ENEA (IT), CIEMAT (ES), LEI (LT), IST (PT)

High plant availability for continuous power production is considered as an essential characteristic to be strongly addressed in the design and development of the future DEMO facility. In the EFDA Work Programme for 2012 on Design Tools and Methodologies (DTM) a specific activity was issued aiming on a review of the state-of-the-art methodologies and an initial specification of processes, methods and tools needed for reliability and availability design and assurance in the DEMO fusion power plant development project. The study aimed to start establishing a vigorous reliability and availability growth and risk minimization programme for the design and development of DEMO systems and components starting already from the pre-conceptual and conseptual design phases.

The study was carried out in a collaboration of five European organisations experienced on RAMI methodologies in the field of fusion and other technologies, i.e. CCFE, ENEA, CIEMAT, LEI, and IST, and comprised five sub-tasks dedicated to: (1) availability growth based on historical data; (2) RAMI requirements analysis; (3) RAMI management process; (4) RAMI assessment methodology; and (5) evaluation of RAMI tools. VTT was involved in particular in tasks four and five.

The study produced recommendations on the establishing of an effective RAMI management process for the DEMO development work. Furthermore, it produced recommendations on the methodologies and available tools for analysis and definition of RAMI requirements for the DEMO systems and for assessment and prediction of the reliability and availability performances of systems and components. The elaboration of RAMI tools and methods for the DEMO development project will be continued with dedicated tasks in the EFDA Work Programme 2013.

4. Activities of the Estonian Research Unit[2]

4.1 Erosion/deposition investigations using laser-induced breakdown spectroscopy (LIBS)

EFDA task:	WP11-ETS-DTM-01-05
Research scientists:	M. Laan, M. Aints, A. Lissovski, P. Paris, K. Piip, UT
	A. Hakola, J. Likonen, VTT
Collaboration:	H. Mändar, I. Jõgi, J. Kozlova, UT
	T. Haikola, J. Kolehmainen, S. Tervakangas, DIARC Technology
	P. Petersson, M. Rubel, KTH

The study is related to the development of ITER relevant laser techniques for deposited layer characterisation. Using LIBS, laboratory testing of samples with mixed W–Al–C deposits on bulk tungsten substrates (simulating ITER-like deposits with Al as proxy for Be) has been carried out. The main task of the study was to find out a method which allows on the basis of LIBS measurements the estimation of relative concentrations of sample constituents.

The coatings were produced by the DIARC® arc-discharge method. Nd:YAG (λ = 1064 nm) laser produced the plasma plume of the sample material. Mechelle 5000 (Andor Technology) spectrometer with an ICCD camera recorded single-shot, time-resolved emission spectra in the 250–850 nm wavelength range. The delay time t_d between the laser pulse and the opening of the time gate was $\approx$ 100 ns and the time gate width was Δt = 400 ns. Single-shot LIBS spectrum was presented as a function of laser shot number.

Using instead of the intensity of spectral line the cumulative intensity, a considerable smoothing of experimental results has been achieved (Figure 4.1). The slope of the cumulative intensity gives the averaged value of the intensity. Neglecting matrix effects, self-absorption and effects caused by differences in surface morphology, the ratio of the slope of a coating species to that of the bulk

---

[2] Other activities with the participation of scientists of Estonian Research Unit are described in sections 3.3.7, 3.3.8 and 3.8.4.

material should give the relative concentration of the species. However, the ratio of tungsten slopes in Figure 4.1 did not match with the results of NRA analyses. Depending on the used spectral line of a species, the ratios had very different and sometimes unreal values. First of all we related this result to the self-absorption which depends on the population of the lower energy state of the corresponding transition. Because of high plasma plume temperature, $T \sim 10^4$ K, the states with ≤ 5 eV energy are highly populated and they could not serve for quantitative LIBS analyses. Most of detectable tungsten lines as well as those of Al I should be influenced by self-absorption. At the same time, states of Al II have energy > 10 eV, i.e. these lines could serve as LIBS analytes. The average value of the slopes' ratios of nine Al II line was 0.45, while from NRA followed the concentration value 0.5 (Figure 4.2). More detailed analyses showed that the self-absorption is not the only factor influencing the ratio of slopes. Figure 4.3 indicates that the ratio of slopes is an exponential function of the upper state energy of the corresponding transition. The effect is explainable assuming different excitation temperatures of samples compared, $T_x \neq T_B$.

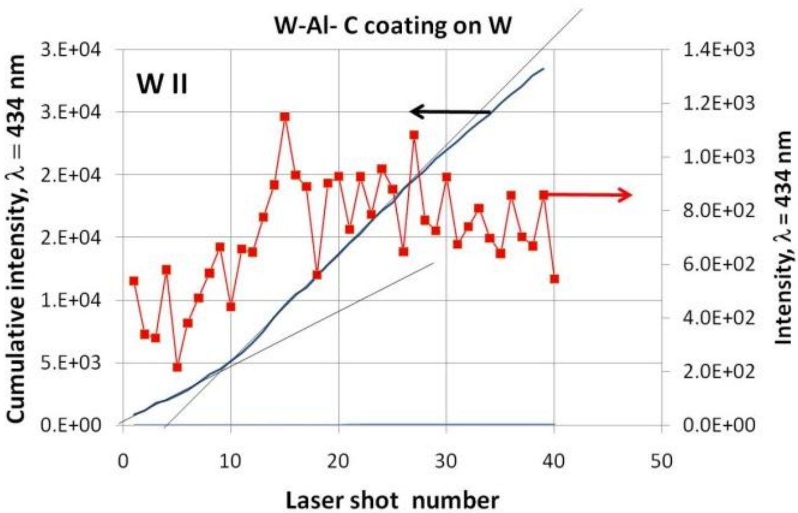

Figure 4.1. The coating is removed by ≈ 10 shots, changing the tungsten slope.

In the case of Boltzmann distribution, in plasma the population of the energy state *k* is

$$N_k = \frac{N_0}{U(T)} \exp[-E_k/k_B T], \tag{3}$$

where N_0 is the total concentration a species in the plasma plume, T is the excitation temperature, $U(T)$ is the partition function and k_B is the Boltzmann constant. Thus, the ratio of slopes is

$$R = \frac{N_0^x}{N_0^B}\frac{U^B(T_B)}{U^x(T_x)}\exp\left[-\frac{E_k}{k_B}\left(\frac{1}{T_x}-\frac{1}{T_B}\right)\right], \quad (4)$$

i.e. the ratio depends exponentially on energy E_k because of different temperatures. It should be pointed that in the case of small temperature difference $U^B \approx U^x$ and for estimation of the relative concentration the knowledge about the temperatures is not needed.

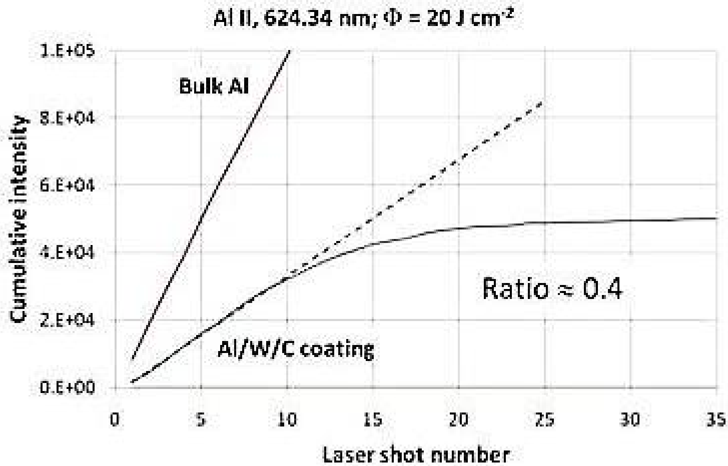

Figure 4.2. Ratio of slopes of a selected Al II line has a realistic value.

4.2 AMS and FC Measurements of tritium in laser cleaned tiles and tritium depth profiles in JET divertor tiles

JET TF-FT task:	JW12-FT-1.20
Research scientists:	M. Kiisk, UT
	J. Likonen, S. Koivuranta, VTT
Collaboration:	G. Kizane, L. Baumane, J. Gabruesnoks, M. Halitovs, L. Avotina, A. Zarins, AEUL-Latvia
	C. Stan-Sion, M. Enachescu, M. Dogaru, A. Petre, MEdC
	JET-EFDA contributors

4.2.1 Introduction

Accelerator Mass Spectrometry (AMS) and Full Combustion (FC) method have been applied for determining the tritium activity concentrations at JET divertor tiles over the last 7–8 years. The two methods have two principle differences – the range of detection and spatial resolution. For those reasons the two methods are complementary to each other. However, these characteristics may complicate the comparison of the two techniques in case of typical JET divertor samples. For that reason a cross comparison exercise for tritium measurements between the two methods was performed. The exercise comprised a manufacturing of identical standard samples for both methods, cross comparison measurements of the standard samples and selected samples from JET divertor tile (laser treated and non-treated samples from tile *14 IN G3B* design SRP 2001–2004). Results of this study provide information concerning the efficiency of tritium removal from the plasma facing surface of the divertor tiles by means of laser ablation.

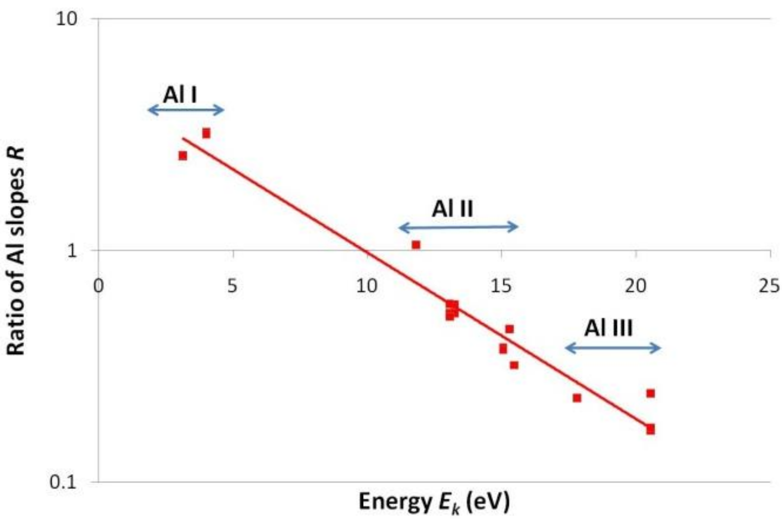

Figure 4.3. Ratio of slopes depends exponentially on the energy of the upper state of the corresponding transition.

4.2.2 Standard samples

Standard samples with different tritium concentration are needed for the calibration of both FC and AMS methods. Their measurement by the two methods will contribute as a first step and important test in the cross-comparison. Standard samples of this type are not commercially available and therefore, homemade manufacturing is needed. For preparation of tritium standards in graphite matrix, a validated sample preparation procedure has been applied [C. Stan-Sion et al., UPB. Sci. Bull. A **66** 2004].

To determine the systematic deviation of the two methods related to the measurement of different tritium activities, standard deviation of three measurements were calculated. Table 4.1 gives the standard deviations for the standard samples measurements performed by the two employed methods.

Table 4.1. Cross comparison of measurements of the new standard samples by AMS and FCM methods.

Standard sample activity (Bq/g)	Uncertainty (Bq/g)	
	AMS	FCM+SD
50	±5	±7
100	±11	±12
200	±15	±14

4.2.3 Sample preparation

Samples were drilled from the JET divertor tile *14 IN G3B* (exposed in 2001–2004). Then, samples were cut as cylinders with a diameter of 16 mm. Figure 4.4 shows the locations of the extracted samples from the tile. Due to the fact that surface is not flat but has a certain curvature, as can be seen from Figure 4.4, the thickness of the drilled core varied between 6 and 7 cm.

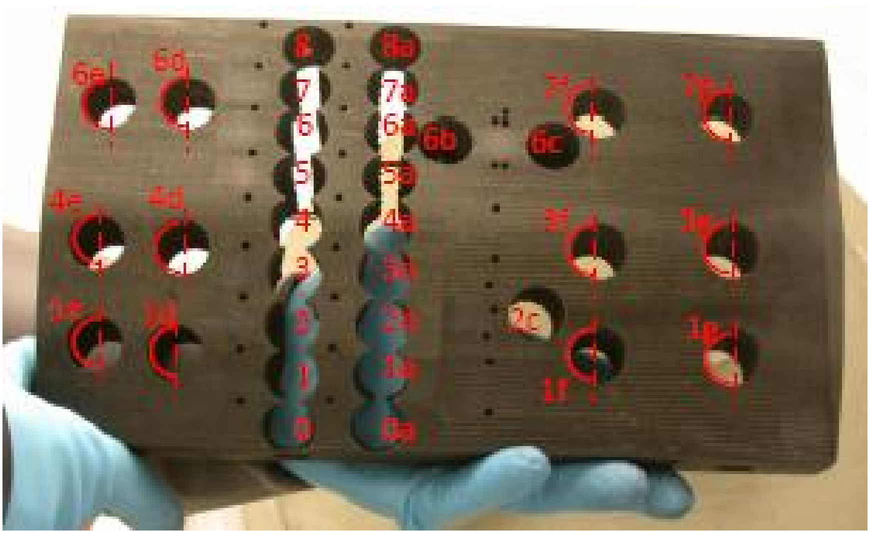

Figure 4.4. The divertor tile 14 IN G3B (2001–2004) and various locations of the cuts performed by Tekes for the tritium analyses. The right half part is the laser treated (detritiated) surface. The corresponding drilled cylinders for the AMS and FCM measurements are 7f, 3f and 1f. While the non-detritiated cylinders 4e and 6e were extracted from the left side of the tile.

4.2.4 Cross-comparison of results

Figure 4.5 presents the comparison of measured tritium values in the first slices of the cylinders: 1f, 3f, 7f, 4e and 6e. The cylinder 1e was destroyed during the cutting procedure and only few slices could be recovered including the first, surface slice. These surface slices contain the peaking of the tritium concentration and consequently the major contribution to the inventory of the tritium retention. Therefore, the comparison of these results is most relevant. There is a clear difference in the absolute surface values between the three detritiated slices (1f, 3f, 7f) and the two untreated slice samples (4e and 6e).

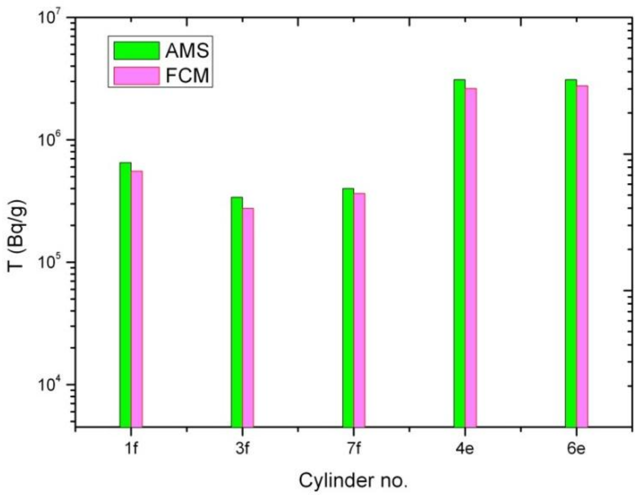

Figure 4.5. Comparison of the integrated values of tritium retention in the surface slice measured by the AMS and FCM methods.

4.2.5 Measurement of the detritiation efficiency by Laser ablation

Figure 4.6 presents the T depth profile measured by AMS from a detritiated (7f) and the neighbouring non detritated slice (6e). Similar spectra were obtained for the other pairs of samples.

4.2.6 Conclusions

The main goal of this investigation was to make an inter-comparison study between the Full Combustion Method followed by Liquid Scintillation detection and the Accelerator Mass Spectrometry method in measuring tritium retention in divertor tiles of JET reactor.

Both methods have proven to be able to measure tritium in an efficient and accurate way in the plasma facing materials with good agreement.

However, some differences occur from the specific part of each experimental method used. AMS method provides best available measurement sensitivity for small sample quantities. The disadvantage of the high sensitivity is that samples with high T activity concentrations pose a risk for a contamination of the detection system and therefore risk for a cross-talk between the samples to be measured.

The FC method has the highest sensitivity among decay detection methods due to high inherent detection efficiency of the liquid scintillation counting. In order to achieve the same sensitivity with AMS, the required sample quantity is larger. However, there are no principle reasons for limiting the upper T activity level. Therefore, it should be emphasized that the two methods are complementary and highly useful in combination, especially when high and low tritium activities have to be measured.

The performed comparison showed that in spite of experimental differences, the two methods provide values of specific tritium activities in divertor samples that agree within an 18 % standard deviation, the largest deviation being 25 %. However, when comparing the deviations of the methods for standard samples and the slices from divertor tiles, majority of the deviation is assumed to originate from actual difference of the parallel samples and possibly from the principle differences between the two methods in averaging the activity over different volume of the sample.

Presented results have been reported at the Task Force Fusion Technology 2012 Semi-Annual Monitoring 11–14 December 2012, JET Culham Science Centre.

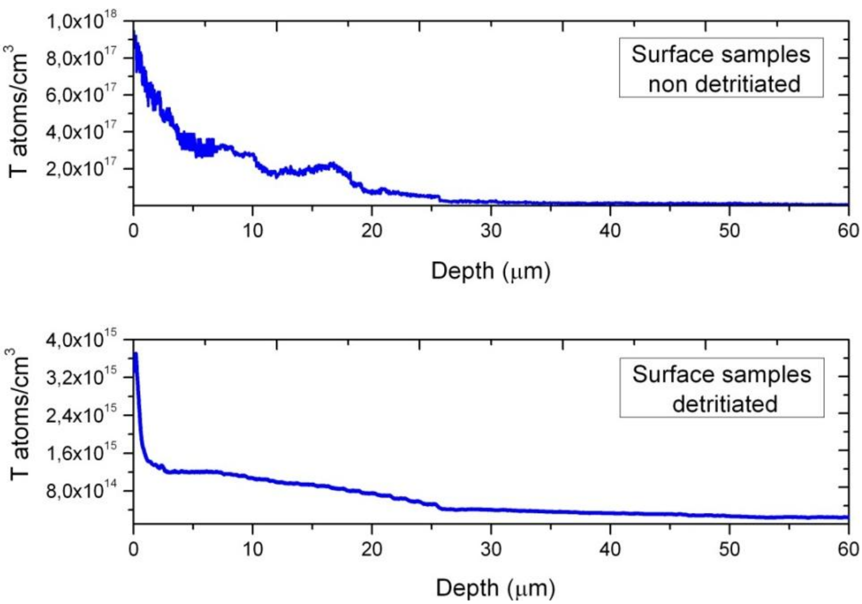

Figure 4.6. AMS concentration depth profiles of tritium retention in CFC tiles before and after LASER ablation.

5. CSU and JOC Secondments, TFL Activities, Staff Mobility and Training

5.1 EFDA CSU Secondment

J. Lönnroth has acted as Responsible Officer in the Programme and Analysis Group in the JET Department of the EFDA Close Support Unit at EFDA-JET in the United Kingdom starting from 1 November 2012.

The work as Responsible Officer has involved assisting with the coordination, preparation and implementation of the JET Work Programme. Important responsibilities have been to contribute to the organisation and monitoring of the EFDA Associates' participation in the JET experimental campaigns, to establish the JET programme priorities in collaboration with the JET Task Force Leaders and to supervise the work done by the JET Task Forces.

Another area of responsibility has been the technical supervision of the JET Operation Contract in interaction with the JET Operator. Most importantly, this work has involved monitoring the activities of the JET Operator in maintaining and upgrading the suite of high level analysis codes provided to JET scientists and to set priorities for the development of these codes.

The duties as Responsible Officer have also included being responsible for providing the JET interface to the EFDA Integrated Tokamak Modelling Task Force, to the International Tokamak Physics Activity expert groups and to the IEA Large Tokamak collaboration agreement. In particular, the work has involved coordinating and managing the licence agreements for the use of JET analysis codes on other machines and by non-EFDA parties.

Finally, an important responsibility has been to develop and reorganise the JET Users' website and to maintain, in particular, the Programme and Analysis branch of it.

5.2 CCFE JOC Secondments

5.2.1 JET Plasma Boundary Group

Name of secondee:	K. Heinola
Sending institution:	University of Helsinki
Host organisation:	JET Plasma Boundary Group
Reporting period:	1 February–31 December 2012

Kalle Heinola was seconded from 1 February 2013 to Erosion/Deposition Section at JET Plasma Boundary Group in CCFE. The secondment is long-term for four years as Plasma-Wall Interaction Scientist. The Erosion/Deposition Section is responsible for the long-term material migration and fuel retention studies in the ITER-like wall (ILW) and Following-ILW campaigns (FILW). These studies involve installing and replacing both passive and active diagnostic systems in dedicated interventions in-between experimental campaigns.

Main responsibilities of the Secondee are

- Organising, with the assistance of JOC technical staff, removal of long-term samples and their sending to European Associations participating in the surface analysis activity
- Design, procurement and installation of long-term samples required for future JET operation
- Participation in development of new surface diagnostic concepts
- Co-ordination of JOC activities linked to exploitation of the marker tiles
- Assisting with operation and/or maintenance of JET systems for which the JET Plasma Boundary Group is responsible of

Summary of Secondee's activities/milestones achieved during the reporting period

- Participation in surface analyses of JET carbon first wall tiles [A. Widdowson, C.F. Ayres, S. Booth, J.P. Coad, K. Heinola, et al., J. Nucl. Mat., accepted]
- Development of a numerical 3-D fitting tool used for surface profiling and scripting surface analysis routines
- Surface analysis of replacement W and Be tiles for FILW intervention 2013 (JW13-FT-3.82 "Material transport and erosion/deposition in the JET torus")
- Research for a 3-D Non-contact Surface Profiling measurement system
- Preparation activities for FILW intervention taking place in beginning of 2013
    - Diagnostics: wiring survey and power supplies for Quartz Microbalance diagnostic (QMB), improvement of ex-vessel QMB diagnostic system and preparation for QMB assembly and refurbishment (JET Experiment M13-03)

  - Diagnostics: Rotating Collector mechanism and wiring survey
  - Diagnostics: replacement Mirror sample reflectivity measurements (JW13-FT-3.78 "Analysis of mirrors exposed in JET-ILW and procurement of mirrors for exposure in JET 2014 campaigns: First Mirror Test for ITER")
  - Planning and setting up designated area for ^{10}Be Sampling Experiment in JET Beryllium Handling Facility 3 (JW13-FT-3.77 "Marker experiment with ^{10}Be in JET with ITER-like wall")
- Fusion Technology Task Proposals
  - Inclusion of Molecular Dynamics Simulations of Be/W alloying accepted in Fusion Technology Task JW13-FT-3.80 "Analyses of mixed materials on ILW samples using XPS/AES, XRD and RBS"
  - Secondee's proposal for a new Task accepted as JW13-FT-5.55 "Activation analysis of JET in-vessel components following DT irradiation". Secondee's JOC responsibility is to provide all the impurity and trace impurity compositions of in-vessel first wall components, which would be manually handled during and/or after JET D-T experiment
- Participation in JET operation
  - Disruption Mitigation Valve (DMV) Operator for the first DMV at JET [C. Reux et al., Fus. Eng. Design, submitted]
- Participation in JET EDGE Modelling Meetings
  - Plasma parameters from JET experiments and EDGE2D modelling to be used in Multi-scale Modelling of fuel retention in JET divertor. Multi-scale calculations are performed with Rate Theory Equations combining results from first-principles DFT calculations, MD simulations and experimental/EDGE2D data.

5.2.2 JET Data and Codes Management Group

Name of secondee:	T. Koskela
Sending institution:	Aalto University
Host organisation:	JET Data and Codes Management Group
Reporting period:	1 August–31 December 2012

Code management work: The version of ASCOT running coupled with JETTO/JINTRAC has been updated. Most noticeably the ripple module which had not been working since 2008 was rewritten and several bugs were fixed. An alternative way of computing the ripple as a 3D field was also added. Ripple runs can now be made with the most recent revisions with ASCOT. A new release version of ascot was made which encompasses the development in revisions from 1115 to

4015. Revision 4015 was tested to produce the same results on a standard test case, /u/fkochl/cmg/catalog/jetto/jet/78703/apr2712/seq#1/ppfseq.193.

Progress has been made towards making ASCOT4 available in JETTO. Most of the 1D output required by JETTO has been prepared, acceleration has been implemented and tested and a draft main program has been written, which compiles with the gfortran compiler, but does not run successfully yet.

Scientific work: Benchmarks between ASCOT and PENCIL have been made. It was found that with very extreme values of density and temperature, ASCOT and PENCIL results can differ quite significantly. Also effects, such as ripple, which are not included in PENCIL create a large discrepancy. The effect of TF ripple on the upgraded JET EP2 neutral beams has been simulated with ASCOT. The simulations showed that the expected heat loads are slightly lower than before, but the variance from discharge to discharge is much larger than the difference caused by the beam upgrade. Therefore, the recommendations for beam power in ripple discharges made in 2007 can still be used. Work has been begun to study the effect of main plasma tungsten impurity on neutral beam heating. The results have been submitted to be presented in EPS 2013.

5.2.3 JET Neutron Group

Name of secondee:	M. Santala
Sending institution:	Aalto University
Host organisation:	JET Neutron Group
Reporting period:	6 August–31 December 2012

During the JET shutdown the main activity has been the preparations for neutron calibration of the main JET neutron diagnostic. This will involve using the remote handling boom to move a high-intensity Cf-252 neutron source around JET vacuum vessel to mimic DD fusion neutrons from plasma. The response of different neutron diagnostics will be recorded in order to recalibrate them. Last time similar exercise has been carried out was in the 80's, and there have been numerous significant changes to the machine structure since. This activity is expected to take place in the early parts of 2013 prior to vessel pump-down at the end of shutdown.

5.3 Task Force Leader Activities

Name of secondee:	M. Groth
Sending institution:	Aalto University
Host organisation:	EFDA-JET
Reporting period:	1 January–31 December 2012

In 2012 **Dr Mathias Groth** was seconded to JET as a deputy task force leader for the exploitation of the JET ITER-like wall (E2). His primary activities included the following tasks: (a) execution of campaigns C29-30, (b) coordination of the JET edge modelling activities, and (c) scientific coordinator of JET experiments. He was stationed at Culham Science Centre during the entire calendar 2012 and visited Aalto University in May 2012 for five days under the secondment recall agreement. The task force leader assignment and thus long-term secondment ended in December 2012.

In executing the JET ILW experimental campaigns C29 and C30, the secondee was involved in the day-to-day activities at JET to ensure successful completion of the run plan, including reviewing of the machine status and scheduling experiments accordingly, holding weekly task force meetings, and contributing to review meetings. Other duties encompassed clearance of JET papers for conferences and scientific journals, including several major conferences in 2012: PSI, EPS, and IAEA-FEC.

In parallel to his regular activities, the secondee organised two edge-modelling meetings in June 2012 (two weeks) and November/December 2012 (three weeks). Both meetings brought together approximately 30 scientists from various European laboratories to simulate data from both the JET-C and JET-ILW experimental campaigns supporting interpretation of the experimental results and the development of predictive capability of future experiments.

The secondee was principal scientific coordinator of experiment Ex 3.1.2 “Characterisation of detached plasmas”, which was carried out in December 2011. Analysis of the data from this experiment and simulations thereof with the edge fluid code EDGE2D/EIRENE continued throughout 2012 and fed into two major conferences and associated publications (PSI 2012 and IAEA-FEC 2012). The seconded was also a co-scientific coordinator of other experiments aiming at the characterisation of the scrape-off layer in the ITER-like wall (Ex 1.1.4 and Ex 3.1.3). This task included the development of the experimental plans, the organisation of the experimental teams, execution of the experiment, and directing the analysis of data.

5.4 Staff Mobility Visits and Reports

5.4.1 Framework agreement between Associations Tekes and IPP: Power and particle exhaust

Names of seconded persons:	L. Aho-Mantila, A. Hakola, S. Koivuranta
Sending institution:	VTT
Names of seconded persons:	T. Makkonen, J. Miettunen, V. Lindholm
Sending institution:	Aalto University
Host institution:	IPP Garching

Toni Makkonen, under the supervision of Dr. Thomas Pütterich, has been developing a new kind of flow and impurity measurements using existing fast cameras and spectrometers. The preliminary results from these diagnostics during the experimental campaign 2011 have appeared very promising. Makkonen has also devised the corresponding synthetic diagnostics into the ERO impurity transport code, and remarkably good agreement with experimental data has been obtained. To further this work on both experimental and numerical sides, Makkonen should stay at IPP participating in the experiments and their analysis. Three to four 2 week-long visits are needed for this work.

Juho Miettunen, together with Dr. Taina Kurki-Suonio, enhanced the Monte Carlo–based orbit-following code ASCOT, normally used for fast ion studies, so that it can be applied for impurity tracing in the SOL. ASCOT is not based on fluid approach and, thus, naturally avoids many short comings of, say, DIVIMP and ERO (not a fluid code). The first results, showing that the 3D features of the first wall should not be ignored in impurity migration studies, have been accepted for publication as NF letter. Furthermore, ASCOT was used to decide which tiles to remove for analysis after the trace element experiments in 2011, and preliminary measurements show a remarkable agreement with ASCOT simulations. Now it is high time for Miettunen to learn to evaluate and extract experimental data from AUG and get networked with the relevant researchers at IPP. Six to eight weeks at IPP is foreseen for this purpose during 2012.

Antti Hakola is in charge of NRA, RBS, and SIMS analyses of various plasma-facing components such as marker tiles prepared for campaign-integrated erosion/deposition studies and marker probes produced for discharge-resolved erosion investigations. Hakola is also the TEKES responsible officer for the global tracer-injection and impurity-migration experiments. All this research is done is collaboration with Drs. Albrecht Herrmann, Karl Krieger, Matej Mayer, Hans Werner Müller, Rudolf Neu, and Volker Rohde, and requires several weeks of stay at IPP annually.

Seppo Koivuranta is doing NRA and RBS measurements of marker tiles at IPP together with Dr. Hakola. He makes one or two 2-week visits per year to IPP.

Leena Aho-Mantila is doing her post-doctoral work on power plant power exhaust studies. Aho-Mantila uses various versions of the SOLPS code package to model the scrape-off layer and divertor plasma both in existing devices and in a future demonstration fusion power plant. She coordinates and analyses experiments in ASDEX Upgrade to validate the edge plasma models needed to produce credible predictions of power exhaust in a reactor. The work requires intensive collaboration with the ASDEX Upgrade team and the SOLPS code developers and experts at IPP. Therefore, Aho-Mantila makes several long visits to IPP per year.

Ville Lindholm, under supervision of Dr. David Coster of IPP Garching and Dr. Mathias Groth of Aalto University, has previously applied the fluid edge code SOLPS to simulate the scrape-off layer plasma in ASDEX Upgrade L-mode discharges with C-13 and N-15 injection. Several edge codes will be used in addition to SOLPS to simulate the transport of carbon and nitrogen in these plasmas, including ASCOT and DIVIMP; these codes utilize the calculated background plasma from SOLPS. Setting up SOLPS, optimizing the choice of transport coefficients, and including a ^{13}C and ^{15}N injection, will required V. Lindholm to travel to IPP Garching for 3 two-week long visits.

5.4.2 Framework agreement between Associations Tekes and IPP: Energetic particle physics

Names of seconded persons:	E. Hirvijoki, A. Snicker, S. Äkäslompolo, T. Kurki-Suonio
Sending institution:	Aalto University
Host institution:	IPP Garching

For several years now Association Euratom-Tekes/Aalto University (previously: Helsinki Univ. of Technology) has been active in investigating the distribution and dynamics of NBI-generated fast ions in ASDEX Upgrade both numerically and experimentally.

Eero Hirvijoki and Antti Snicker, in collaboration with Drs. Philipp Lauber and Emanuele Poli, have developed a numerical model for drift islands into ASCOT in order to study the effect of various MHD modes, e.g., NTMs and various Alfven Eigenmodes, on fast ion confinement. The model features a novel approach applicable also for non-axisymmetric systems, and it has been submitted for publication in Computer Physics Communications. The model has been benchmarked against HAGIS, and in 2012, in collaboration with Dr. Manuel Garcia-Munoz, the purpose is to validate the model in AUG experiments in which such MHD modes are available. The validation can be carried out by comparing FILD measurements against the synthetic FILD built into ASCOT. Both Hirvijoki and Snicker should spend four to six weeks at IPP to participate in the experiments and familiarize themselves with the data analysis.

Simppa Äkäslompolo has been actively involved in the FILD measurements of NBI ions. He has contributed to the data acquisition and analysis software of the FILD probes and the NPA. As part of an ITM task he has also defeatured the ASDEX Upgrade first wall so that it is suitable for numerical simulations. In 2011, he wrote BioSaw, a support program for ASCOT to calculate the magnetic field perturbation from the geometry and currents of the B-coils. The model has been used to calculate the effect of the B-coils on NBI-ion confinement, which is particularly important for the reversed-current campaign foreseen to take place in 2012. One 3-week and one 2-week visit are needed to continue this work on external perturbations and FILD measurements in general.

Taina Kurki-Suonio coordinates the fast ion collaboration between Tekes and IPP. The goal is “ASCOT Upgrade”, a comprehensive fast ion code to be used to model fast ion experiments not only in ASDEX Upgrade but also in ITER. She has been active in investigating the role of fast ions in the pedestal region, particularly in the context of the quiescent H-mode. The work is strongly coupled to the experiments and, therefore, three 2–3 week visits per year has been found necessary.

5.4.3 Momentum and particle transport (1)

Name of seconded person: T. Tala
Sending Institution: VTT
Host Institution: MIT, Boston
Dates of secondment / mission: 12–19 January 2012

5.4.3.1 Work Plan / milestones

Tuomas Tala is the spokesperson of ITPA TC-15 Joint Experiment and he will act as a scientific co-ordinator of ITPA TC-15 experiment on C-Mod, as he has already done on AUG, DIII-D and JET. This is a joint ITPA experiment TC-15 (between JET, DIII-D, NSTX, ASDEX-U and C-Mod) where the main objective is to clarify the parametric dependencies of momentum pinch on several plasma parameters that are known to play a key role. The main dependence to be studied is the collisionality, the other ones being q-profile and density gradient length R/L_n. These parametric dependencies of the pinch terms must be known in order to make reliable extrapolations for ITER toroidal rotation profiles, in particular its peaking. In addition to the momentum pinch, the corresponding dependencies of the momentum diffusion coefficients on these plasma parameters will be obtained.

This experimental run day on C-Mod is a direct continuation from January 2011 when one run day was devoted to the ITPA TC-15 experiment. 3 different methods to create a periodic rotation perturbation were tested. The diagnostic beam modulation did not create an observable perturbation in rotation, however, with some further optimisation, it could still turn out to be a feasible method. The LH power modulation yielded a significant rotation modulation, but only with the expense of a massive electron temperature modulation, thus not useful for any transport analysis. The septum sweeping modulation, between the upper and lower single null modulation created a small rotation modulation. This will be the method to be employed now much more extensively in the coming experiment to perform the planned scans. Certainly further development of the septum sweeping modulation is needed but hopefully within a full run day, also the parametric scans necessary for understanding more about momentum transport will be performed.

5.4.3.2 Report

The second run day (the first one being in 2011) was carried out in January 2012. SSEP modulation was further elaborated, but partly due to technical difficulties not related to the actual experiment, and partly due to the difficulties to optimise the magnitude of the rotation perturbation from SSEP, no further useful data were obtained using this method. In conclusion of using SSEP sweeping, one can state that this is not an adequate method to create the rotation perturbation on C-Mod. As the back-up option, ICRH modulation was performed and a clear rotation perturbation was achieved. The preliminary results indicate that the perturbation is originated from the plasma centre, and therefore, it will be challenging to separate the actual rotation source/sink from momentum transport when determining the pinch and diffusion. The first results were presented in the ITPA meeting in Hefei, China in April. For future plan, the scarce data collected during these two run days using SSEP modulation technique in 2011 and ICRH modulation in 2012 will be analysed, with the aim to exploit all the possible ways to extract useful data for momentum transport analysis.

5.4.4 Characterization of L-mode discharges in forward and reversed magnetic field

Name of seconded person:	L. Aho-Mantila
Sending Institution:	VTT
Host Institution:	IPP Garching
Dates of secondment / mission:	26 January – 29 July 2012

5.4.4.1 Work Plan / milestones

During this visit, Leena Aho-Mantila will plan and coordinate experiments at ASDEX Upgrade for characterization of the L-mode domain in forward and reversed magnetic field. These experiments will provide important information on the relations between divertor in-out asymmetries, scrape-off layer radial electric field and parallel ion flows. The discharges will serve as reference plasmas in which the effects of N impurity seeding will be investigated later in 2012. Leena Aho-Mantila will initialize SOLPS5.0 modelling of these discharges, including also predictive studies of the effects of impurity seeding. The work will be done in close collaboration with both the experimental and theoretical departments at IPP. Goals:

1. Coordinate L-mode discharges in forward and reversed magnetic field, with varying density and heating levels, including measurements of the parallel ion flows and radial electric field in the scrape-off layer.
2. Initialize SOLPS5.0 modelling of these new discharges
3. Introduce N impurities in the SOLPS5.0 solutions and revise the simulation setup accordingly
4. Scan the effects of various levels of N seeding in low-density L-mode discharges, with comparison to earlier experiments where possible
5. Preliminary comparison with similar studies made in JET.

5.4.4.2 Report

1. L-mode discharges were successfully coordinated in both forward (9 discharges) and reversed (3 discharges) magnetic field and plasma current. In

forward field, the discharges covered operational regimes in L-mode and I-phase, with the outer divertor in low- and high-recycling regimes. Low-density discharges were conducted in deuterium, hydrogen and helium, whereas the rest of the discharges were in deuterium only. In reversed field, the outer divertor regime was varied from low- to medium- to high-recycling, with various levels of in-out asymmetry. These discharges significantly expand the available data for detailed code validation.

2. SOLPS5.0 modelling of these discharges, as well as data evaluation, was initialized and will continue during the rest of the year.
3. Simulations were set up for D+He+C+N species with all ionization states together with the local code experts. Furthermore, a new density boundary condition formulation was implemented in the code package in order to better model the effects of fuel dilution by impurity seeding.
4. Converged solutions with various levels of N seeding and drifts activated in the whole simulation region were obtained. These runs were compared to earlier N-seeded low-density discharges. Strong in-out divertor asymmetries were observed in both the simulations and the experiments. Cross-field drifts were identified as the main contributors to these in-out asymmetries.
5. Strong in-out asymmetries in the effects of N_2-seeding were observed in JET as well. However, differences likely associated with the divertor geometry were identified between ASDEX Upgrade and JET, and these will be analysed in further detail in the future.

In addition: During this visit, two manuscripts were finalized on earlier work on low-density L-mode discharges. These papers were accepted for publication in Nuclear Fusion.

5.4.5 VTT / UT meeting for coordinating PWI collaboration actions

Names of seconded persons: M. Aints, M. Kiisk, M. Laan, A. Lissovski, P. Paris
Sending Institution: University of Tartu
Host Institution: VTT
Dates of secondment / mission: 1–2 February 2012

5.4.5.1 Work Plan / milestones

1. Cleaning project
2. LIBS research and FOM collaboration in 2012 under EFDA
3. New DIARC coatings in 2012
4. Administrative and other issues

5.4.5.2 Report

Participants: A. Hakola, S. Karttunen, J. Likonen, VTT
J. Kolehmainen, M. Koskinen, S. Tervakangas, DIARC
M. Aints, M. Kiisk, M. Laan, A. Lissovski, P. Paris, UT

1. Kolehmainen and Koskinen presented the design of the arc-discharge system and the cleaner head. The design is now fixed and the necessary components have been ordered. After the device has been constructed and set into operation, optimal cleaning parameters will be determined. The actual cleaning will be a two-step process: (i) dust removal in the same way as in a vacuum cleaner and (ii) evaporation of material from the surface with the help of arc discharges. For efficient dust collection, a filter will be installed before the mechanical pump. The first real experiments can be carried out in September – including in situ spectral measurements. To study the feasibility of the present approach for detecting the spectrum of the emitted light, a series of tests will be done in DIARC in March-April. Hakola takes care of the necessary optomechanical components (some pieces have already been ordered), while Laan and Paris are in charge of the measurements.
2. Laan gave a presentation (i) on the status of the LIBS studies for the EFDA Dust and Tritium Management programme and (ii) on the latest XRD results of the samples exposed to Pilot-PSI plasma at FOM in December 2011. Increasing the diameter of the laser spot on the target (now around 1 mm) and using a reasonably high pulse energy (90 mJ) have resulted in promising outcomes. XRD studies of another W-Al-C sample, exposed to Pilot-PSI plasma, show that plasma treatment leads to the growth of crystallites and in some regions also to the formation of W_2C. Broad peak structures indicate that carbon (DLC) is in an amorphous state. XRD results also show a large difference between DIARC and Balinit DLC coatings. New experiments with the Be chamber were discussed. A wishlist about suitable samples has been sent to C. Lungu, who will produce a set of samples in Feb-Mar. J. Karhunen will start his Master's Thesis on LIBS studies of Be samples in May-June. Mobility visits by Lissovski and Paris are foreseen in June and/or in August.
3. New AUG tiles are expected to be coated only in the latter half of 2012 or in early 2013. Hakola will discuss the issue with the IPP staff in Garching in February.
4. Karttunen gave an overview of the status of ITER and presented the Horizon 2020 program and the new structure and programme of EFDA for 2012. Annual accounts were discussed and the deadline for the contributions of the annual report was set to 1 March.

5.4.6 Ion-beam analysis of ASDEX Upgrade marker tiles

Name of seconded person:	A. Hakola
Sending Institution:	VTT
Host Institution:	IPP Garching
Dates of secondment / mission:	5–10 February 2012

5.4.6.1 Work Plan / milestones

RBS and/or NRA measurements of marker tiles at IPP

5.4.6.2 Report

Since 2002, erosion of first-wall components, deposition of the eroded material and retention of plasma fuel on them, and migration of material in the torus have been addressed with the help of special marker tiles and probes produced by the Finnish coating company DIARC-Technology. To determine erosion, the thicknesses of the marker layers are measured before and after their plasma exposure, whereas for the deposition studies the depth profiles of different elements and the total amount of each of them on the coatings are evaluated. The analyses are done using secondary ion mass spectrometry (SIMS) at VTT and Rutherford backscattering spectroscopy (RBS) and nuclear reaction analysis (NRA) at IPP.

During the present visit, two marker tiles, exposed to plasma discharges in the outer strike-point region of ASDEX Upgrade during its 2010–2011 experimental campaign, were analysed using RBS and NRA. Both of the tiles had three poloidal regions of different surface roughness but coated differently. The first one had a 2 μm thick W coating while the other one was equipped with a 2 μm thick Mo coating.

The RBS measurements provide data on erosion of the different materials and the effect of roughness on net and gross erosion, while from the analysed NRA data the deuterium and boron inventories on the tiles can be extracted. The results will be compared with the existing data for four other 2010–2011 marker tiles. These tiles were located in a different toroidal location than the two tiles measured now, which makes it possible to study the toroidal symmetry of erosion.

The analyses of the tiles were carried out in the accelerator lab of IPP using the Bombardino analysis chamber. For the RBS measurements, protons with energy of 3 MeV were applied while in the case of NRA, 2.5 MeV $^{3}He^{+}$ ions were used. In both cases, the energy spectrum of emitted protons was recorded: in the case of RBS, backscattered protons at 165° and in the case of NRA, protons formed in the nuclear reactions $D(^{3}He, p)^{4}He$ and $^{11}B(^{3}He, p)^{13}C$ at 150°. The step between adjacent measurement points along each marker stripe or region was 5–20 mm. All the planned measurements were carried out and the milestone was therefore reached.

5.4.7 JET tiles analysis in Culham

Name of seconded person: J. Likonen
Sending Institution: VTT
Host Institution: JET/CCFE, UK
Dates of secondment / mission: 16–22 February 2012

5.4.7.1 Work Plan / milestones

1. Participation in the JET tiles analysis under the FT task JW11-FT-3.68 using SIMS and ion beam techniques
2. Evaluation and comparison of SIMS and ion beam results

5.4.7.2 Report

Milestone 1: Main aim of the visit was to evaluate the data obtained with SIMS and ion beam techniques. Various divertor tiles exposed in 1998–2009, 2004–2009 and 2007–2009 have been analysed with SIMS and IBA techniques for erosion and deposition. The purpose of the measurements is to determine the overall erosion/deposition pattern at JET. The inner divertor tiles 1 and 3 have high Be/C ratio near the bottom of tile 1 and top of tile 3. On the inner floor tile 4 D/C ratio is highest in the shadowed region which is shielded from plasma by tile 3. On the outer floor tile 6 two peaks in the Be profile have been observed. This double peak in the Be concentration has been shown to correspond to the most favoured positions of outer strike point. The outer divertor tiles 7 and 8 had carbon marker coatings (thickness ≈10μm) and SIMS analyses indicated that the C marker layer has been eroded more or less completely from both tiles.

Milestone 2: During the last day of the C27 campaign in 2009, pure $^{13}CH_4$ was injected into the torus from the outer divertor. During this staff mobility visit SIMS and IBA data for tiles 6 were compared with each other. Four tiles 6 have been analysed both with SIMS and IBA techniques. Results agree for 3 tiles 6, but in the case of tile G6A the IBA results have to be recalculated because WiNDF program assumes too thick ^{13}C layers on this tile resulting in too high ^{13}C amounts.

5.4.8 JET tiles analysis in Uppsala

Name of seconded person: J. Likonen
Sending Institution: VTT
Host Institution: University of Uppsala, Sweden
Dates of secondment / mission: 28–29 February 2012

5.4.8.1 Work Plan / milestones

Participate in the JET tiles analysis under the FT task JW12-FT-3.74 using SIMS and ion beam techniques, and evaluation and comparison of SIMS and ion beam results.

5.4.8.2 Report

Main aim of the visit was to evaluate the data obtained with SIMS and ion beam techniques. Various divertor tiles exposed in 1998–2009, 2004–2009 and 2007–2009 have been analysed with SIMS and IBA techniques for erosion and deposition. The purpose of the measurements is to determine the overall erosion/deposition pattern at JET. The inner divertor tiles 1 and 3 have high Be/C ratio near the bottom of tile 1 and top of tile 3. On the inner floor tile 4 D/C ratio is highest in the shadowed region which is shielded from plasma by tile 3. On the outer floor tile 6 two peaks in the Be profile have been observed. This double peak in the Be concentration has been shown to correspond to the most favoured positions of outer strike point. The outer divertor tiles 7 and 8 had carbon marker coatings (thickness ≈ 10 µm) and SIMS analyses indicated that the C marker layer has been eroded more or less completely from both tiles. Cross sectional samples from same tiles will be analysed using micro beam NRA technique at University of Uppsala.

5.4.9 Preparations for plasma-exposure experiments at Pilot-PSI and Magnum-PSI

Name of seconded person: A. Hakola
Sending Institution: VTT
Host Institution: DIFFER, Netherlands
Dates of secondment / mission: 22–24 March 2012

5.4.9.1 Work Plan / milestones

1. Making preparations for plasma experiments in Pilot-PSI and Magnum-PSI and discussing the existing results with the DIFFER team
2. Planning the integration of a LIBS system into Magnum-PSI.

5.4.9.2 Report

This visit was related to the active collaboration between the DIFFER Institute and Tekes (research units VTT and University of Tartu) in the field of plasma-surface interactions. The main research themes within this collaboration are studying erosion/re-deposition of ITER-relevant materials when exposed to high-flux plasma discharges and developing laser induced breakdown spectroscopy (LIBS) an *in situ* diagnostics tool for ITER.

During the visit, the results obtained from D-doped W-Al samples exposed to plasma discharges in Pilot-PSI in 2011 were discussed with the DIFFER team. Furthermore, both short- and long-term plans concerning new exposure experiments in 2012 and 2013 were made. The following actions were agreed on:

- The radial erosion profiles of the different samples will be determined using secondary ion mass spectroscopy (SIMS) at a resolution of about 1 mm. This will be done by the summer 2012.
- Simultaneously, the SIMS and LIBS profiles will be compared with each other as well as cross-correlated with the already obtained SEM images and X-ray diffraction patterns.
- Once decent erosion profiles have been extracted, the DIFFER team will numerically model them with the ERO code. Particularly, the effect of the different sputtering rates of W and Al on the results will be studied.
- The DIFFER people will carry out desorption measurements for calibration samples to find out how much deuterium is released from them at different temperatures.
- In late 2012, a set of new samples – this time W-Al coatings on W substrates – will be exposed to plasma in Pilot-PSI.
- In 2013, similar samples are planned to be exposed to even more powerful plasma discharges in Magnum-PSI. In these experiments, the inclination angle of the samples with respect to the magnetic field will be varied. This way, reactor-relevant conditions can be reached.

Another topic of the discussions was the continuation of the LIBS development, started in 2009. The possibility to lend the gated, high-resolution spectrometer to DIFFER for their experiments in the autumn 2012 was discussed. In addition, it was agreed that a PhD student from University of Tartu could regularly visit (under staff mobility) DIFFER and participate in the LIBS development, data analysis, and integration of the LIBS system into Magnum-PSI. The student would work in collaboration with a post doc of DIFFER. This milestone was reached.

5.4.10 BeD sputtering modelling

Name of seconded person: C. Björkas
Sending Institution: University of Helsinki
Host Institution: EFDA-JET
Dates of secondment / mission: 25–31 March 2012

5.4.10.1 Work Plan / milestones

The objectives were to obtain information about the appearance of BeD molecules in JET and to discuss necessary parameters for ERO modelling of the situation.

5.4.10.2 Report

Spectral line intensities were obtained that revealed the BeD presence in the limiter area. The geometry of the area of interest and which is to be implemented into ERO was explained. The discussion of plasma parameters important for modelling was started. In addition to this I also took part in the meetings related to the modelling month.

5.4.11 TF-FT task force leader activities

Name of seconded person: J. Likonen
Sending Institution: VTT
Host Institution: JET/CCFE, UK
Dates of secondment / mission: 26–30 March 2012

5.4.11.1 Work Plan / milestones

Participate in the TF-FT activities within the role as a deputy task force leader.

5.4.11.2 Report

During the visit evaluation of report for FT tasks JW9-FT-3.46, JW10-FT-3.62 and JW11-FT-3.70 was completed. In these tasks selected samples from JET divertor tiles were analysed using accelerator mass spectrometry (AMS) and full combustion method (FC). The goal in the task JW11-FT-1.19 was to compare AMS with FC. In task JW11-FT-3.70 the aim was to clean mirrors using a powerful laser. Planning of the JET TF-FT work programme for 2013 was started and a preliminary program was drafter.

5.4.12 Impurity flow measurements in the HFS of AUG

Name of seconded person:	T. Makkonen
Sending Institution:	Aalto University
Host Institution:	IPP Garching
Dates of secondment / mission:	9–13 April 2012

5.4.12.1 Work Plan / milestones

Understanding impurity transport is crucial for future fusion reactor design. Impurity transport in the scrape off layer (SOL) of current tokamaks is dominated by the parallel background plasma flow in typical scenarios. Unfortunately, there are not many measurements of the flow profile in the SOL, and current fluid code results do not always seem to be consistent with these measurements.

During the 2011 campaign, methane was injected a valve located about midplane in the HFS of AUG. The ensuing CII and CIII clouds were followed with spectroscopy and fast video cameras in order to study the flow and plasma conditions in the HFS. These results will be presented at the PSI 2012 conference. The purpose of this visit is to gather more data for the PSI presentation. Also, software analysis tools created during this work will be integrated into the AUG data gathering system. The key persons for this visit are Dr. Pütterich and Dr. Lunt.

5.4.12.2 Report

During the visit, new experiments were made and the results will be presented at the PSI 2012 conference. We did density ramps to see how the density affects the flow in the HFS SOL. This was done both in L-mode and H-mode. Also, the spectroscopic measurements were done with spectrometer with a higher time resolution compared to last year in order to better see the effects of ELMs.

Preliminary results indicate that density does not affect the HFS SOL flow noticeably. The flow profiles gathered during this visit were qualitatively similar to previous experiments. Work was started to integrate the developed data analysis software into the ASDEX Upgrade data gathering system.

5.4.13 Validating a model for MHD modes in ASCOT

Name of seconded person:	E. Hirvijoki
Sending Institution:	Aalto University
Host Institution:	IPP Garching
Dates of secondment / mission:	22 April – 5 May 2012

5.4.13.1 Work Plan / milestones

A recent update to ASCOT code includes a model for MHD instabilities acting on fast particles. The model was benchmarked against HAGIS and an article has been submitted to Computer Physics Communications regarding the benchmark and the methods of the model. Encouraged by the agreement with HAGIS the model was used to calculate redistribution of NBI ions during NBI current drive under the influence of neoclassical tearing modes. As the simulation showed decent agreement with experiments, the validation process should be continued to consider Alfvén Eigenmodes as well.

The validation of Alfvén Eigenmodes requires close collaboration with personnel from IPP Garching to get sufficient data. Thus, the purpose of the stay was to obtain proper data, make initial try-outs of fast ion redistribution caused by the Eigenmodes, and discuss the next steps with local experts. A training course for the users of the new supercomputer Helios was also attended in Garching.

Milestones:

1. Tearing modes
   - Further discuss the preliminary simulation results
   - Agree on possible additional simulation(s)
2. Eigenmodes
   - Obtain sufficient data for simulations
   - Make try-outs if enough time
3. Other
   - Attend IFERC-CSC training.

5.4.13.2 Report

Achievements / Results:

Milestone 1: The results were discussed with the local staff. Although local experts agreed that the code produces qualitatively similar results to the experiments, the overall agreement is still not good enough for quantitatively predictive studies It was agreed to make no more comparisons to experimental data, but to concentrate on getting an even more accurate benchmark to HAGIS. The essential difference is that HAGIS uses magnetic coordinates, whereas ASCOT uses Cartesian or cylindrical coordinates. Though the collisionless orbits seemed to agree well with HAGIS, the collisions change something and the agreement deteriorates. Another source of discrepancy between ASCOT and HAGIS is the different particle source in the case of NBI.

Milestone 2: Proper data for Eigenmode simulations for ASDEX Upgrade was not obtained. The only real outcome was to use Gaussian profiles for several poloidal mode numbers keeping the toroidal mode number and frequency fixed. Problems were also encountered regarding the particle input for Eigenmode simulations. Due to the time-dependency of the mode, the phase-space initialization must also include time sampled according to the mode frequency. To get steady state statistics, this means that the amount of test particles has to be increased by roughly ten to a hundred times from standard slowing-down simulations. The current input data format is not designed for such large numbers, and problems occurred in reading the data during parallel simulations. The I/O routines had to be rewritten, and it took more time than was available.

Milestone 3: The training course was attended and information on how to run ASCOT on the Helios platform was obtained.

5.4.14 Spectral diagnostics studies in a vacuum arc cleaning system

Name of seconded person:	A. Lissovski
Sending Institution:	University of Tartu
Host Institution:	VTT
Dates of secondment / mission:	24–27 April 2012

5.4.14.1 Work Plan / milestones

1. First test spectral measurements of arc excited emission from Al-doped Ti targets
2. Analyze the recordings (signal to noise ratio, optical path optimization etc), discussing the observed spectra, differences of them from real cleaning spectra and further plans

5.4.14.2 Report

The research units VTT and University of Tartu of Tekes have collaborated with DIARC-Technology Inc. since 2007. Particular attention has been paid to studying the efficiency of a vacuum-arc system of DIARC that is applied to remove contaminants deposited onto the surfaces during plasma ablation. A new arc-discharge cleaning system, capable of operating in the pressure range 10^{-2}–1000 mbar, is being built at DIARC.

The present visit is connected with designing a spectroscopic detection setup for the cleaning system. The quality of cleaning process will be estimated spectroscopically by recording spectra of the cleaning arc-discharge. The current ideas will be tested in one of the vacuum arc-discharge systems of DIARC (whether the emitted light can be efficiently collected, whether the spectral lines can be resolved etc.). In the present stage Al-doped Ti targets will be used as samples. Once successfully realized, the optical setup will be further designed and fine-tuned with the aim it later on (in the autumn 2012) integrated into the actual cleaning system.

Milestone 1: During the visit an Avantes spectrometer was taken into use and integrated into the experimental setup by DIARC-Technology Inc. The setup consisted of a vacuum chamber with a base pressure of 10^{-5} mbar, where initiated vacuum arc on Al-doped Ti cathode with emission duration of several milliseconds, fiber coupling for the spectrometer, and computer. Spectra were recorded parallel to the main direction of plasma expansion. Because of absent of synchronization, the spectra recording was random with exposure time 20 ms and 50 ms in single shot and also in accumulation modes. There were stored spectra, received in different registration modes. This milestone was reached.

Milestone 2: It was carried out in detail the analysis of received spectra. In spectra, the lines of Ti and Al are presented. Additionally, the traces of hydrogen ware detected. The spectra have a good quality (signal-to-noise ratio, spectral resolution about 0.3 nm) for this spectral device.

In future, the synchronization of registration system with pulse plasma device is planned. It allows also measuring the temporal behaviour of arc and optimizing the arc parameters for cleaning system. This milestone was reached.

Additional milestones: In the last day of my visit, I carried out the measurements of crater profiles on the profilometer by VTT for samples that have been tested with LIBS in Tartu workgroup of Tekes association in the frame of EFDA tasks.

Additionally, a new spectral device, consisting of Shamrock spectrometer and an ICCD camera, purchased recently by VTT, was tested for operability. All the milestones were reached.

5.4.15 Fast-ion experimental campaign and related modelling

Name of seconded person:	S. Äkäslompolo
Sending Institution:	Aalto University
Host Institution:	IPP Garching
Dates of secondment / mission:	7 May – 1 June 2012

5.4.15.1 Work Plan / milestones

The proposed visit is part of the European experimental programme carried out at ASDEX Upgrade tokamak.

Fast ions or suprathermal ions have energy far higher than the thermal bulk of the plasma. The fast ions are mostly born during non-inductive heating of the plasma. Because of their high energy, the fast ions have a potential to quickly erode the plasma facing components. On the other hand, it is believed that the fast ions play a significant role in high performance plasma operational modes. Magnetohydrodynamic (MHD) instabilities of the plasma can drive fast ions from the plasma. Such instabilities include the Edge Localised Mode (ELM).

In ASDEX Upgrade the fast ions can be measured with a number of diagnostics. In this plan the fast ion loss detector (FILD) is used in concert with other fast ion diagnostics. The goal is to gain further understanding of the behaviour of the fast ions during ELMs and the effect of the resonant magnetic perturbation (RMP) from ELM mitigation coils to the fast ions.

We have an established collaboration with Dr. Garcia-Munoz, who is the fast ion diagnostician at AUG. During last years I have assisted him in setting up the diagnostics and operating them during the exceptionally taxing time frame: Annually for a few weeks an extra FILD probe is attached to the midplane manipulator of AUG, and a large number of fast ion dedicated discharges are performed. In addition to help during the experiments, I provide theoretical fast ion distributions with the ASCOT code. ASCOT is guiding centre following plasma simulation code developed in Helsinki.

During my mobility visit I wish to accomplish the following tasks:

1. During the first week, prepare the DAQ software and hardware for measurements. Plan for the dedicated discharges I'll request later during the visit.
2. During the first week of FILD probe on the MEM, up and calibrate the diagnostics as well as do scenario development.
3. Perform the actual experiments during the last three two of measurements. The experiments should include at least the ELM and RMP studies.

Other pending tasks that can benefit from my visit:

1. Any ITM-work requiring collaboration with IPP personnel, especially David Coster, Tilmann Lunt and Hans-Joachim Klingshirn.
2. Prepare for modelling of the experiments with the activation probe proposed by Georges Bonheure.

5.4.15.2 Report

First I'd like to report the specifc goals:

Dr. Garcia-Munoz and I were able to get all the diagnostics up and runing during my first two weeks. The dedicated discharges were planned to a sufficient detail and a shot request was made. ASCOT simulations were used for optimizing discharge parameters.

1. On the second week of my visit, the diagnostics was working already succesfully and good measurements of non-dedicated discharges were made.
2. I got my first dedicated discharges on the third and fourth weeks of my visit. Also the International tokamak physics activity (ITPA) energetic particle (EP) topical group resonant magnetic perturbation discharges were performed. I will be most likely involved in the simulation of these discharges.

In addition:

- Meetings with new and old colleagues: K. Shinohara (JAEA, Japan), Michael van Zeeland (GA), Philip Schneider (IPP)
- Measurements to validate the fast ion simulations against
- Improvement of the data analysis and data acquisition software at IPP
- Participation in the assembling of the fast ion loss diagnostic.

5.4.16 Implementing spin-lattice electron dynamics into PARCAS

Name of seconded person:	A. Meinander
Sending Institution:	University of Helsinki
Host Institution:	CCFE
Dates of secondment / mission:	8–17 May 2012

5.4.16.1 Work Plan / milestones

The aim of this project is to take steps towards the realization of large-scale atomistic simulations including inter-atomic magnetic effects, applicable to magnetic materials such as FeCr alloys. Since magnetic effects play an important role in the behaviour of iron alloys at high temperatures, the simultaneous treatment of both the spin magnetic moment and lattice degrees of freedom in dynamic non-equilibrium atomistic simulations of radiation damage processes is a necessary step towards the understanding of such materials' response under the operating conditions of future fusion reactors. Currently no model combining magnetic and structural effects exists for Fe-Cr systems of the order of 1 million atoms.

The immediate goal of this visit will be to develop a model describing the dynamics of thermalization of magnetic moments in simulations of a system coupled to an external electronic thermostat. This is necessary to enable the correct treatment of evolution of atomic, magnetic and electron subsystems in a cascade simulation. Further work would then include studying effects of antiferromagnetic ordering that are known to occur in FeCr alloys,

5.4.16.2 Report

During this visit I have familiarized myself with the method of spin-lattice-electron dynamics [P.W. Ma et al., Phys. Rev. B **85** (2012) 184301] which we plan to incorporate into the classical molecular dynamics code PARCAS. The model is suitable for simulating the time-dependent evolution of large systems of coupled spin, atomic, and electronic degrees of freedom. I have also written and tested a piece of code simulating a spin moment coupled to a heat reservoir. The code solves the Langevin-type equation of motion governing the evolution of a quantum mechanical spin operator subject to a stochastic force [P.W. Ma and S.L. Dudarev, Phys. Rev B **83** (2011) 134418], and will be the starting point of the spin dynamics implementation. The complete model describes the dynamical evolution of spin and lattice subsystems, including a coupling between electron, lattice and spin subsystems via Langevin dynamics, where the electronic subsystem is treated as a heat reservoir for the lattice and spin subsystems. Despite the coupling to a heat bath, the longitudinal component of the spin moments is conserved in these equations. Further development of this method for simulations of radiation damage processes such as collision cascades will require a treatment of longitudinal fluctuations of magnetic moments, which are known to have an effect on the high temperature properties of magnetic alloys, as well as on finite temperature properties of defects and dislocations.

In addition, plans were laid out for molecular dynamics studies of the microstructural evolution of ion-irradiated tungsten, relating to recent experimental results which were presented at a meeting I was invited to attend during this visit. Although collision cascades have been extensively studied in e.g. iron, tungsten exhibits certain unexpected behaviour, and has aroused recent interest due to its use as a fusion reactor wall material.

5.4.17 Momentum and particle transport (2)

Name of seconded person:	T. Tala
Sending Institution:	VTT
Host Institution:	IPP Garching
Dates of secondment / mission:	21–25 May 2012

5.4.17.1 Work Plan / milestones

Tuomas Tala is the spokesperson of ITPA TC-15 Joint Experiment and he will act as a scientific co-ordinator of ITPA TC-15 experiment on ASDEX-U together with Dr. McDermott, as he has already done on DIII-D, JET and C-Mod. This is a joint ITPA experiment TC-15 (between JET, DIII-D, NSTX, ASDEX-U and C-Mod) where the main objective is to clarify the parametric dependencies of momentum pinch on several plasma parameters that are known to play a key role. The main dependence to be studied is the collisionality, the other ones being q-profile and density gradient length R/L_n. Furthermore, plasmas with RMP coils switched on are compared with the one having them off. In order to confirm the existence of the pinch in electron heated plasmas (towards TEM dominated plasma), high ECRH power plasmas with NBI will be performed.

The second part of the experiment (ITPA TC-17 on Intrinsic Torque) aims to infer the effective torque associated with the drive of intrinsic rotation on AUG. The idea is to use small frequency NBI modulation to infer the momentum characteristics of the plasma, and then deduce the missing torque in the plasma (if any) required to account for the steady state rotation. We will also use the new RMP coils to apply a non-resonant magnetic field (NRMF) perturbation as an alternate means of applying a torque step to investigate the intrinsic torque provided that the new set of coils will create a measurable perturbation in the rotation. The main goal of this experiment is to clarify some of the main dependencies and scaling of the intrinsic torque, in particular ρ^*, pedestal gradients, power and current and further, compare them with JET and DIII-D. In addition, the effect of ECRH/ICRH power (dominant electron heating) on intrinsic torque is to be studied.

5.4.17.2 Report

For TC-15 experiment on momentum transport, a part of R/L_n scan and a *q*-scan were executed on AUG. The Prandtl number does not depend on R/L_n as the scatter of the points is rather uniform. On the other hand, similarly to JET and DIII-D, the pinch number was found to depend strongly on R/L_n, a scaling indicating $-Rv_{pinch}/\chi_{\phi} \approx 1.5R/L_n$. Further points will be added once the analysis progresses further. A 3-point q-scan was executed by trying to minimize the changes in other dimensionless plasma parameters, in particular in R/L_n. The pinch number was found to decrease with increasing *q* although the dependence is quite weak. This observation is consistent with the JET *q*-scan but in contrast with momentum transport theory.

The first ever set of intrinsic torque experiments were performed in 2012 on AUG by using the slow NBI modulation technique (2 Hz). The results show that the compensated modulation (by varying the off-axis and on-axis NBI torque but keeping the total power constant) does not yield a rotation perturbation from which one can extract the intrinsic torque with small enough error bars. The uncompensated modulation at 2 Hz does create a large enough perturbation.

While the momentum transport part of the analysis is well advanced, for the intrinsic torque part of the experimental data, many shots have the noise level too high to be able to unambiguously determine the torque. Detailed analysis of existing data and the effect of measurement noise have given several concrete and feasible ways for optimising the experimental conditions, modulation waveforms, and diagnostics resolution to gain sufficient accuracy. The most important one will be the use of RMP coils on a regular basis and assigning no torque originating from the coils themselves. The second one is the sawtooth control to avoid sawtooth occurring at the same frequency (or multiple of it) as the modulation frequency.

5.4.18 Neutral beam current drive modelling

Name of seconded person:	O. Asunta
Sending Institution:	Aalto University
Host Institution:	CCFE, UK
Dates of secondment / mission:	28 May–12 June 2012

5.4.18.1 Work Plan / milestones

Steady-state operation of a tokamak requires the toroidal current to be driven non-inductively. Moreover, driving current off-axis is of vital importance for the steady-state (or advanced) operating scenario in ITER where it is needed for tailoring the *q*-profile in order to avoid detrimental MHD activity. One means foreseen for driving off-axis current is using neutral beam injection (NBI). In MAST experimental evidence of off-axis neutral-beam driven current has been observed.

The purpose of the visit was to model neutral beam injection and current drive in MAST with three codes: ASCOT, TRANSP/NUBEAM, and LOCUST-GPU. All the codes are test particle MC codes, but they use different methods for following the particles: NUBEAM follows the particles' guiding-centres, but includes a FLR correction, LOCUST-GPU is a full-orbit following code, and ASCOT is able to follow either one. Since MAST is a small aspect ratio tokamak with a relatively low magnetic field, FLR effects are assumed to play a role in particles' overall behaviour. Therefore, a benchmark activity between ASCOT, NUBEAM, and LOCUST-GPU was initiated in collaboration with Dr Rob Akers. An additional goal of this visit was to collaborate with Dr Michele Romanelli and establish ASCOT as the NBI module of the JINTRAC code suite for transport modelling of MAST.

5.4.18.2 Report

1. All the outstanding problems were solved and ASCOT was successfully ran with MAST data within JINTRAC.
2. The shots to be modelled were decided (in collaboration with R. Akers, M. Turnyanskiy, and D. Keeling) and to ensure the validity of inputs, they were extracted from existing NUBEAM runs.
3. ASCOT simulations were performed and the results compared to those of NUBEAM. Some new TRANSP/NUBEAM runs were also requested in order to understand the remaining differences between the codes (due to plasma rotation and maybe different equilibria). For LOCUST-GPU, more work is needed before it can be compared to the two above-mentioned codes, because it turned out that its data I/O is not yet developed enough.

In addition, automatic MAST input generation for ASCOT within JINTRAC was discussed with several colleagues.

5.4.19 Surface analysis of collector probes

Name of seconded person: P. Coad
Sending Institution: VTT
Host Institution: Ion Beam Analysis laboratory at IST/ITN, Lisbon
Dates of secondment / mission: 6–8 June 2012

5.4.19.1 Work Plan / milestones

The work to be undertaken will be:

1. Analysis of beryllium-coated silicon samples in preparation for an experiment using the JET Reciprocating Probe
2. Further analysis of a series of beryllium marker tiles for mounting in JET during the shutdown commencing in July 2012.

The milestone to be achieved will be recorded results of the ion beam analysis of the silicon samples.

5.4.19.2 Report

Two collector probes had previously been sent to Dr Alves by Dr R Doerner, University of California at Los Angeles for analysis by Ion Beam Analysis methods. Each probe consisted of a boron carbide cylinder, with two slots designed for silicon samples, plus the samples. One cylinder was coated with molybdenum and then beryllium, and samples to fill the slots were coated with beryllium. The cylinder for the other probe was merely coated with molybdenum, and the Si samples left uncoated as a reference. The coatings were performed by General Atomics under an EU-US bilateral agreement. The Be-coated probe is designed to measure how Be is eroded and re-deposited in the plasma scrape-off layer (SOL), whilst the uncoated probe is to provide the background level of Be and other impurities present in the SOL.

Some preparatory work by Dr Coad was necessary on the ex-Sussex analysis chamber in order to accommodate the probes, then the Si samples were fitted to the probe body, and the probe assembly was mounted for analysis. Analysis scans were made every ≈ 2mm along each row of Be-coated Si samples, and also around the probe body near the end and ≈ 20mm further from the end. The analyses of the Si samples showed only a small variation in Be coating thickness, and provide the reference for comparison after exposure of the probe in JET. Following analysis the probes were packed up ready for despatch to JET.

The first JET campaign with the ITER-like Wall (ILW) was scheduled for completion at the end of July, at which point a series of beryllium marker tiles were to be removed from the vessel and replaced with new marker tiles. All marker tiles have to be analysed prior to mounting in JET, so that the extent of erosion/deposition can be assessed by comparison with re-measurement data after exposure. Due to observations early in operations with the ILW of plasma interaction in areas without the presence of any marker tiles, it was decided to rapidly arrange for some extra marker tiles. These marker tiles were also analysed by IBA by Dr Coad during his visit.

All data from the analyses of probes and marker tiles were recorded in the analysis files, which are located on the IST/ITN computers, and suitably backed up. The objectives and milestone for the mission were fully met.

5.4.20 TF-FT task force leader activities (2)

Name of seconded person:	J. Likonen
Sending Institution:	VTT
Host Institution:	JET/CCFE, UK
Dates of secondment / mission:	21–22 June 2012

5.4.20.1 Work Plan / milestones

Participation in the TF-FT activities within the role as a deputy task force leader

5.4.20.2 Report

During the visit evaluation of report for FT task JW11-FT-1.19 was completed. In this task selected samples from JET divertor tiles were analysed using accelerator mass spectrometry (AMS) and full combustion method (FC). The goal in the task JW11-FT-1.19 was to compare AMS with FC. TF-FT arranged a semi annual monitoring meeting at JET on 13–14 June. Responsible officer for TF-FT at JET had prepared minutes for the monitoring meeting. I reviewed the minutes and made some comments on it.

Other activities:

- Planning of JET experiment Ex-1.2.5
- I participated in the preliminary planning of JET experiment Ex-1.2.5. This experiment will be done during the last two weeks of JET operations in late July. During these two weeks similar H-type plasma will be run. The aim in the experiment is to study erosion/deposition and fuel retention.

5.4.21 Energetic ions in AUG

Name of seconded person: T. Kurki-Suonio
Sending Institution: Aalto University
Host Institution: IPP Garching
Dates of secondment / mission: 14–27 July 2012

5.4.21.1 Work Plan / milestones

Participate in the reversed-current campaign. In particular, we wish to find out the differences in the behaviour of the QHM with the present all-metal wall as compared to the previous carbon wall.

5.4.21.2 Report

During the reversed-current campaign, main effort was put on obtaining useful NPA data: even piggy-backing ctr-beams should give a high edge beam population, so this might give good data for determining the capability of NPA to measure edge E_r behaviour. Unfortunately, the heating beams applied failed to give sufficiently high signal in the channels monitoring the plasma.

The most interesting outcome of the campaign, related to my agenda, were obtained in the shots designed by Dr. Suttrop in an attempt to produce QHM operation using the DIII-D recipe. While the primary goal was not reached, these experiments might have given first experimental evidence on NTV spin-up on AUG. We plan to collaborate on this topic later this year.

5.4.22 Ion-beam analysis of ASDEX Upgrade marker tiles and probes

Name of seconded person: A. Hakola
Sending Institution: VTT
Host Institution: IPP Garching
Dates of secondment / mission: 27 July–10 August 2012

5.4.22.1 Work Plan / milestones

1. RBS measurements of P92 and W/Ni marker tiles of AUG
2. RBS measurements of erosion probes and NRA investigations of silicon samples of AUG

5.4.22.2 Report

Milestone 1: This part of the visit concentrated on the RBS analyses of 13 marker tiles, having either a 2-μm thick P92 steel coating or 1.5–2 μm thick W and Ni marker stripes on graphite. The tiles originated from different poloidal locations of the central heat-shield of AUG. Three of the P92 tiles had a new coating, and they will be mounted in AUG for its autumn experiments, starting in September 2012. Measurements from these tiles thus provided the necessary reference data for future erosion investigations. The remaining 10 tiles – five of them coated with P92, the remaining five with equally wide toroidal W and Ni markers – had been exposed to AUG plasmas during the first half of the 2012 experimental campaign. They were briefly removed from the vessel for the RBS measurements to obtain first results on how steel is eroded in the first wall of a fusion reactor. After all the RBS analyses had been carried out, the tiles were re-mounted in the torus.

First results indicate that only little erosion has taken place. For most of the tiles, the determined erosion (around 10 nm) was within the error bars of the fittings which were done using the program SIMNRA. Only for the tile located in the midplane region of the heat shield, some erosion (approximately 100 nm) seems to have taken place. Instead, there was a 500—1000 nm thick boron layer on all the analysed tiles, indicating that the heat shield is a net deposition region in AUG. All the planned measurements were carried out and this milestone was therefore reached.

Milestone 2: Another main goal of the visit was to analyse using RBS one marker probe that will be exposed to H-mode plasma discharges in AUG later on in 2012. The measurements will be repeated after the probe has been exposed such that erosion of its marker stripes can be extracted.

The probe was made of graphite and coated with 5 mm wide, 30–50 mm long, and 50–100 nm thick marker stripes. The materials of the marker stripes were carbon (in the form of diamond-like carbon, DLC, with a 50 nm thick intermediate layer of tungsten), aluminium, nickel, and tungsten. In these measurements, 2.0 MeV $^{4}He^{+}$ ions were used, and the step between adjacent measurement points along each marker stripe was 3–5 mm. Due to limited beam time available, measurements from the silicon samples were postponed to future visits to IPP. Otherwise, the planned measurements were carried out and this milestone was therefore reached.

5.4.23 LIBS measurements of Be test samples

Name of seconded person: A. Lissovski
Sending Institution: University of Tartu
Host Institution: VTT
Dates of secondment / mission: 6–17 August 2012

5.4.23.1 Work Plan / milestones

1. Test beryllium-compatible control and LIBS recording optical system
2. Recording first LIBS spectra with Be contained samples
3. Analyze obtained spectra, estimate the ablation rate of Be
4. Compare the spectra of samples corresponding to different Be percentages
5. Develop the methods for further experiments with beryllium containing samples.

5.4.23.2 Report

The collaboration between VTT and University of Tartu aims at making LIBS a suitable tool for in situ determination of erosion/deposition of plasma-facing components in ITER. Up to now, the LIBS data on pure beryllium and Be-containing mixed materials is largely missing even though the importance of studying true beryllium samples has been stressed many times. Aluminium is often used in LIBS studies instead of Be but Al is far from a perfect proxy because of its quite different physical and chemical properties and interaction mechanisms with the laser beam compared to the case of beryllium.

Be needs special care in handling it in dedicated facilities such as those at VTT. VTT has now a new beryllium-compatible LIBS chamber available which is similar to the system in University of Tartu. The Tartu team has several years of experience in working with LIBS-related projects.

For the experiments discussed here, a set of samples with Becontaining coatings – pure Be films on stainless steel (SS) substrates and W-Be coatings with a percentage of Be about 70 % on SS – have been prepared in cooperation with our Romanian partner Christian Lungu from the MedC Association. The samples were pre-characterized at IPP-Garching and then shipped to VTT for analyses.

Milestone 1: During the first 2 days of the visit, the spectroscopic detection system of the LIBS setup at VTT was set into operation. The settings were adjusted to get the best signal-to-noise ratio. The setup now consists of a Nd:YAG laser (λ = 1064 nm) producing 5–7-ns long pulses typically with energies up to 30 mJ, the necessary focusing and imaging optics, fiber coupling for the spectrometer (Avantes AvaSpec-2048USB2 for the whole spectral range or Andor iStar iCCD+SR750 for selected spectral ranges of about 40 nm), and a vacuum chamber with a base pressure of 10^{-8} mbar. Before my visit, a new stepper-motor driven rotating mirror was installed between the last focusing lens and the vacuum chamber. The rotating mirror enables realizing pre-determined patterns on the studied samples. The LIBS spectra were recorded perpendicular to the laser beam, but also parallel measurements through the front window were done. This milestone was reached.

Milestone 2: During the visit, altogether 16 Be-containing samples and 6 reference samples (SS, Cr, Si etc.) were analyzed. The spectra of pure Be was recorded with both spectrometers (Avantes and Andor SR750) in the spectral range 260–750 nm from a Be sample with a thickness of about 2 μm. All the strong lines in the spectrum were identified. For other samples containing Be, the spectral ranges 300–340 nm and 440–480 nm were chosen to detect the atomic (332 nm and 457 nm) and ionic (313 nm and 467 nm) lines of Be with the SR750 spectrometer. The registration system allows getting an acceptable signal-to-noise ratio in one-pulse registration mode. This milestone was reached.

Milestone 3: The positive outcome of the experiments was that the intense Be lines become visible even at low fluences (ca. 2–5 J/cm^2). This allows increasing the number of laser shots to remove the coating and, consequently, to reduce the ablation rate. The ablation rate is estimated in the range of 30–50 nm/shot depending on the sample. Thus, about 20–50 shots are necessary to remove Be coating for the tested samples. The variation of shot numbers for the same kind of samples has a linear dependence on the thickness of the Be coating. At the applied fluence levels, the spectra contain relative weak Fe lines (from the SS substrate) in comparison with those of Be. As a result, overlapping of one of the Be lines with Fe lines at 313 nm is not a major problem. In the spectral range 440–480 nm, with the exception of Be lines, there are no intense lines of elements that belong to samples with stainless steel substrate (Fe, Cr, C etc.). This milestone was reached.

Milestone 4: The spectra of samples corresponding to different Be contents of the samples were compared. It was found that the kinetics (intensity of Be line as a function of the number of laser shots) have exactly the same behaviour for samples with the same thickness, but the intensities of the Be lines are different in the same proportion as is the difference between the Be contents of the samples. This milestone was reached.

Milestone 5: After analysing of this first series of measurements with Be-containing samples, the conclusion is that the system is suitable for further experiments. The next steps are:

1. Make another series of measurements after getting a new, more powerful laser.
2. Increase the signal-to noise ratio using a special fiber that allows utilizing the entire height of the entrance slit of the spectrometer. The desired gain is approx. 5 times.
3. Test more carefully the gate width and delay time of the registration system with an oscilloscope.
4. Repeat identical measurements and average them over several craters to obtain results for presentations on conferences and for publishing in scientific journals.

5.4.24 Merging of development versions of the ERO code

Name of seconded person:	M. Airila
Sending Institution:	VTT
Host Institution:	FZ Jülich
Dates of secondment / mission:	13–15 August 2012

5.4.24.1 Work Plan / milestones

Recent development of the impurity transport code ERO includes several general-purpose features that are presently implemented as separate development branches. In order to all users and developers to benefit from these developments, a collaborative effort is needed to merge the various branches into the main version. To this end, all active developers have been invited to FZJ for three days to complete this task and place the merged version available in the CVS server hosted by FZJ. The following milestones are to be completed:

1. Merge the existing branches into CVS one by one. Some conflicts are expected where different developments have been done for same parts of the source code. Try to resolve all conflicts during the meeting.
2. Provide documentation of the new implemented features.
3. Provide test cases for each new option to be tested in the automatic software testing platform JuBE (Juelich Benchmarking Experiment).

5.4.24.2 Report

Our group's recent contributions to ERO development include:

- A surface model that takes into account the formation of compounds in the Be/C/W system. Sputtering data for the relevant compounds has been generated with Molecular Dynamics and are available with the source code of ERO.
- A new, more user-friendly handling of different divertor geometries and background plasma parameters.

During the meeting, the compatibility of both of these features with other new simulation options (BeD molecule formation model, higher hydrocarbons, and tracing of hydrogen species) was proved. The features are now made available in CVS and can be switched on and off during compilation. Concerning the new surface model, a remaining inconsistency was identified: The model uses the Bohdansky sputtering formula while the ERO code is presently being upgraded to use a more recent Eckstein sputtering formula. It was agreed that the new surface model will be upgraded accordingly in the near future.

Documentation files describing the background and usage of these features were written and saved into the CVS repository. In addition, sample input files for both cases were created and saved into the repository.

5.4.25 Investigating the connection between thermal ion orbit losses and boundary rotation in Asdex Upgrade tokamak

Name of seconded person:	A. Salmi
Sending Institution:	VTT
Host Institution:	IPP Garching
Dates of secondment / mission:	13–17 August 2012

5.4.25.1 Work Plan / milestones

The aim of the one week mobility visit between 13–17 August 2012 was to get acquainted with ASDEX Upgrade experimental data, to obtain a computing account in order to generate input data for modelling with the orbit following Monte Carlo code ASCOT, and to discuss the experimental data and the modelling capabilities with the AUG experimentalists and collaborators: T. Pütterich, E. Viezzer and R. McDermott.

5.4.25.2 Report

During the visit the experimental measurements with the edge charge exchange recombination diagnostics CXRS were discussed with the AUG collaborators. Discharge 27 169 with nitrogen impurity puffing (≈ 2 % of pedestal density) and with a separatrix sweep (to enhance the radial resolution of the measurements to around 3mm) was chosen for the initial modelling.

ASDEX Upgrade magnetic equilibrium data was imported from the experimental database after setting up the computing account and necessary tools for doing this. Experimental data of plasma profiles including radial electric field and toroidal and poloidal rotation were received from the collaborators and converted into a suitable form for simulations. A synthetic diagnostics for CXRS rotation measurement that was prepared for this modelling was tested in ASCOT and debugged using a simple collisionless test case. It was found to produce sensible results.

It was not possible to finalise the task in this short period. However, collaboration was established and all necessary data and access to AUG computers were obtained to allow continuing the task remotely, making the visit a successful start for these efforts.

5.4.26 Modelling of low-density ASDEX Upgrade discharges with SOLPS5.0

Name of seconded person:	L. Aho-Mantila
Sending Institution:	VTT
Host Institution:	IPP Garching
Dates of secondment / mission:	20 August–12 October 2012

5.4.26.1 Work Plan / milestones

During this visit, Leena Aho-Mantila will analyse experimental data from low-density L-mode discharges in the 2012 ASDEX Upgrade campaign, and model these discharges using the SOLPS5.0 code package. The work will be done in close collaboration with both the experimental and theoretical departments at IPP. Goals:

1. Develop SOLPS5.0 solutions for the 2012 low-density discharges in AUG
2. Assess the effect of drifts on the solutions with and without N impurities
3. Prepare a report on N seeding for the ITPA DSOL meeting.

5.4.26.2 Report

1. First results from SOLPS5.0 simulations of the 2012 low-density discharges were obtained during the visit, and the primary experimental profiles (pedestal and target) were evaluated. The activation of drift terms was observed to lead to a small numerical error in the calculations, which led to discrepancies between the modelled and measured pedestal profiles. The numeric settings in the simulations were adjusted accordingly, which led to an increase in computational times. Modelling of the same shots using another version, SOLPS5.2, was initialized to test the differences in the calculations in the presence of drifts.

2. Drifts were found to have a significant influence on the divertor conditions in unseeded discharges. The addition of nitrogen in the solution led to an increase in radiated power which, due to the drifts, was asymmetrically distributed in between the two divertor volumes. Due to the slow convergence of runs with impurity seeding, only a few data points were obtained for comparing drift and no-drift cases. Work will continue to assess the quantitative differences between these two cases.

3. An ITPA presentation on N-seeded discharges and their modelling was prepared during this visit, in collaboration with the AUG team.

5.4.27 Implementing spin-lattice electron dynamics into PARCAS (2)

Name of seconded person:	A. Meinander
Sending Institution:	University of Helsinki
Host Institution:	CCFE
Dates of secondment / mission:	21 August–21 September 2012

5.4.27.1 Work Plan / milestones

The collaboration, which was begun in May 2012, will be continued during this visit, with the goal of incorporating spin dynamics into classical molecular dynamics simulations of magnetic alloys and steels. A general method has now been developed which includes the treatment of evolution of both longitudinal and directional magnetic degrees of freedom, and yet is computationally effective enough to allow for dynamic simulations of very large systems of interacting spins. Since magnetic effects play an important role in the behaviour of iron alloys at high temperatures, the simultaneous treatment of both the spin magnetic moment and lattice degrees of freedom in dynamic non-equilibrium atomistic simulations of radiation damage processes, such as collision cascades, is a necessary step towards the understanding of such materials' response under the operating conditions of future fusion reactors.

In addition, molecular dynamics investigations will be conducted of the microstructural evolution of ion-irradiated tungsten, to elucidate recent experimental results from in-situ self-ion irradiation studies in pure tungsten samples.

5.4.27.2 Report

During this visit, work begun in May of this year was continued, with the goal of incorporating spin-lattice electron dynamics [P.W. Ma, et al., Phys. Rev. B **85 (2012)** 184301] into the classical molecular dynamics code PARCAS. Issues were worked out regarding the integration of the full spin dynamics equations, and necessary modifications of the integration scheme used in PARCAS were begun. In order to achieve a self-consistent dynamical evolution of both spin and lattice subsystems, including a coupling between electron, lattice and spin subsystems via Langevin dynamics, the Suzuki-Trotter decomposition needs to be used. Integration rules for the lattice subsystem derived through the Suzuki-Trotter decomposition form the basis for the velocity Verlet algorithm, and a form of this algorithm must be used in order to add the spin part of the dynamics. Furthermore, this scheme facilitates easy incorporation of Langevin dynamics, which also needs to be added to PARCAS.

In addition, defect production in high energy cascades in tungsten (W) was studied. Special attention was devoted to the clustering and configuration of the defect distribution as seen in molecular dynamics (MD) simulations of 150 keV collision cascades. These results were used as input for rate equation calculations by Dr. Daniel Mason from CCFE, and compared to recent yet unpublished experimental results from in-situ irradiation studies of self-ion damaged W, performed by Xiaoou Yi from the University of Oxford. From these MD simulations, uncertainties were uncovered in the description of electron effects in cascade evolution, as described by the approximations commonly used in current molecular dynamics calculations. Further investigations of these issues are now a main priority, since a correct description of primary damage is crucial for successful multi-scale simulations of irradiation effects in W. Additional benefit of this visit was gained from numerous discussions with visiting researchers, as well as my own presentation of the ongoing work on W cascades at the Materials Department of the University of Oxford, and from discussions that followed.

5.4.28 Planning meeting for major revision of the ERO code

Name of seconded person:	M. Airila
Sending Institution:	VTT
Host Institution:	FZ Jülich
Dates of secondment / mission:	18–19 September 2012

5.4.28.1 Work plan / milestones:

The ERO code dates back to the 1990's and has established a steady position as the leading European software for impurity migration studies in fusion devices. Applications of ERO range from present limiter and divertor tokamaks to linear machines, ITER and DEMO. The code has recently undergone a profiling and a code review, the results of which suggest a major rewriting. This rewriting would prepare the way for

- Significantly improved computational performance by using modern programming techniques and advanced optimization
- Successful parallelization
- Continued development and use until 2020 and beyond by ensuring the sustainability of the code in an international developer community.

Such a rewriting is a multi-year effort and is planned to be realized as a PhD project, the contributing institutions being FZJ, Åbo Akademi University, VTT, and CSC – IT Center for Science. The purpose of the present visit is to identify the needs and goals as well as to agree on major guidelines, funding and manpower needed for the project.

5.4.28.2 Report

A half-day discussion on project goals, available funding schemes and practical arrangements concerning the actual execution and supervision of the programming work was held between U. Samm, D. Reiter and A. Kirschner (FZ Jülich); J. Westerholm (ÅA); and M. Airila (VTT). It was concluded that

- Potential funding sources are FZJ, ÅA and EFDA
- Final decision on launching the project and the funding shares will be done once an employee has been assigned to the project and the technical scope has been specified
- It is not necessary to define the project as a dissertation work.

The second day of the visit was dedicated to planning the next steps of the project. It was agreed that FZJ and VTT start preparing a specifications document for ÅA, defining the requirements for the new code in sufficient detail for code design.

5.4.29 Power exhaust studies with radiative divertor plasmas

Name of seconded person:	L. Aho-Mantila
Sending Institution:	VTT
Host Institution:	General Atomics, San Diego
Dates of secondment / mission:	12–27 October 2012

5.4.29.1 Work Plan / milestones

The aim of this visit is to exchange information on experimental and modelling work done on radiative divertor plasmas in ASDEX Upgrade, JET and DIII-D. Dr. Aho-Mantila has performed SOLPS calculations for dedicated N_2-seeded discharges in the full-metal devices ASDEX Upgrade and JET. She will discuss the results and experience obtained in this work with the DIII-D program research staff. The aim is to develop plans for future experiments and modelling in these devices, in order to address the problem of divertor power exhaust in fusion reactors. Experience in performing reactor-relevant simulations with edge fluid codes will be communicated. If time allows, the predictive capabilities of the codes and code development needs will be discussed.

5.4.29.2 Report

During the visit, Dr. Aho-Mantila gave a talk describing SOLPS modelling of N-seeded discharges in ASDEX Upgrade and JET, and the results and status of the work were discussed within the boundary physics team at DIII-D. It was concluded that DIII-D, having similar size as ASDEX Upgrade, could contribute particularly with experiments addressing the effects of the divertor geometry and magnetic field direction on impurity seeding. The local experts described their experience with earlier DIII-D experiments using Ar injection, and possibilities to use other seeded impurities, such as carbon which is intrinsically present at DIII-D, were discussed. Dr. Leonard described the status of edge plasma modelling at DIII-D and new diagnostic capabilities foreseen for the 2013 experimental campaign. Dr. Aho-Mantila described the present efforts in boundary physics research at ASDEX Upgrade.

Possible links between the research programs in all three devices were discussed, in connection to the ITPA/DSOL activities. The aim is to pursue collaboration in this area in 2013. Dr. Aho-Mantila was introduced to the analysis programs used to access DIII-D experimental data.

5.4.30 Detachment modelling using SOLPS and UEDGE

Name of seconded person:	M. Groth
Sending Institution:	Aalto University
Host Institution:	General Atomics, San Diego
Dates of secondment / mission:	15 October–4 November 2012

5.4.30.1 Work Plan / milestones

1. Presentation of data analyses of detached divertor plasmas in DIII-D and JET L-mode discharges
2. Discussion of UEDGE, SOLPS, and EDGE2D/EIRENE modelling results.
3. Seminar presentation to boundary group at General Atomics
4. Discussion of experimental proposals for 2013 run campaign.

5.4.30.2 Report

1. Discussion of SOLPS and UEDGE simulations of DIII-D L-mode plasmas with DIII-D boundary groups: Tony Leonard/GA. Further investigations of parameters
2. Setup and coaching of Cedric Tsui of University of Toronto how to post-process UEDGE simulations for flows in the divertor
3. Discussion of JET results and implications of including molecular ions in EDGE2D/EIRENE simulations
4. Setting up and executing SOLPS simulations with fluid and kinetic neutrals
5. Presentation of recent UEDGE and SOLPS simulations for DIII-D L-mode plasmas at DIII-D boundary group meeting
6. Discussion of further collaboration with DIII-D and LLNL edge modelling teams: proposed experiments for 2013 run campaign and input to 5-year plan (Tony Leonard and David Humphreys, GA).

5.4.31 Spectral measurements of the cleaning efficiency with vacuum arc device

Name of seconded person: P. Paris
Sending Institution: University of Tartu
Host Institution: Diarc Technology
Dates of secondment / mission: 22–24 October 2012

5.4.31.1 Work Plan / milestones

1. Recording plasma spectra during cleaning process with prototype of vacuum-arc device of test samples with different coatings (W-Al, W-Al-C, Al, C-W)
2. Analysing spectra and discussing the possible ways to improve the cleaning efficiency and quality.

5.4.31.2 Report

For the spectroscopical measurements the system is supplied with special viewing window. Spectra of the arc-generated plasma can be recorded through this view-port with the help of Avantes CCD spectrometer. The rate and quality of cleaning will be estimated spectroscopically by recording time-dependent (pulse-to pulse) spectra of the cleaning arc-discharge plasma. Ideas and plans made during earlier visits to DIARC are realised in the present set-up.

Milestone 1: Test samples with 1-μm coatings of different materials and material mixtures (W-Al, W-Al-C, Al, C-W, where Al was used as a substitute to Be) on the stainless steel substrate should simulate deposition layers on the tokamak walls. Dimensions of the samples were about 25 × 25 cm^2, which size enables to simulate the real cleaning (coatings removing) process. During the arc processing of the surface an Avantes spectrometer with optical alignment system recorded plasma pulse-to-pulse spectra in perpendicular direction to the discharge propagation. Vacuum arc pulses were generated in low-pressure Ar gas flow in the pressure range 0.1–0.6 mbar. The repetition rate of arc pulses was varied in the range 2–5 Hz. In experiments were varied also the distance of the arc electrode from the processed surface and basic electrical parameters supplying the arc as well the total number of cleaning pulses. The cleaning was monitored spectroscopically, the results of every cycle were judge also visually. We foresee additional physical measurements as SIMS to estimate the cleaning rate of testes surfaces. This milestone was reached.

Milestone 2: It was carried out in detail the analysis of received spectra. In spectra, the lines of surrounding Ar gas are dominating over the lines of Fe and Cr from the substrate. Al, W and C lines can be found in the spectra of the first sweep of the arc electrode which indicates that after the very first arc pulses are reached to the substrate. In later phases lines from cover layer atoms are overshadowed with the strong spectrum from the substrate and surrounding gas. For the H doped samples the hydrogen lines were detected. The spectra have a good quality (signal-to-noise ratio, spectral resolution about 0.3 nm) for this spectral device.

Back-deposition of removed layers to the neighbouring areas seems possibly become to a problem.

In future can be foreseen the optimizing of the arc parameters of cleaning system for different coatings. For reliable recording of spectra the scanning of sample instead of electrode would be a good option. This milestone was reached.

5.4.32 JET TF and IAEA-FEC 2012 review

Name of seconded person: M. Groth
Sending Institution: Aalto University
Host Institution: EFDA-JET
Dates of secondment / mission: 5–7 November 2012

5.4.32.1 Work Plan / milestones

1. General TFL activities, start review of IAEA 2012 / Nuclear Fusion papers.
2. Preparation of edge modelling meeting 26 November–14 December, 2012.

5.4.32.2 Report

I spent three days at JET enroute from San Diego to Helsinki intending to start the review process of papers pertaining to the IAEA-FEC 2012 conference. Since no paper has yet been submitted I reviewed other papers that were submitted prior to the FEC conference, including Paula Belo's paper on model validation of carbon sputtering yields and Andreas Kirschner's paper on ERO/3D-GAPS simulations of quartz microbalance measurements in JET. Together with Johnny Lönnroth, we set up the schedule and website for the upcoming edge modelling meeting in November (Nov 26–Dec 14, 2012).

5.4.33 Energetic ions and 3D effects in AUG

Name of seconded person: T. Kurki-Suonio
Sending Institution: Aalto University
Host Institution: IPP Garching
Dates of secondment / mission: 11–24 November 20112

5.4.33.1 Work Plan / milestones

1. Together with Dr. Wolfgang Suttrop explore if, combining experiments at AUG and ASCOT simulations, it would be possible to experimentally demonstrate NTV in action.

2. Introduce to Dr. Karl Krieger the most recent upgrades to ASCOT that facilitate ever more realistic simulations of impurities in real 3D tokamak geometries and decide on the most pressing issues to be addressed with the code.

5.4.33.2 Report

1. The possibility of experimentally demonstrating braking/speeding up by NTV was discussed with Dr. Suttrop and Dr. Bergmann. The idea for the next experimental campaign is to repeat the shot from this year where rotational braking was observed with *resonant* perturbation. The problem with resonant perturbations is that they are likely to produce islands that in themselves provide braking of rotation. Therefore, in the repetition shot a *non-resonant* perturbation would be applied so that no islands ought to be there.
2. Due to other issues, the PWI work was postponed to February 2013.

Other, unforseen tasks:

In a couple of meetings with the TOK group Yuki Homma's PhD work was discussed: tungsten transport including a non-Maxwellian background (due to radial gradient of T). Homma has developed a model for this and would like to include it in particle following. However, this has proven non-trivial, and it was discussed what would be more cost-efficient: to continue trying to create his own particle following algorithm, or to include his model in ASCOT.

Together with Profs. Günter and Lackner, the important issue of calculating the plasma shielding of external perturbations was discussed. The original attempt with CASTOR had failed to yield the desired effect and, thus, the discussions were broadened to include other codes, such as XTOR and JOREK, as well as the ideal MHD code VMEC. The conclusion was that at the moment probably the best approach would be using VMEC. Even with its limitations it can still account even for the resonant amplification at high beta.

Further actions that are needed in order to turn the spectroscopic flow diagnostic, developed as the PhD work of T. Makkonen, into a routine measurement in AUG, were discussed with Dr. Thomas Pütterich.

5.4.34 Numerical studies of nitrogen seeded JET baseline ELMy H-mode plasmas

Name of seconded person: A. Järvinen
Sending Institution: Aalto University
Host Institution: EFDA-JET, UK
Dates of secondment / mission: 3–14 December 2012

5.4.34.1 Work Plan / milestones

The aim of the mobility visit was to participate the discussion between edge-plasma modellers and experimentalist in JET during the edge modelling meeting in December 2012. The overarching goal of the project is to conduct interpretive and predictive numerical studies of deuterium fuelled and nitrogen seeded JET baseline ELMy H-mode plasmas for tungsten, and nitrogen transport, and power exhaust. The numerical tools are EDGE2D-EIRENE and DIVIMP on the one hand, and JINTRAC and DIVIMP on the other. The plan during the mobility is to agree and specify the modelling approaches by discussing about the general guidelines and details of the project with both experimentalists and modellers participating into the modelling month. The specific goals of these discussions are listed below.

1. Agree with S. Lisgo and M. Groth about the general objectives and boundaries of the project.
2. Discuss and agree with experimentalists about the specific JET plasmas to be modelled.
3. Discuss and agree with experimentalists about the diagnostic data to be used in constraining the models.

5.4.34.2 Report

The milestone number one was started, and it will be continued in the subsequent collaboration. Related to this, onion-skin modelling of the chosen ITER-like wall plasmas will be considered during the spring 2013.

The milestones number two and three were successfully achieved. Related to this milestone, the JET shot numbers of interest were identified and the most significant limitations of the current modelling attempts were diagnosed, both of which aid to establish a strong basis for the forthcoming steps in the project. The diagnostic data for constraining the models was agreed and identified with experimentalists.

In addition, comparisons of experimental and EDGE2D/EIRENE modelled divertor D_α emissions during ELMs between JET carbon and ITER-like wall ELMy H-mode discharges were conducted. It was observed that in the carbon wall discharges, the EDGE2D/EIRENE tended to strongly underestimate the divertor D_α

emissions during ELMs, probably due to strong, ELM heat pulse induced, desorption of deuterium from the carbon surface, which has not been taken into account in the model. In the ITER-like wall discharges, on the other hand, the ELMs were observed to lead to slower, in-out -asymmetric D_α emissions during ELMs, suggesting smaller deuterium desorption from tungsten surfaces compared to carbon surfaces. Therefore, EDGE2D/EIRENE should be able to reproduce the D_α emissions during ELMs in the ITER-like wall discharges. The EDGE2D/EIRENE simulations for the ITER-like wall case showed that the D_α emission at the outer target was still underestimated compared to the experimental measurements, while at the inner target, where D_α emission peak during ELMs was not observed experimentally, the values calculated with EDGE2D/EIRENE were comparable to the experimental ones. Therefore, it seems plausible to reproduce the neutral responses at the divertor targets during ELMs in the ITER-like wall discharges. These investigations will be continued and further dissected in the subsequent modelling attempts with EDGE2D/EIRENE and JINTRAC.

5.4.35 Molecular Dynamics simulation of the effect of Be in D retention in W

Name of seconded person: A. Lasa
Sending Institution: University of Helsinki
Host Institution: EFDA-JET, UK
Dates of secondment / mission: 3–14 December 2012

5.4.35.1 Work Plan / milestones

During the Edge Modelling Meeting, I work on: Molecular Dynamic Simulation of the effect of Be in D retention in W.

5.4.35.2 Report

1. During the visit, we carried out a Molecular Dynamics simulation study of W irradiated by different D plus Be mixtures. We focused on the data analysis of the simulations run since the visits in 2011, studying the effect of the Be concentration and ion impacting energy on aspects such as the D and Be sticking coefficients and their depth profiles. We also analysed the differences between the consecutive and simultaneous Be-D irradiation.
2. Besides the data analysis, we started new simulations of D plus Be irradiation on W for a direct comparison to BCA codes (SDTrimSP). The aim is to determine until which energy the many-body effects are relevant (to the sticking coefficients, depth profiles and sputtering yields).
3. All this information will be later used by other larger-scale codes in order to improve their predictions or to be able to directly compare with experiments. For example, the Be, D and BeD molecule reflection data will be

used by codes such as ERO and WALLDYN. Furthermore, the depth profiles will be part of the input for rate equation calculations to study the effect of Be on the D retention in W at pulse scale.

5.4.36 Exposing tungsten samples to Pilot-PSI plasmas

Name of seconded person:	A. Hakola
Sending Institution:	VTT
Names of seconded persons:	P. Paris and K. Piip
Sending Institution:	University of Tartu
Host Institution:	DIFFER
Dates of secondment / mission:	10–14 December 2012

5.4.36.1 Work Plan / milestones

1. Exposing tungsten samples to Pilot-PSI plasmas.
2. Discussing with the DIFFER team the possibility to do in situ LIBS experiments at Magnum-PSI in 2013.

5.4.36.2 Report

Milestone 1: During the visit, altogether 8 test samples were exposed to plasma discharges in Pilot-PSI. All the samples were produced by DIARC-Technology Inc. and they had a 2-μm thick W coating on Mo (diameter of the Mo substrate 30 mm and thickness 2.5 mm). In addition, two of the samples had been doped with D (about 1-at. %) during their deposition. Before and after plasma exposure the samples were weighted using a Mettler Toledo microbalance to estimate net erosion of their coatings.

Six of the samples were exposed to mixed deuterium and helium plasmas such that the maximum surface temperature remained at 900–950°C. The plasma jet had an approximately Gaussian shape with a diameter of 10–15 mm. In the case of pure D_2 plasmas, the temperature decreased from the peak value to around 600°C towards the edges of the samples whereas for He plasmas the drop was more dramatic: from 900°C to 400°C.

By visual inspection, plasma exposure had left clear marks close to the centre of each sample. However, when He was added to the plasma, the resulting spot was more prominent than in the case of pure D_2. On the other hand, deuterium was able to modify the entire surface to some degree while the effect of He was better localized in the vicinity of the central plasma spot. One of the samples was accidentally subjected to too high a magnetic field (0.8 T), resulting in local melting and re-crystallization of the coating. The measured mass loss of the samples was around 0.2–0.3 mg, the exception being the sample exposed to pure D_2: for this, the mass loss was very small, completely within error bars.

For the last two samples, the 0.4/0.6 mixture of D_2 and He was used but now the surface temperature was increased to 1250°C and the ion energy was varied. Now almost the whole surface had been modified showing a black ring close to the edge, a greyish region closer to the centre, and finally a shiny metal-like surface in the region coinciding with the centre of the plasma jet. The last sample was exposed also at around 1200°C but this time the bias was increased to 70 V. The end result was a beautiful black surface, possibly indicating the formation of W fuzz. The mass loss of these samples was of the same order of magnitude as the values discussed above.

All the planned experiments were carried out and the samples will now be analyzed using SEM, XRD, SIMS, and LIBS. Also the plasma-exposed spot on the samples will be investigated with a profilometer. This milestone was reached.

Milestone 2: A LIBS diagnostics is now in routine use in Magnum-PSI. During the visit possible forms of collaboration in this front were discussed, and according to preliminary plans, short visits will be paid to DIFFER in 2013 such that the LIBS system can be further developed and in situ erosion experiments can be carried out. This milestone was reached.

5.5 Euratom and EFDA Fusion Training Scheme

5.5.1 EFDA goal oriented training in remote handling – GOTRH

EFDA GOT:	WP10-GOT-GOTRH
Project coordinator:	J. Mattila, TUT
Tekes trainees:	P. Alho, J. Väyrynen, TUT
	R. Sibois, VTT
Tekes mentors:	J. Mattila, TUT
	K. Salminen/T. Määttä, VTT

5.5.1.1 Objectives

The aim of the EFDA’s European Goal Oriented Training programme on Remote Handling (RH), “GOT RH”, is to train engineers for activities to support the ITER project and the long-term fusion programme in European associations, the work of associates, Fusion for Energy, and the ITER organization and industry.

The principal objective is to implement a structured, remote handling system *design and development oriented training task* that is carried out in a multidisciplinary systems engineering framework through the use of ITER / Fusion for Energy task-related and quality assurance processes and the available documents, document templates, and ITER-relevant software products. Special emphasis is placed on a top-down engineering approach with multidisciplinary consideration of design requirements related to reliability, availability, maintainability, and inspectability (cf. RAMI approach). Within this SE framework, each GOT RH trainee will work within the context of a multi-site collaborative design team on a RH system design task, facilitated by mentors with ITER remote handling and general engineering experience. The activity will increase the coherence in European RH activities, networking in training activities, the transfer of knowledge and will connect engineering from other disciplines (viz. plug engineering) to the remote handling community. The GOT RH project serves as a practical level project for increasing the coherence within RH context of collaborative training project between 5 participating European associations.

ITER will consist of around 10 million parts (roughly 10 times more than the largest airplane in production) and hundreds of systems with thousands of interfaces among them that must be identified and controlled. A key requirement for the success of such a large project is that a systematic and standardized approach is adopted to ensure the consistency of the design with the required performance. In its own part, the science and technology objective of this project is to develop common standards and tools for ITER design and development activities. Common standards and tools are necessary to guide ITER development while ensuring that ITER is properly designed to make it affordable to build, operate and maintain.

GOT RH project has five EURATOM partners with 10 trainees

- Association Euratom-Tekes, Finland (3)
- Association Euratom-CEA, France (2)
- Association Euratom-FOM, Netherlands (2)
- Association Euratom-KIT, Germany (1)
- Association Euratom-CIEMAT, Spain (2).

The EFDA GOT project is coordinated by Prof. Jouni Mattila (TUT) from the association Euratom-Tekes. EFDA Responsible Officer is Jon Harman.

5.5.1.2 Main results in 2011

Jukka Väyrynen is the TUT trainee working on the work package (WP) 1.3 in GOT RH. Topic of the WP1 is remote handling procedures and tools. The goal of this particular project (*WP1.3: RAMI requirements assessment of ITER remote handling equipment components for their future procurement and life-cycle management*) is to study the ITER RH equipment RAMI requirements and evaluate a set of equipment against the requirements through qualitative and quantitative methods. Furthermore, based on the evaluation, the goal is to create a scheme with which the RAMI requirements could be met, and based on the concept scheme, to create a process for building reliability in further ITER RH equipment development.

The previously developed method was tested against a more complex target. Again, the test subject was a prototype instead of a concurrent design process, but this was an ample opportunity to demonstrate the scalability of the method. It was noticed that while the number of components doubled and the number of unique failure modes was increased, the calculation time was not dramatically increased yet the information yielded by the analysis remained high.

Further work on addressing controller reliability is planned. This should address both the hardware and software aspects of controller systems.

Pekka Alho is the TUT trainee working on the WP2.1. Focus of the WP2 is software and control systems. The main research objective for this project (*WP2.1: Fault tolerant device control system architectures for ITER RH system)* is development of a fault tolerant and dependable architecture for ITER remote handling systems. The architecture must not only fulfil the strict functional and non-functional requirements set by the ITER environment but also balance the cost efficiency aspects of the fault tolerant designs.

The implementation of the project is proceeding as defined by the GOT RH task process, which includes documentation such as system requirements document and conceptual control system design architecture. Control system architecture development is in the prototyping phase where different solutions are tested on an open source real time operating system used to control a commercial industrial manipulator. Next steps will include a design description document and updates to the RH system requirements and architecture based on the research efforts.

Romain Sibois is the VTT trainee working on the WP 1.5. The objective of this project (*WP1.5: Verification and Validation (V&V) of ITER RH System Requirement using Digital Mock-ups*) is to enhance verification and validation methods, models and processes during the early design phases of ITER Remote Handling equipment. The project aims to find out and utilize the most useful and efficient V&V approach to fulfil the requirements of the concept design towards reducing physical testing and replacing some aspects by virtual testing and verification.

A concept of the enhanced V&V approach has been performed and related requirements have been documented in the system requirements document as required by the GOT RH task process. The conceptual design phase is still proceeding and will be documented in the conceptual design document. The model verification will be performed by applying the developed concept method on selected test cases related to ITER RH equipment.

6. Fusion for Energy and ITER Activities

6.1 Divertor RH design updates and DTP2 Phase 2 testing

F4E Contract:	F4E-GRT-143; F4E-GRT-401
Research scientists:	M. Siuko, J. Järvenpää, VTT J. Mattila, TUT/IHA

6.1.1 Objectives

The main objectives of the activities foreseen in this Grant are:

- To continue the campaign of operational CMM and WHMAN trials started in the previous Contract (F4E-2008-GRT-MS-RH-01) and to assess the performance and robustness of the RH equipment when performing under non-nominal operating conditions.
- To identify, implement and test a series of modifications and upgrades to the RH equipment and its Control System as a result of the experiences acquired in previous Trials campaigns and in order to add new functionalities required for the execution of further RH Trials with new RH equipment.

The new grant (F4E-GRT-401) with F4E was signed in December 2012 and main work with it will start 2013. This grant continues the work started in previous grants. The Grant F4E-GRT-143 started in September 2010 and ended in May 2012. The grant was divided in three tasks:

1) DTP2 trials and control system updates
2) Design and procurement activities
3) Development of RH Control system using DTP2 platform.

6.1.2 Grant description and main results in 2012

The Grant started in the end of 2010, and the work was mainly carried out in 2011. Some testing, reporting and design was done in 2012. Detailed descriptions of activities and results for tasks during 2012 are explained in the next chapters.

6.1.2.1 Task 2

Subtask 2.1: Second Cassette end-effector (SCEE) improvements

The objective of this sub-task 2.1 was to conduct a refurbishment of the SCEE to solve the issues found during the DTP2 test campaign, and consequently to improve the reliability of the results obtained in the Divertor RH test campaigns being carried out at DTP2.

Main focus was to improve the bearing and resolver solution of SCEE joints. Interfaces between the Second Cassette End-Effector, Divertor Cassette Mock-up and CMM were analysed. As a result of these analyses were designed some modifications to SCEE for better RH properties. After modifications and assembly of SCEE it was tested in the test stand (Figure 6.1). As a result of the tests and measurements it could be concluded that the modifications improved the performance characteristics of the SCEE. Deflections were smaller and position accuracy of the resolvers was better.

Figure 6.1. Testing the refurbished SCEE in the test stand after modifications.

Subtask 2.2: Management of requirements

Requirements form the basis for project planning, risk management, acceptance testing, trade-off and change control. Within the lifecycle of the ITER RH equipment, several sets of requirements are going to be defined and verified at different stages of design, manufacturing, integration and commissioning phases.

In this task was given an example of the requirements management process using a requirement management software tool. The tool can integrate written requirements, functional behaviour, architecture, and detailed design of a certain system. In this task, one part of the ITER divertor remote handling operations was taken as an example and it was implemented to Enovia software tool. Comparison to Doors software was also done.

As a result of this task can be found that both tools enable the traceability representation with minor differences in usability and scalability. Traceability also enables assessing the impact of a change to the system context. For example the effect of changing the description of one requirement can be indicated in all artefacts that are linked to the said requirement.

By using the data model, presented in Figure 6.2, the requirement satisfaction arguments can be implemented directly into the database of the described system. I.e. by using the verification report that includes traces to the test executions and to the requirements the fulfilment of each requirement can be monitored.

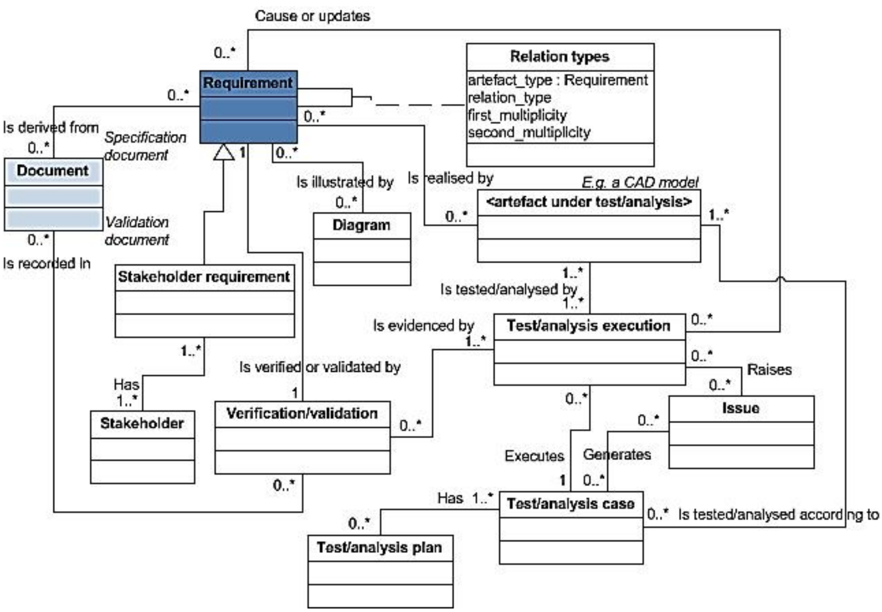

Figure 6.2. Concept model of the requirements management system.

Also the design review processes can be greatly enhanced by using PLM-tools. Enovia and also Doors can be utilized efficiently for the use of system design and also to design reviews. The implementation and data-model behind the tool is affecting largely to how efficiently the defined processes can be executed.

6.1.2.2 Task 3

Demonstration

In the demonstration phase we saw the new software in action. The main software development was done previously in the implementation phase. In this demonstration phase, the co-operation different software subsystems were tested and demonstrated. The demonstrations were named as:

- Integrated Operations
- Accurate Virtual Reality
- Condition Monitoring
- Optimized Viewing
- Standard Controller.

Some of the systems were demonstrated as a "stand alone" (Viewing System and Standard Controller), but mostly the new pieces of the software were demonstrated as a co-operation between other systems and DTP2 equipment (Integrated Operations, Accurate Virtual Reality and Condition Monitoring).

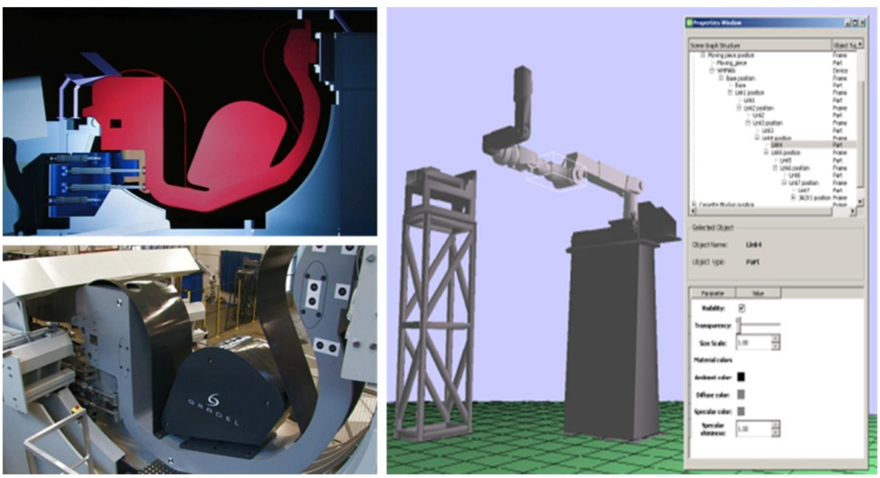

Figure 6.3. Demonstration of off-line execution of RH tasks without using the actual RH equipment.

By using an OMS and VR, the Integrated Operations demonstrated the off-line execution of RH tasks without using the actual RH equipment. Changes in noninstrumented tool and equipment movements are reflected to the VR. Integrated operations also demonstrated the cooperation of OMS and C&C by giving e.g. trajectory suggestions and logging operation execution (Figure 6.3)

Basically accuracy of the virtual model is a combination of the reached accuracy of the entities in the system. The purpose of the accurate virtual reality demonstration was to improve accuracy of the virtual reality by improving modelling of deformations in the system.

Condition monitoring detects the faults in the components of remote handling equipment during the operation. It can improve the safety and efficiency of the remote handling operations by providing the beforehand knowledge about the status of the equipment. It can also help the maintenance by narrowing down the possible causes of failures. Logically condition monitoring is located within in the equipment controller of the device. Remote diagnostics is an additional module of condition monitoring, which records the commands and sensor feedback data. During operations, remote diagnostics functions as a higher level online application to interconnect the faults between multiple remote handling devices, so the failure of one device can be used to plan the actions for other devices. Remote diagnostics can also be used offline to analyse the recorded data and improve the efficiency of maintenance operations (Figure 6.4).

The optimized viewing system is the system that provides the operators with visual sensing of the remote environment. It is seen as essential for all manual interactions with the environment, and the ability to perform man-in-the-loop remote operations is directly linked to the viewing capabilities.

The RH Standard Controller is an architecture (SW and HW), behaviour and interfacing model for all the RH controllers, including the equipment controllers, device controllers, tool controllers and sensor controllers. The scope of this demonstration is the divertor remote handling control system, especially CMM and WHMAN equipment controllers.

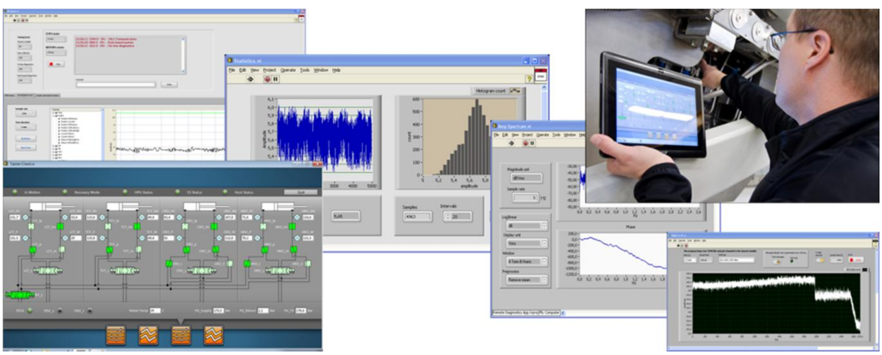

Figure 6.4. The mover condition monitoring detects exceptional sensor readings.

6.2 Upgrade of the Divertor Cassette Mock-Up and verification of the Locking System – Part 2

ITER Contract: ITER/CT/12/4300000674
Research scientists: J. Järvenpää, H. Mäkinen, VTT

The aims of the project are:

- Design and manufacturing divertor cassette test mock-up meeting the latest ITER cassette design.
- Testing of the new cassette installation and its locking system operation.

The new cassette mock up was designed to meet the latest development of the ITER cassette. The main design drivers were geometry, dimensions and weight of the ITER cassette, location of the center of gravity and the stiffness of the ITER cassette. The cassette mock up was also designed modular to allowing later updates.

After the tendering process the heavy cassette body was manufactured by Hollming Works, Kankaanpää. The locking system (Knuckle) was manufactured by Logistics, Pirkkala. The design of locking system components included very tight tolerances and therefore the final inspection and measuring of the components was done by third-party, ATA-Gears and Tampere University of Technology.

The cassette components were delivered during November 2012. The final assembly of the locking system and the cassette was done in DTP2 workshop to be able to see the compatibility of the components and to learn the components behavior.

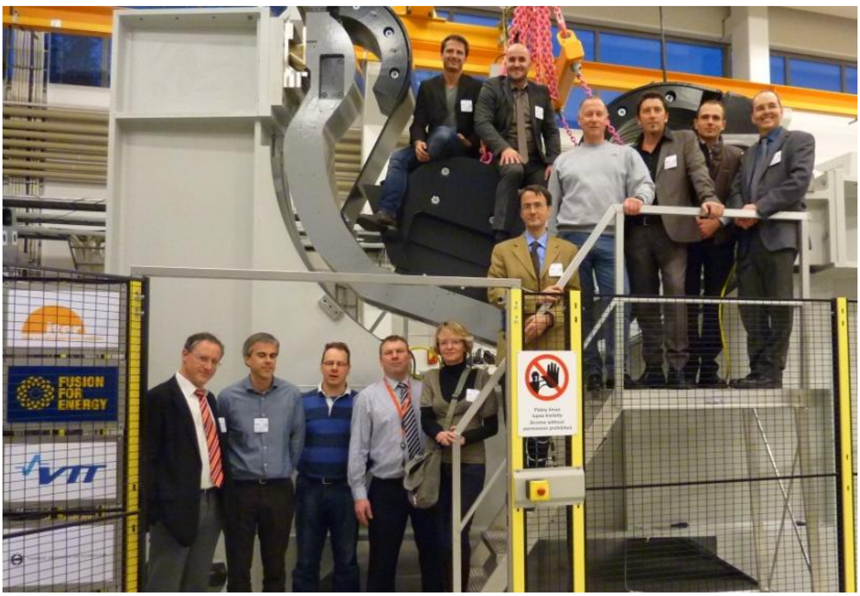

Figure 6.5. First Divertor cassette tests in Tampere.

During the assembly, all the components were carefully cleaned and recommended molybdenum-sulfide dry lubricant used for threads. All the cassette locking system components were matching tightly but well as planned.

The test period started mid December 2012 with a kick-off meeting. Participants were from IO – divertor and RH section and F4E divertor and RH representatives. The new cassette test cycles will be performed during 2013.

6.3 R&D/design of sensors for the ITER magnetics diagnostic: design of the outer-vessel steady-state discrete sensor system

F4E contract: F4E-2010-GRT-156

Research scientists: J. Kyynäräinen, H. Rimminen, J. Saarilahti, P. Kotiluoto, T. Seren, J. Flak, VTT

Background: Magnetic diagnostics on tokamaks provide local measurements of the magnetic field and large-area measurements of magnetic flux close to the surface of the plasma. Combinations of these measurements are processed to determine a variety of plasma parameters, such as its position, shape or the electrical current it carries, in both static and a range of dynamic conditions. Some of the plasma parameters are determined in real time for plasma control applications while others are determined off line for physics studies. The subject of this grant is to develop detailed designs for a steady-state discrete magnetics sensor system including sensor assemblies to be installed on the outer vessel of the ITER tokamak, to provide measurements of the plasma equilibrium field.

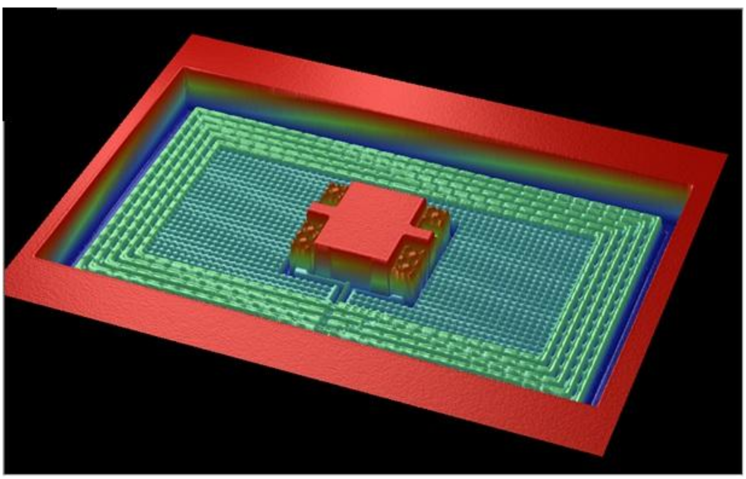

Figure 6.6. Optical profilometer image of a semi-finished sensor. The rectangular spiral coil can be seen at the bottom of the recess. The red areas are to be bonded to the capping wafer.

Goals: R&D and design activities to detail designs for steady-state discrete magnetics sensor system, aimed at measuring the equilibrium field outside the tokamak vessel. The detailed designs and associated documentation shall be developed to a level consistent with the requirements for an F4E Preliminary and Detailed Design Reviews. The designs shall aim at meeting the performance, reliability and operating life requirement targets. Grant duration is 26 months.

Progress in 2012: Fabrication of the sensors continued throughout the year. Several sensor designs were included in the fabrication batch to provide more flexibility during testing and because of uncertainties in the simulations. An optical profilometer image of one type of the semi-finished sensors is shown in Figure 6.6.

Fabrication has been delayed by several equipment failures and by difficulties encountered due to previously untested processing steps. At the end of the year, all three sets of processed silicon wafers were ready for the wafer bonding.

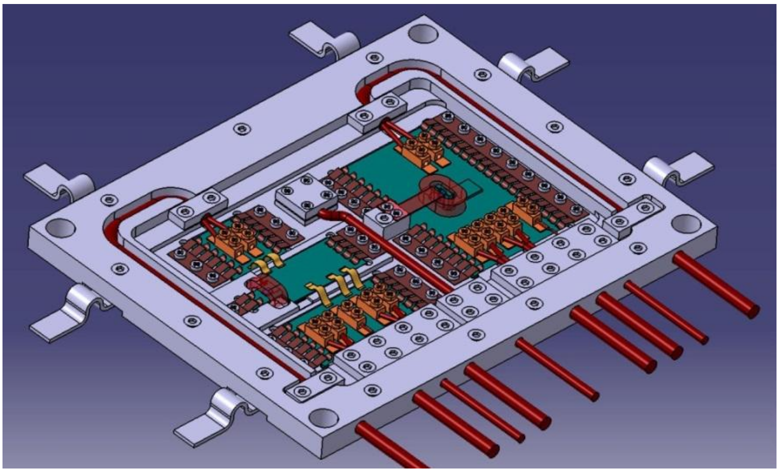

Figure 6.7. 3D model of the enclosure housing two sensors, one for the poloidal field component and one for the radial component.

Stainless steel sensor enclosure has been designed to fit in the 11 mm narrow gap between the vacuum vessel outer surface and the thermal radiation shield (Figure 6.7). The sensors will be glued to aluminium nitride based DBC substrates using cyanate ester based adhesive and electrical contacts will be made using gold wire bonding. To ensure reliability, cables will be laser or electron beam welded to the substrates. The enclosures will be capacitive discharge welded to the vacuum vessel outer surface. FEM simulations were carried out to find mechanical stresses in the package due to differential thermal expansion. Radiation-induced effects including nuclear heating, gas generation, transmutation etc. were simulated as well. Electromagnetic loads during disruptions on the sensor enclosure were analysed, leading to a conclusion in which the attachment legs have to made out of Inconel because of the risk fatigue failure with stainless steel legs.

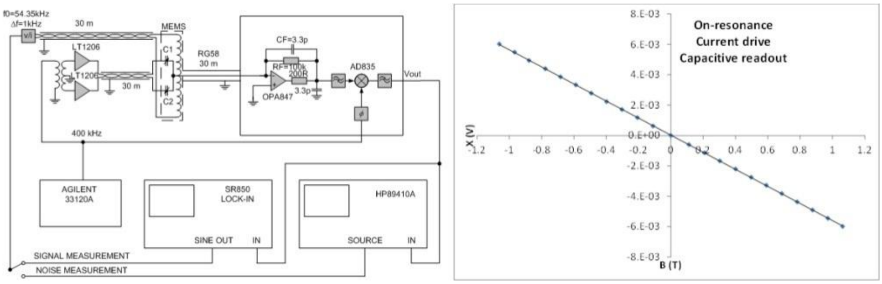

Figure 6.8. Test electronics for the current drive/capacitive readout (left) and the measured signal on resonance vs. flux density (right).

Several types of prototype electronics have been constructed. The challenge in the design is that the radiation level at the sensors locations is too high for preamplifiers to survive and up to 30 m long cables will be needed between the sensors and the front-end electronics. The baseline design is based on feeding an ac current to the sensor coil and reading the signal using a transimpedance amplifier to reduce the effect of cable capacitance (Figure 6.8, left). Tests in laboratory environment show that the signal amplitude follows linearly the flux density (Figure 6.8, right). More recently, an alternative readout electronics configuration was constructed and tested, in which the sensor coil is vibrated electrostatically (Figure 6.9, left). The induced voltage across the coil ends is proportional to the flux density (Figure 6.9, right). Both readout methods were shown to yield a magnetic flux density resolution of about 2 mT at a 20 Hz measurement bandwidth, meeting the specifications. The second method requires less cabling than the first one, a fact which is important in the practical realization of the diagnostics systems.

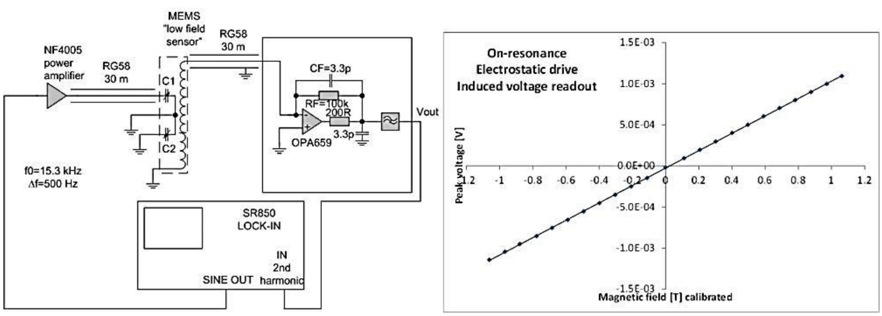

Figure 6.9. Test electronics for the electrostatic drive/induced voltage readout (left) and the measured signal on resonance vs. flux density (right).

The Preliminary Design Review Preliminary of ITER Steady-State Sensor (PBS 55.A5/A6) was held in Cadarache on 5–6 December, 2012.

6.4 Ab initio calculations of 3D vacuum magnetic field in ITER

F4E Contract: F4E-GRT-379

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

Since energetic particles are very collisionless, the quality of the magnetic background that determines their orbits is the deciding factor in the quality of the simulation results. In a previous ITER task, TW6-TPO-RIPLOS, an external provider was used to obtain the magnetic field. Since the provider was outside the tokamak community, the task had to be redone several times due to various misunderstandings. Therefore it has been decided to use in-house software and personnel, thus eliminating the communication errors that otherwise easily arise.

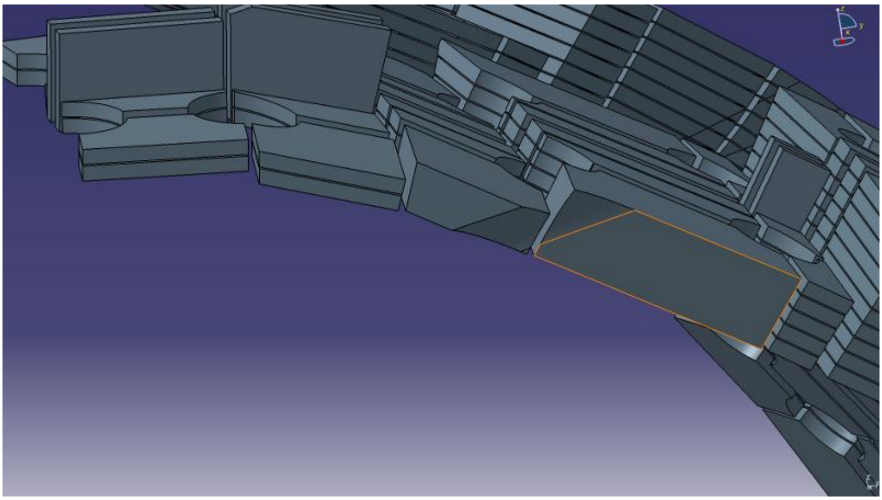

Figure 6.10. Simplification of the ITER ferritic inserts (ferritic parts of the in-vessel-shielding) being simplified in CATIA. The air gaps between the steel plates for one stack have already been removed.

A strategy to calculate the 3D magnetic field of ITER was drawn up. The calculations take into account the 3D features in the ITER magnetic field, and therefore include all main sources of magnetic field perturbations, such as the finite number of toroidal field coils, in-vessel ferromagnetic corrective inserts, test blanket modules (TBM), ferritic shields of the neutral beam boxes, and ELM mitigation coils. This requires the capability to calculate the magnetic fields from CAD drawings of ITER toroidal field coils, poloidal field coils and the central solenoid. The effect of the plasma current also has to be included. The magnetic fields thus obtained cause ferromagnetic components to become magnetized. Calculations of the magnetization require a description of the ferromagnetic structures (coordinates, mass, magnetic properties, operation conditions) of the reference ferritic cladding and of the NBI boxes, as well as simplified models of the FIs and TBMs together with their mass and material parameters. Figure 6.10 shows the simplification of the ITER ferritic inserts.

The 0th order vacuum magnetic field is calculated using a 2D equilibrium together with the geometry of the external coils and the currents running in them. The calculation is accomplished using the locally developed integrator BioSaw, which is equivalent to the well-established VACFIELD code. BioSaw calculates the vacuum magnetic field produced by the various coils in the entire vacuum chamber, cryostat and beyond, assuming that the current flows in thin conductors. The effect of the magnetization is calculated using the commercial COMSOL Multiphysics engineering simulation software that inherently allows for arbitrary geometries due to its finite element method approach. The vector potential calculated with BioSaw is used as the background field for the COMSOL model. This eases the requirements for the computational mesh since the grid does not need to be dense near the coils.

The implementation of this strategy was begun in autumn by identifying the required input data with F4E. The first transformation from CAD into a format suitable for COMSOL and FORTRAN programs was also commenced.

7. Other Activities

7.1 Conferences, workshops and meetings

S. Karttunen participated in the 41st IEA FPCC Meeting, Paris, 24–25 January 2012.

A. Hakola participated in a project meeting with the colleagues from University of Tartu and DIARC-Technology Inc., Espoo, 2 February 2012.

A. Hakola participated in a monitoring meeting on Dust and Tritium Management, JET, Culham, UK, 23–24 February 2012.

L. Aho-Mantila participated in the EFDA PPP&T Task Planning Meeting (SYS/PEX) in Garching, 27–29 February 2012.

M. Airila participated in the Finnish Nuclear Society seminar on "Communications in nuclear", Helsinki, 28 February 2012.

S. Karttunen participated in the 54th CCE-FU Meeting, Brussels, 29 February 2012.

A. Salmi was seconded to JET, Culham, UK, 5–23 March 2012.

S. Janhunen participated in 1st High Level Support Team meeting, 16 March 2012, Garching, Germany. The second meeting, 23 October 2012 , was participated in remotely.

S. Karttunen participated in the 50th EFDA SC Meeting, Utrecht, 21–22 March 2012.

L. Aho-Mantila (19–23 March), C. Björkas (26–30 March), A. Lasa and J. Miettunen participated in the JET Edge modelling meeting, Culham, UK, 19–30 March 2012.

A. Salmi (26–30 March), S. Äkäslompolo (19–23 March) participated in the ITM code camp, Garching, Germany, 19–30 March 2012.

T. Tala and K. Koskela participated in the 23rd F4E governing board meeting at F4E, Barcelona, Spain, 28 March.

T. Tala participated in the ITPA T&C meeting in at ASIPP, Hefei, China, 30 March–6 April 2012.

L. Aho-Mantila participated and gave a talk at the E2M seminar in Ringberg, Germany, 23–27 April 2012.

C. Björkas and T. Makkonen gave an oral presentation, and L. Aho-Mantila, M. Airila, M. Groth, A. Hakola, A. Järvinen, A. Meinander, J. Miettunen, A. Lasa and J. Likonen presented a poster in the 20th International Conference on Plasma Surface Interactions, Aachen, Germany, 20–25 May 2012.

S. Janhunen participated in the ITM-IMP4 Working session on Turbulence and Micro stability codes in Risø, Denmark, on 21–25 May, 2012.

46 participants attended the Euratom-Tekes Annual Fusion Seminar, Tartu, Estonia, 28–29 May 2012. The invited speaker was Dr. Duarte Borba, EFDA CSU Culham.

K. Koskela participated in the 55th CCE-FU meeting, Brussels, 29 May 2012.

M. Airila participated in the ITM code camp, Kudowa Zdroj, Poland, 28 May–5 June 2012.

L. Aho-Mantila (11–29 June), M. Airila, A. Lasa (11–22 June) and J. Miettunen participated in the JET Edge modelling meeting, Culham, UK, 18–29 June 2012.

A. Hakola participated in the EFDA PPP&T kick-off meeting for Work Programme 2012 – PEX-03, Garching, Germany, 18–19 June 2012.

L. Aho-Mantila participated and gave a talk in the EFDA PPP&T PEX kick-off meeting in Culham, UK, 19 June 2012.

K. Koskela participated in the 24th F4E governing board meeting at F4E, Barcelona, Spain, 27–28 June.

A. Lasa and A. Meinander participated in the Computer Simulation of Radiation Effects in Solids, Santa Fe, USA, 24–29 June 2012.

J. Karhunen, T. Korpilo and T. Kurki-Suonio participated in 39th European Physical Society Conference on Plasma Physics, Stockholm, Sweden, 2–6 July 2012.

T. Kurki-Suonio participated in the 50th EFDA SC meeting at KTH, Stockholm, Sweden, 10 July 2012.

O. Asunta and S. Äkäslompolo participated in the ITM code camp, KTH, Stockholm, Sweden, 8–13 July 2012.

T. Kiviniemi participated in the EFTSOMP Workshop on Electric Fields, Turbulence and Self-Organisation in Magnetized Plasmas 9–10 July, 2012, Stockholm, Sweden.

P. Sirén participated in the 49th Culham Plasma Physics Summer School, Culham, UK, 16–27 July 2012.

T. Tala participated in the Fusion Roadmap 2050 workshop at EFDA CSU Garching, Germany, 25–27 July 2012.

L. Aho-Mantila participated and gave a talk in the JET Science Meeting on Radiative Scenarios, Culham, UK, 30 July 2012 (remote participation).

C. Björkas participated in the Theory of Fusion Plasmas, Joint Varenna-Lausanne International Workshop, Varenna, Italy, 27–31 August 2012.

A. Hakola participated in a project meeting with the colleagues from University of Tartu, Tallinn, Estonia, 28–29 August 2012.

A. Hakola participated in a monitoring meeting on Dust and Tritium Management, Garching, Germany, 2–4 September 2012.

T. Tala, J. Likonen and M. Groth participated in 4^{th} JET GPM meeting in JET, Culham, UK, 12–14 September.

A. Salmi participated in the 17th Joint EU-US Transport Task Force Meeting, Padova, Italy, 3–6 September 2012.

O. Asunta, E. Hirvijoki, T. Kurki-Suonio, A. Snicker, S. Sipilä, S. Äkäslompolo participated in the F4E-GRT-379 Kick-off meeting, Barcelona, Spain, 27 September 2012.

T. Tala and K. Koskela participated in the 50th EFDA SC meeting Marseilles, France, 3–4 October 2012.

M. Groth, T. Kurki-Suonio, S. Janhunen and T. Tala participated in the 24th IAEA Fusion Energy Conference, 8–13 October 2012, San Diego, US, and gave 2 orals and two poster presentations at the meeting.

L. Aho-Mantila participated and gave a talk at the ITPA divertor and scrape-off layer expert meeting in San Diego, 15–17 October 2012.

T. Tala participated in the ITPA T&C meeting in San Diego, US, 15–17 October 2012.

K. Koskela participated in the 25th F4E governing board meeting at F4E, Barcelona, Spain, 23 October 2012.

M. Groth gave a presentation in the seminar of the Finnish Nuclear Society, 9 November 2012.

L. Aho-Mantila (12–16 November) and A. Hakola participated in the Annual ASDEX Upgrade Program Seminar, Ringberg, Germany, 11–16 November 2012.

M. Airila, J. Heikkinen, T. Korpilo, T. Kurki-Suonio, A. Meinander and S. Äkäslompolo participated in the Annual seminar for the Computational Science Research Programme, (LASTU), Helsinki, 28 November 2012.

A. Hakola participated in the 11th Annual Meeting of the EFDA PWI Task Force, Tartu, Estonia, 28–30 November 2012.

M. Airila (15–19 October) and O. Asunta participated in the ITM code camp, University of Cyprus, Nicosia, Cyprus, 15–26 October 2012.

T. Tala participated in the 56th CCE-FU meeting, Brussels, 5 November 2012.

A. Meinander participated in the MAT-IREMEV monitoring meeting, Garching, Germany, 2–5 December 2012.

A. Salmi (3–7 December), E. Hirvijoki, S. Sipilä and A. Snicker (10–14 December) participated in the ITM code camp, Innsbruck, Austria, 2–14 December 2012.

L. Aho-Mantila participated in the European Fusion Physics Workshop in Ericeira, Portugal, 3–5 December 2012.

T. Tala and K. Koskela participated in the 26th F4E governing board meeting at F4E, Barcelona, Spain, 11–12 December.

L. Aho-Mantila participated in the JET edge modelling meetings in Culham Science Center, Abingdon, United Kingdom, 11–14 December 2012.

L. Aho-Mantila participated and gave a talk in the EFDA PPP&T Task Planning Meeting (SYS/PEX) in Garching, 12 December 2012 (remote participation).

T. Kurki-Suonio, S. Janhunen, A. Salmi, M. Airila and A. Hakola gave presentations in Finnish-Russian Seminar on Fusion Research 17–18 December at Aalto University.

7.2 Visits

T. Tala visited MIT, US, 12–20 January.

A. Hakola visited Hiden Analytical Ltd., Warrington, UK, 25–26 January 2012.

L. Aho-Mantila worked as a visiting researcher at the Max-Planck-Institut für Plasmaphysik, Garching, Germany, 30 January–31 December 2012.

T. Tala was seconded to JET, 12–16 March and 13–17 May 2012.

T. Määttä and P. Pale visited in JET and Oxford Technologies Ltd in Culham, United Kingdom, 15–16 May 2012.

M. Siuko and J. Järvenpää visited in EFDA Garching, Germany 20 March and 25 October 2012.

S. Karttunen visited the FOM Institute DIFFER, Rijnhuizen, the Netherlands, 22 March 2012.

A. Hakola worked at the FOM Institute DIFFER, Rijnhuizen, the Netherlands, 22–24 March and 10–14 December 2012.

A. Hakola worked at Max-Planck-Institut für Plasmaphysik, Garching, Germany, 5–10 February and 27 July–10 August 2012.

S. Äkäslompolo visited F4E, Barcelona, Spain, 24–28 September 2012.

A. Lasa visited University of Tennessee, Knoxville (TN), USA, 5–21 October, 2012.

A. Hakola visited University of Tartu, Estonia, 11–12 October 2012.

L. Aho-Mantila worked at General Atomics, San Diego, 15–26 October, 2012.

M. Siuko and H. Saarinen visited in CEA LIST Paris, France, 29–30 October 2012.

M. Santala was seconded to a JOC position in JET neutron group, 6 October–31 December 2012.

7.3 Visitors

S. Wikman and S. Heikkinen from F4E, Barcelona, Spain, visited VTT (DTP2), 3 February 2012.

M. de Baar from FOM, Niuwegein, the Netherlands, visited VTT (DTP2), 23 March 2012.

J. Harmon from EFDA, Garching, Germany visited VTT (DTP2), 26–27 March 2012.

S. Schreck from Karlsruhe Institute of Technology, Karlsruhe, Germany visited VTT (DTP2), 26–27 March 2012.

F. Conrad from Technical University of Denmark, Copenhagen Denmark visited VTT (DTP2), 14 June 2012.

Z. Zhendong, Q. Wei, L. Fan from Shanghai Institute of Work Safety Science and L. Jianzhong, C. Weimin, L. Zhengyuan from Shanghai Administration of Work Safety and Jiading District Administration of Work Safety Shanghai, China visited VTT (DTP2), 12 October 2012.

V. Marchese and M. Cosyns from European Commission Brussel, Belgium, and M. Kiisk from University of Tartu, Estonia, visited VTT (DTP2), 26 October 2012.

C. Bourdelle, CEA Cadarache, France, visited Aalto University, 9 November 2012, and acted as the opponent in the doctoral defense of Antti Salmi.

A. Loving, M. Townsend and N. Sykes from CCFE, Culham, United Kingdom, visited VTT (DTP2), 14 November 2012.

F. Escourbiac, L. Ferrand, J. Palmer, S. Gicquel from ITER Gadarache, France and S. Esqué, B. Riccardi, P. Gavila, P. Lorenzetto from F4E, Barcelona, Spain visited VTT (DTP2), 11–12 December 2012.

A. Popov, A. Altukhov and A. Novohatskiy (17–19 December), M. Irzak (17–20 December), E. Gusakov and A. Gurchenko (17–21 December), Ioffe Institute, St. Petersburg, Russia, visited Aalto University and participated in the Finnish–Russian Seminar on Fusion Research, 17–18 December 2012 arranged by Aalto University.

T. Fülöp, Chalmers University of Technology, Gothenburg, Sweden, visited Aalto University, 21 December 2012, and acted as the opponent in the doctoral defense of Susan Leerink.

8. Publications 2012

8.1 Fusion Physics and Plasma Engineering

8.1.1 Publications in scientific journals

1. S. Leerink, V.V. Bulanin, A.D. Gurchenko, E.Z. Gusakov, J.A. Heikkinen, S.J. Janhunen, S.I. Lashkul, A.B. Altukhov, L.A. Esipov, M. Yu. Kantor, T.P. Kiviniemi, T. Korpilo, D.V. Kuprienko, and A.V. Petrov, Multiscale investigations of drift wave turbulence and plasma flows: Measurements and total-distribution-function gyrokinetic simulations, Physical Review Letters **109** (2012) 165001.

2. L. Garzotti, P. Belo, G. Corrigan, F. Köchl, J. Lönnroth, V. Parail, G. Pereverzev, S. Saarelma, G. Tardini, M. Valovič, I. Voitsekhovitch, S. Wiesen and JET EFDA contributors, Simulations of Density Profiles, Pellet Fuelling and Density Control In ITER. Nuclear Fusion **52** (2012) 013002.

3. J. Miettunen, T. Kurki-Suonio, T. Makkonen, M. Groth, A. Hakola, E. Hirvijoki, K. Krieger, J. Likonen, S. Äkäslompolo and the ASDEX Upgrade Team, The effect of non-axisymmetric wall geometry on ^{13}C transport in ASDEX Upgrade, Nuclear Fusion **52** (2012) 032001.

4. C. Giroud, G. Maddison, K. McCormick, M.N.A. Beurskens, S. Brezinsek, S. Devaux, T. Eich, L. Frassinetti, W. Fundamenski, M. Groth, A. Huber, S. Jachmich, A. Järvinen, A. Kallenbach, K. Krieger, D. Moulton, S. Saarelma, H. Thomsen, S. Wiesen, Integration of a radiative divertor for heat load control into JET high triangularity ELMy H-mode plasmas, Nuclear Fusion **52** (2012) 063022.

5. G. Bonheure, M. Hult, R. González de Orduña, D. Arnold, H. Dombrowski, M. Laubenstein, E. Wieslander, T. Vidmar, P. Vermaercke, Ch. Perez Von Thun, M. Reich, S. Jachmich, A. Murari, S. Popovichev, J. Mlynar, A. Salmi, O. Asunta, M. Garcia-Munoz, S. Pinches, R. Koslowski, S. Kragh Nielsen and JET EFDA Contributors, Experimental investigation of the confinement of d(^{3}He,p)α and d(d,p)t fusion reaction products in JET, Nuclear Fusion **52** (2012) 083004.

6. Y. Sun, Y. Liang, K.C. Shaing, Y.Q. Liu, H.R. Koslowski, Jachmich, B. Alper, A. Alfier, O. Asunta, P. Buratti, G. Corrigan, E. Delabie, C. Giroud, M.P. Gryaznevich, D. Harting, T. Hender, E. Nardon, V. Naulin, V. Parail, T. Tala, C. Wiegmann, S. Wiesen, T. Zhang, and JET-EFDA contributors, Non-resonant magnetic braking on JET and TEXTOR, Nuclear Fusion **52** (2012) 083007.

7. C. Perez von Thun, A. Salmi, A. Perona, S.E. Sharapov, S.D. Pinches, S. Popovichev, S. Conroy, V.G. Kiptily, M. Brix, M. Cecconello, T. Johnson, JET EFDA contributors,

Study of fast ion transport induced by fishbones on JET, Nuclear Fusion **52** (2012) 094010.

8. A. Snicker, S. Sipilä, T. Kurki-Suonio, Orbit-following fusion alpha wall load simulation for ITER scenario 4 including full orbit effects, Nuclear Fusion **52** (2012) 094011.

9. M. Nocente, M. García-Muñoz, G. Gorini, M. Tardocchi, A. Weller, S. Äkäslompolo, R. Bilato and V. Bobkov, Gamma-Ray Spectroscopy Measurements of Confined Fast Ions on ASDEX Upgrade. Nuclear Fusion **52**, (2012) 094021.

10. O. Asunta, S. Äkäslompolo, T. Kurki-Suonio, T. Koskela, S. Sipilä, A. Snicker, M. García-Muñoz and the ASDEX Upgrade Team, Simulations of Fast Ion Wall Loads in ASDEX Upgrade in the Presence of Magnetic Perturbations due to ELM-Mitigation Coils. Nuclear Fusion **52** (2012) 094014.

11. L. Aho-Mantila, M. Wischmeier, H.W. Müller, S. Potzel, D.P. Coster, X. Bonnin, G.D. Conway and the ASDEX Upgrade Team, Outer divertor of ASDEX Upgrade in low-density L-mode discharges in forward and reversed field: I. Comparison between measured plasma conditions and SOLPS5.0 code calculations, Nuclear Fusion **52** (2012) 103006.

12. L. Aho-Mantila, M. Wischmeier, K. Krieger, V. Rohde, A. Hakola, S. Potzel, A. Kirschner, D. Borodin and the ASDEX Upgrade Team, Outer divertor of ASDEX Upgrade in low-density L-mode discharges in forward and reversed magnetic field: II. Analysis of local impurity migration, Nuclear Fusion **52** (2012) 103007.

13. H. Weisen, Y. Camenen, A. Salmi, T. Versloot, P. deVries, M. Maslov, T. Tala, M. Beurskens, C. Giroud and JET-EFDA contributors, Ubiquity of non-diffusive momentum transport in JET H-modes, Nuclear Fusion **52** (2012) 114024.

14. M. Yoshida, S. Kaye, J. Rice, W. Solomon, T. Tala, R.E. Bell, K.H. Burrell, J. Ferreira, Y. Kamada, P. Mantica, Y. Podpaly, H. Reimerdes, M.L. Reinke, Y. Sakamoto, A. Salmi and ITPA Transport & Confinement Topical Group, Momentum transport studies from multi-machine comparisons, Nuclear Fusion **52** (2012) 123005.

15. C. Björkas, K. Nordlund, M.J. Caturla, Influence of the picosecond defect distribution on damage accumulation in irradiated alpha-Fe, Physical Review B **85** (2012) 024105.

16. J.A. Heikkinen, T. Korpilo, S.J. Janhunen, T. Kiviniemi, S. Leerink and F. Ogando, Interpolation for momentum conservation in 3D toroidal gyrokinetic particle simulation of a plasmas, Computer Physics Communications **183** (2012) 1719.

17. E. Hirvijoki, A. Snicker et al., Alfvén Eigenmodes and Neoclassical Tearing Modes for Orbit-Following Implementations, Computer Physics Communications **183** (2012) 2589.

18. B. Baiocchi, P. Mantica, C. Giroud, T. Johnson, V. Naulin, A. Salmi, T. Tala, M. Tsalas, and JET-EFDA contributors, Discriminating the role of rotation and its gradient in determining ion stiffness mitigation in JET, Plasma Physics and Controlled Fusion **55** (2012) 025020.

19. Y. Lin, P. Mantica, T. Hellsten, V. Kiptily, E. Lerche, M.F.F. Nave, J.E. Rice, D. Van Eester, R. Felton, C. Giroud, P. de Vries, T. Tala and JET EFDA contributo, Ion cyclotron range of frequency mode conversion flow drive in D(^{3}He) plasmas on JET, Plasma Physics and Controlled Fusion **54** (2012) 074001.

20. M.F.F. Nave, L.-G. Eriksson, C. Giroud, T. Johnson, K, Kirov, M.-L. Mayoral, J.-M. Noterdaeme, J. Ongena, G. Saibene, R. Sartori, F. Rimini, T. Tala, P. de Vries, K.-D. Zastrow, JET-EFDA Contributors, JET intrinsic rotation studies in plasmas with a high normalized beta and varying toroidal field ripple, Plasma Physics and Controlled Fusion **54** (2012) 074006.

21. T. Hellsten, T. Johnson, D. Van Eester, E. Lerche, Y. Lin, M.-L. Mayoral, J. Ongena, G. Calabro, K. Crombé, D. Frigione, C. Giroud, M. Lennholm, P. Mantica, M.F.F. Nave, V. Naulin, C. Sozzi, W. Studholme, T. Tala, T. Versloot and JET-EFDA Contributors, Observations of rotation in JET plasmas with electron heating by ion cyclotron resonance heating, Plasma Physics and Controlled Fusion **54** (2012) 074007.

22. B. Baiocchi, P. Mantica, T. Tala, G. Corrigan, E. Joffrin, K. Kirov, V. Naulin and JET-EFDA contributors, Numerical analysis of the impact of the ion threshold, ion stiffness and temperature pedestal on global confinement and fusion performance in JET and in ITER plasmas, Plasma Physics and Controlled Fusion **54** (2012) 085020.

23. J. Hobirk, F. Imbeaux, F. Crisanti, P. Buratti, C.D. Challis, E. Joffrin, B. Alper, Y. Andrew, P. Beaumont, M. Beurskens, A. Boboc, A. Botrugno, M. Brix, G. Calabro, I. Coffey, S. Conroy, O. Ford, D. Frigione, J. Garcia, C. Giroud, N.C. Hawkes, D. Howell, I. Jenkins, D. Keeling, M. Kempenaars, H. Leggate, P. Lotte, E. de la Luna, G.P. Maddison, P. Mantica, C. Mazzotta, D.C. McDonald, A. Meigs, I. Nunes, E. Rachlew, F. Rimini, M. Schneider, A.C.C. Sips, J.K. Stober, W. Studholme, T. Tala, M. Tsalas, I. Voitsekhovitch, P.C. de Vries and JET EFDA contributors, Improved Confinement in JET hybrid discharges, Plasma Physics and Controlled Fusion **54** (2012) 095001.

24. T. Koskela, O. Asunta, E. Hirvijoki, T. Kurki-Suonio and S. Äkäslompolo, ITER ELM Control Coils: Effect on Fast Ion Losses and Edge Confinement Properties, Plasma Physics and Controlled Fusion **54** (2012), 105008.

25. F. Sattin, D.F. Escande, Y. Camenen, A.T. Salmi, T. Tala and JET EFDA Contributors, Estimate of convection–diffusion coefficients from modulated perturbative experiments as an inverse problem, Plasma Physics and Controlled Fusion **54** (2012) 124025.

26. E. Hirvijoki and T. Kurki-Suonio, Monte Carlo Diffusion Operator for Anomalous Radial Transport in Tokamaks, Europhysics Letters **97** (2012) 55002.

27. A. Lasa, C. Björkas, K. Vörtler, K. Nordlund, MD Simulations of low energy deuterium irradiation on W, WC and W_2C surfaces, Journal of Nuclear Materials **429** (2012) 284.

28. V. Kekkonen, A. Hakola, J. Likonen, Y. Ge, T. Kajava, Pulsed laser deposition using diffractively shaped excimer-laser beams, Applied Physics A **108** (2012) 423.

29. L. Äkäslompolo, A.M. Sanchez, Q.H. Qin, A. Hakola, T. Kajava, van Dijken S., Structural and magnetic properties of pulsed laser deposited $SrRuO_3/CoFe_2O_4/La_{2/3}Sr_{1/3}MnO_3$ magnetic oxide heterostructures on $SrTiO_3$(001) and MgO(001), Applied Physics A **110** (2013) 889.

30. E. Marenkov, V. Kurnaev, A. Lasa, K. Nordlund, On the molecular effect in hydrogen molecular ions penetration through thin films, Nuclear Instruments and Methods in Physics Research B **287** (2012) 46.

31. T. Kiviniemi, S. Leerink, J.A. Heikkinen, S. Janhunen, T. Korpilo, Gyrokinetic Simulations of the Edge Pedestal in the TEXTOR Tokamak. Contributions to Plasma Physics **52** (2012) 406.

32. L. Aho-Mantila, M. Bernert, J.W. Coenen, R. Fischer, M. Lehnen, C. Lowry, S. Marsen, K. McCormick, H.W. Müller, B. Sieglin, M.F. Stamp, M. Wischmeier, X. Bonnin, D.P. Coster, D. Reiter, S. Brezinsek, the ASDEX Upgrade Team, the JET-EFDA Contributors, L-mode radiative plasma edge studies for model validation in ASDEX Upgrade and JET, Journal of Nuclear Materials, accepted.

33. M.I. Airila, C. Björkas, A. Lasa, A. Meinander, K. Nordlund and K. Vörtler, Sputtering of Be/C/W compounds in Molecular Dynamics and ERO simulations, Journal of Nuclear Materials, accepted.

34. C. Björkas, D. Borodin, A. Kirschner, R.K. Janev, D. Nishijima, R. Doerner, K. Nordlund, Multiscale Modeling of BeD Release and Transport in PISCES-B, Journal of Nuclear Materials, accepted.

35. H. Bergsåker, P. Petersson, I. Bykov, G. Possnert, J. Likonen, S. Koivuranta, J.P. Coad, A.M. Widdowson and JET EFDA contributors, Microanalysis of deposited layers in the divertor of JET following operations with carbon wall, Journal of Nuclear Materials, accepted.

36. D. Borodin, M. Stamp, A. Kirschner, C. Björkas, S. Brezinsek, J. Miettunen, D. Matveev, C. Silva, O. Van Hoey, M. Groth, S. Marsen, V. Philipps, and JET-EFDA contributors, Spectroscopic Measurements of Be Erosion at JET ILW and interpretation with ERO modelling, Journal of Nuclear Materials, accepted.

37. A. Hakola, S. Koivuranta, J. Likonen, M. Groth, T. Kurki-Suonio, V. Lindholm, T. Makkonen, J. Miettunen, K. Krieger, M. Mayer, H.W. Mueller, R.L. Neu, V. Rohde, P. Petersson, ASDEX Upgrade Team, Global migration of ^{13}C in high-density L-mode plasmas at ASDEX Upgrade, Journal of Nuclear Materials, accepted.

38. O. Van Hoey, A. Kirschner, C. Björkas, D. Borodin, D. Matveev, I. Uytdenhouwen, and G. Van Oost, Improved carbon migration modelling with the ERO code, Journal of Nuclear Materials, accepted.

39. D. Ivanova, J. Likonen, A. Widdowson, J.P. Coad, M. Rubel, G. De Temmerman and JET- EFDA Contributors, Assessment of Cleaning Methods for First Mirrors Tested in JET for ITER, Journal of Nuclear Materials, accepted.

40. A. Kirschner, P. Wienhold, D. Borodin, C. Björkas, O. Van Hoey, D. Matveev, S. Brezinsek, A. Kreter, M. Laengner, K. Ohya, V. Philipps, A. Pospieszczyk, U. Samm, B. Schweer, and the TEXTOR team, Studies of impurity migration in TEXTOR by local tracer injection, Journal of Nuclear Materials, accepted.

41. S. Koivuranta, J. Likonen, A. Hakola, J.P. Coad, A. Widdowson, D.E. Hole, M. Rubel and JET-EFDA contributors, Post-mortem measurements on fuel retention at JET in 2007–2009 experimental campaign, Journal of Nuclear Materials, accepted.

42. S. Krat, J.P. Coad, Yu. Gasparyan, A. Hakola, J. Likonen, M. Mayer, A. Pisarev, A. Widdowson, and JET-EFDA contributors, Erosion and deposition on JET divertor and limiter tiles during the discharge campaigns 2004–2009, Journal of Nuclear Materials, accepted.

43. A. Lasa, K.O.E. Henriksson, K. Nordlund., MD simulations of onset of tungsten fuzz formation under helium irradiation, Nuclear Instruments and Methods in Physics Research B, accepted.

44. J. Likonen, A. Hakola, S. Koivuranta, E. Ahonen, M.I. Airila, E. Alves, N. Barradas, J.P. Coad, A. Widdowson, M. Rubel, S. Brezinsek, and JET- EFDA Contributors, Local deposition of ^{13}C tracer in the JET MKII-HD divertor, Journal of Nuclear Materials, accepted.

45. T. Makkonen, M. Groth, M.I. Airila, A. Janzer, T. Kurki-Suonio, T. Lunt, H.W. Müller, T. Pütterich, E. Viezzer and the ASDEX Upgrade team, Measurements and ERO simulations of carbon flows in the high-field side main SOL in AUG, Journal of Nuclear Materials, accepted.

46. L. Marot, E. Meyer, M. Rubel, D. Ivanova, A. Widdowson, P. Coad, J. Likonen, A. Hakola, S. Koivuranta, G. De Temmerman and JET-EFDA Contributors, Performances of Rh and Mo Mirrors Under JET Exposure, Journal of Nuclear Materials, accepted.

47. M. Mayer, S. Krat, J.P. Coad, A. Hakola, J. Likonen, S. Lindig, A. Widdowson, and JET-EFDA contributors, Erosion at the inner wall of JET during the discharge campaigns 2001–2009, Journal of Nuclear Materials, accepted.

48. A. Meinander, K.O.E. Henriksson, C. Björkas, K. Vörtler, K. Nordlund, The Effect of C Concentration on Radiation Damage in Fe-Cr-C Alloys, Journal of Nuclear Materials, accepted.

49. J. Miettunen, M. Groth, T. Kurki-Suonio, H. Bergsåker, J. Likonen, S. Marsen, C. Silva, S. Äkäslompolo and JET EFDA contributors, Predictive ASCOT Modelling of ^{10}Be Transport in JET with the ITER-like Wall, Journal of Nuclear Materials, accepted.

50. B. Pégourié et al. (incl. A. Hakola and J. Likonen), Deuterium inventory in Tore Supra: Coupled carbon–deuterium balance, Journal of Nuclear Materials, accepted.

51. P. Petersson, A. Hakola, K. Krieger, M. Mayer, J. Miettunen, R. Neu, G. Possnert, V. Rohde, M. Rubel and the ASDEX Upgrade Team, Development and Results of Tracer Techniques with Nitrogen-15, Journal of Nuclear Materials, accepted.

52. G.J. van Rooij, J.W. Coenen, L. Aho-Mantila, S. Brezinsek, M. Clever, R. Dux, M. Groth, K. Krieger, S. Marsen, G.F. Matthews, A. Meigs, R. Neu, S. Potzel, T. Pütterich, J. Rapp, M.F. Stamp, the ASDEX Upgrade Team and JET-EFDA Contributors, Tungsten divertor erosion in all metal devices: Lessons from the ITER like wall of JET, Journal of Nuclear Materials, accepted.

53. M. Rubel, J.P. Coad, A. Widdowson, G.F. Matthews, H.G. Esser, T. Hirai, J. Likonen, J. Linke, C.P. Lungu, M. Mayer, L. Pedrick, C. Ruset, and JET-EFDA Contributors, Overview of erosion–deposition diagnostic tools for the ITER-Like Wall in the JET tokamak, Journal of Nuclear Materials, accepted.

54. A.M. Widdowson, C.F. Ayres, S. Booth, J.P. Coad, D. Ivanova, J. Likonen, M. Mayer, M. Stamp and JET-EFDA contributors, Comparison of JET main chamber erosion with dust collected in the divertor, Journal of Nuclear Materials, accepted.

55. A. Meinander, C. Björkas, K. Nordlund, The Effect of Hydrocarbon Chemistry on Sputtering in Mixed Be-C-H Materials, Nuclear Instruments and Methods in Physics Research B, accepted.

56. R.J. Buttery, S. Gerhardt, A. Isayama, R.J. La Haye, E.J. Strait, D. Chandra, S. Coda, J. De Grassie, P. Gohil, M. Gryaznevich, C. Holcomb, D.F. Howell, G. Jackson, M. Maraschek, A. Polevoi, H. Reimerdes, D. Raju, A. Sen, T. Tala, JET-EFDA contributors, the DIII-D, JT-60 and NSTX teams, Cross-Machine Scaling of Neoclassical Tearing Modes Thresholds with Rotation, Nuclear Fusion (2011).

57. R.J. Buttery, S. Gerhardt, A. Isayama, R.J. La Haye, E.J. Strait, D. Chandra, S. Coda, J. De Grassie, P. Gohil, M. Gryaznevich, C. Holcomb, D.F. Howell, G. Jackson, M. Maraschek, A. Polevoi, H. Reimerdes, D. Raju, A. Sen, T. Tala, JET-EFDA contributors, the DIII-D, JT-60 and NSTX teams, Cross-Machine Scaling of Neoclassical Tearing Modes Thresholds with Rotation, Nuclear Fusion, submitted.

58. M. Yoshida, S. Kaye, J. Rice, W. Solomon, T. Tala, R.E. Bell, K.H. Burrell, J. Ferreira, Y. Kamada, P. Mantica, Y. Podpaly, H. Reimerdes, M.L. Reinke, Y. Sakamoto, A. Salmi and ITPA Transport & Confinement Topical Group, Momentum transport studies from multi-machine comparisons, Nuclear Fusion, submitted.

59. T. Makkonen, M. Groth, M. Airila, A. Janzer, T. Kurki-Suonio, T. Lunt, H.W. Mueller, T. Puetterich, E. Viezzer and the ASDEX Upgrade team, Synthetic Doppler spectroscopy and non-linear camera diagnostics in the ERO code, Computer Physics Communications, submitted.

60. T. Korpilo, J.A. Heikkinen, S.J. Janhunen, T.P. Kiviniemi, S. Leerink, and F. Ogando, Numerically stable method for kinetic electrons in gyrokinetic particle-in-cell simulations of toroidal plasmas, Journal of Computational Physics, submitted.

8.1.2 Conference articles – physics and plasma engineering

61. M. Mayer, S. Krat, A. Hakola, J.P. Coad, Yu. Gasparyan, S. Koivuranta, J. Likonen, R. Neu, A. Pisarev, V. Rohde, K. Sugiyama, A. Widdowson, JET-EFDA contributors, ASDEX Upgrade Team, Erosion and Deposition Studies at JET and ASDEX Upgrade, Third Sino-German Workshop on Plasma-Wall Interactions, Dalian, China, 6–9 November, 2012.

62. H. Weisen, Y. Camenen, A. Salmi, T.W. Versloot, P.C. deVries, M. Maslov, T. Tala, M. Beurskens, C. Giroud and JET-EFDA contributors, Non-diffusive momentum transport in JET H-mode regimes: modeling and experiment, 24th IAEA Fusion Energy Conference, San Diego, USA, 8–13 October, 2012 Paper EX/P2-17.

63. M.F.F. Nave, L.-G. Eriksson, C. Giroud, J.S. de Grassie, T, Hellsten, T. Johnson, Y. Lin, J. Mailloux, P. Mantica, M.-L. Mayoral, F.I. Parra, J. Ongena, T. Tala, J.H.F. Severo, P.C. de Vries and JET-EFDA Contributors, Scalings of Spontaneous Rotation in the JET Tokamak, 24th IAEA Fusion Energy Conference, San Diego, USA, 8–13 October, 2012 Paper EX/P3-31.

64. H. Reimerdes, J.M. Hanson, Y. In, M. Okabayashi, N. Oyama, J.-K. Park, A. Salmi, M.J. Schaffer, J.A. Snipes, W.M. Solomon, E.J. Strait, and T. Tala, Rotation Braking and Error Field Correction of the Test Blanket Module Induced Magnetic Field Error in ITER, 24th IAEA Fusion Energy Conference, San Diego, USA, 8–13 October, 2012 Paper EX/P4-09.

65. V. Philipps, A. Malaquias, A. Hakola, G. Maddaluno, P. Gasior, M. Laan, H. van der Meiden, M. Rubel, S. Almaviva, L. Caneve, F. Colao, N. Gierse, A. Huber, B. Schweer, M. Zlobinski, A. Czarnecka, M. Kubowska and P. Petersson, Development of Laser Based Techniques for In-situ Characterization of the First Wall in ITER and Future Fusion Devices, 24th IAEA Fusion Energy Conference, San Diego, USA, 8–13 October, 2012 Paper EX/P5-14.

66. M. Wischmeier, S. Potzel, L. Aho-Mantila, M. Bernert, D. Coster, H.-W. Müller, F. Reimold and ASDEX Upgrade Team, Symmetries and Asymmetries in the Divertor Detachment in ASDEX Upgrade, 24th IAEA Fusion Energy Conference, San Diego, USA, 8–13 October, 2012 Paper EX/P5-34.

67. T. Tala, R.M. McDermott, J.E. Rice, A. Salmi, W. Solomon, C. Angioni, C. Gao, C. Giroud, J. Ferreira, S. Kaye, P. Mantica, Y. Podpaly, G. Tardini, M. Yoshida, JET-EFDA contributors, the ASDEX-Upgrade team, the DIII-D team, the C-Mod team, the NSTX team, the ITPA Transport & Confinement Topical Group, Multi-Machine Tokamak Experiments to Study the Parametric Dependencies of Momentum Transport, 24th IAEA Fusion Energy Conference, San Diego, USA, 8–13 October, 2012 Paper ITR/P1-19.

68. S. Janhunen, J.A. Heikkinen, S. Leerink, T. Kiviniemi, and T. Korpilo, Gyrokinetic total distribution simulations of drift-wave turbulence and neo-classical dynamics in tokamaks with Elmfire, 24th IAEA Fusion Energy Conference, San Diego, USA, 8–13 October, 2012 Paper TH/6-3.

69. X. Litaudon, I. Voitsekhovitch, J.F. Artaud, P. Belo, J.P.S. Bizarro, T. Casper, J. Citrin, E. Fable, J. Ferreira, J. Garcia, L. Garzotti, G. Giruzzi, J. Hobirk, G.M.D. Hogeweij, F. Imbeaux, E. Joffrin, F. Koechl, F. Liu, J. Lönnroth, D. Moreau, V. Parail, P.B. Snyder, M.

Schneider, Modelling of Hybrid Scenario: from Present-Day Experiments toward ITER, 24th IAEA Fusion Energy Conference, San Diego, USA, 8–13 October, 2012, Paper TH/P2-05.

70. D. Escande, F. Sattin, Y. Camenen, A. Salmi and T. Tala, New Technique for the Calculation of Transport Profiles in Modulation Experiments, 24th IAEA Fusion Energy Conference, San Diego, USA, 8–13 October, 2012 Paper TH/P2-18.

71. E.Z. Gusakov, V.V. Bulanin, A.D. Gurchenko, S. Leerink, A.B. Altukhov, L.A. Esipov, J.A. Heikkinen, S.J. Janhunen, M. Yu. Kantor, T.P. Kiviniemi, T. Korpilo, D.V. Kouprienko, S.I. Lashkul, and A.V. Petrov, Multi-Scale Drift Turbulence Dynamics in Ohmic Discharge as Measured at the FT-2 Tokamak and Modeled by Full-f Gyrokinetic ELMFIRE-code, 24th IAEA Fusion Energy Conference, San Diego, USA, 8–13 October, 2012 Paper TH/P7-05.

72. T. Koskela, O. Asunta, E. Hirvijoki, T. Kurki-Suonio and S. Äkäslompolo, Assessing the Effect of TBMs and ELM Mitigation Coils on Fast Ion Confinement in ITER. 39th European Physical Society Conference on Plasma Physics, Stockholm, Sweden, 2–6 July, 2012, Paper O4.109.

73. I. Voitsekhovitch, X. Litaudon, E. Barbato, V. Basiuk, P. Belo, J. Bizarro, T. Casper, J. Citrin, E. Fable, J. Ferreira, J. Garcia, L. Garzotti, J. Hobirk, G.M.D. Hogeweij, I. Ivanova-Stanik, E. Joffrin, D. Kalupin, F. Köchl, F. Liu, J. Lönnroth, D. Moreau, V. Parail, A. Polevoi, M. Schneider, P.B. Snyder, Integrated Modelling for Tokamak Plasma: Physics and Scenario Optimisation, 39th European Physical Society Conference on Plasma Physics, Stockholm, Sweden, 2–6 July 2012, Paper P4.066.

74. O. Asunta, R. Akers, G. Corrigan, D. Keeling, T. Kurki-Suonio, D. Muir, M. Romanelli, A. Salmi, and M. Turnyanskiy, Neutral beam current drive simulations on MAST, 39th European Physical Society Conference on Plasma Physics, Stockholm, Sweden, 2–6 July, 2012 Paper P1.006.

75. J.W. Coenen, G.J. van Rooij, L. Aho-Mantila, S. Brezinsek, M. Clever, R. Dux, M. Groth, D. Ivanova, K. Krieger, S. Marsen, A. Meigs, H.W. Müller, R. Neu, S. Potzel, M.F. Stamp, ASDEX Upgrade Team and JET-EFDA Contributors, Tungsten Erosion in the All-Metal Tokamaks JET and ASDEX Upgrade, 39th European Physical Society Conference on Plasma Physics, Stockholm, Sweden, 2–6 July, 2012 Paper P1.036.

76. J. Karhunen, M.I. Airila, A. Hakola, A. Herrmann, M. Mayer, H.W. Müller, R. Neu, V. Rohde, and the ASDEX Upgrade Team, Discharge-resolved erosion processes at the low-field side midplane of ASDEX Upgrade, 39th European Physical Society Conference on Plasma Physics, Stockholm, Sweden, 2–6 July, 2012 Paper P1.084.

77. A.D. Gurchenko, V.V. Bulanin, E.Z. Gusakov, S. Leerink, J.A. Heikkinen, A.B. Altukhov, L.A. Esipov, S.J. Janhunen, M. Yu. Kantor, T.P. Kiviniemi, T. Korpilo, D.V. Kouprienko, S.I. Lashkul, and A.V. Petrov, Multi-scale turbulence dynamics in ohmic discharge: measured at the FT-2 tokamak and simulated by full-f gyrokinetic ELMFIRE code, 39th European Physical Society Conference on Plasma Physics, Stockholm, Sweden, 2–6 July, 2012 Paper P4.003.

78. T. Korpilo, J.A. Heikkinen, S.J. Janhunen, T.P. Kiviniemi, S. Leerink, Conservation of total energy and toroidal angular momentum in gyrokinetic particle-in-cell simulations, 39th European Physical Society Conference on Plasma Physics, Stockholm, Sweden, 2–6 July, 2012 Paper P5.055.

79. S. Äkäslompolo, T. Koskela, T. Kurki-Suonio, T. Lunt, J. Miettunen, E. Hirvijoki and the ASDEX Upgrade Team, Preparing Tokamak 3D Wall and Magnetic Data for Particle Tracing Simulations, 39th European Physical Society Conference on Plasma Physics, Stockholm, Sweden, 2–6 July, 2012, Paper P5.058.

80. T. Kiviniemi, S. Leerink, V.V. Bulanin, E.Z. Gusakov, A.D. Gurchenko, J. Heikkinen, S. Janhunen, T. Korpilo, and S.J. Lashkul, Full-f gyrokinetic simulations of drift wave turbulence and plasma flows in the FT-2 tokamak and comparison to experiments, EFTSOMP 2012, Workshop on Electric Fields, Turbulence and Self-Organisation in Magnetized Plasmas, Stockholm, Sweden, 9–10 July, 2012.

81. G.J. van Rooij, J.W. Coenen, L. Aho-Mantila, S. Brezinsek, M. Clever, R. Dux, M. Groth, K. Krieger, S. Marsen, G.F. Matthews, A. Meigs, R. Neu, S. Potzel, T. Pütterich, J. Rapp, M.F. Stamp, the ASDEX Upgrade Team, JET-EFDA Contributors, Tungsten divertor erosion in all metal devices: Lessons from the ITER like wall of JET, 20th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Aachen, Germany, 21–25 May, 2012 Paper I3.

82. T. Makkonen, M. Groth, M.I. Airila, A. Janzer, T. Kurki-Suonio, T. Lunt, H.W. Müller, T. Pütterich, E. Viezzer and the ASDEX Upgrade team, Measurements and ERO simulations of carbon flows in the high-field side main SOL in AUG, 20th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Aachen, Germany, 21–25 May, 2012 Paper O25.

83. L. Aho-Mantila, X. Bonnin, S. Brezinsek, C. Lowry, S. Marsen, H.W. Müller, S. Potzel, S. Wiesen, M. Wischmeier, the ASDEX Upgrade Team and JET-EFDA Contributors, Modelling of L-mode Radiative Plasma Edge in ASDEX Upgrade and JET, 20th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Aachen, Germany, 21–25 May, 2012 Paper P1-003.

84. D. Borodin, A. Kirschner, C. Björkas, D. Matveev, M. Airila, D. Nishijima, R. Doerner, M. Stamp, M. Groth, C. Silva, S. Brezinsek, V. Philipps and JET EFDA contributors, ERO modelling of Be erosion at PISCES-B and JET ILW, 20th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Aachen, Germany, 21–25 May, 2012 Paper P1-081.

85. J. Miettunen, M. Groth, T. Kurki-Suonio, H. Bergsåker, J. Likonen, S. Marsen, C. Silva, S. Äkäslompolo and JET EFDA contributors, Predictive ASCOT Modelling of 10Be Transport in JET with the ITER-like Wall, 20th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Aachen, Germany, 21–25 May, 2012 Paper P1-090.

86. P. Petersson, M. Rubel, A. Hakola, G. Possnert, K. Krieger, M. Mayer, R. Neu, V. Rohde ASDEX Upgrade Team, Development and Results of Tracer Techniques with Nitrogen-15, 20th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Aachen, Germany, 21–25 May, 2012 Paper P1-092.

87. M.I. Airila, C. Björkas, A. Lasa, A. Meinander, K. Nordlund and K. Vörtler, Revised predictions of beryllium accumulation on ITER divertor, 20th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Aachen, Germany, 21–25 May, 2012 Paper P2-001.

88. H. Bergsåker, P. Petersson, I. Bykov, G. Possnert, J. Likonen, S. Koivuranta, J.P. Coad, A.M. Widdowson and JET EFDA contributors, Microanalysis of deposited layers in the divertor of JET following operations with carbon wall, 20th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Aachen, Germany, 21–25 May, 2012 Paper P2-006.

89. A. Hakola, S. Koivuranta, J. Likonen, M. Groth, T. Kurki-Suonio, V. Lindholm, T. Makkonen, J. Miettunen, K. Krieger, M. Mayer, H.W. Mueller, R.L. Neu, V. Rohde, P. Petersson, ASDEX Upgrade Team, Global migration of 13C in high-density L-mode plasmas at ASDEX Upgrade, 20th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Aachen, Germany, 21–25 May, 2012 Paper P2-016.

90. S. Koivuranta, J. Likonen, A. Hakola, J.P. Coad, A. Widdowson, D.E. Hole, M. Rubel and JET-EFDA contributors, Post-mortem measurements on fuel retention at JET in 2007–2009 experimental campaign, 20th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Aachen, Germany, 21–25 May, 2012 Paper P2-028.

91. S. Krat, J.P. Coad, Yu. Gasparyan, A. Hakola, J. Likonen, M. Mayer, A. Pisarev, A. Widdowson, and JET-EFDA contributors, Erosion and deposition on JET divertor and limiter tiles during the discharge campaigns 2004–2009, 20th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Aachen, Germany, 21–25 May, 2012 Paper P2-030.

92. P. Paris, A. Hakola, K. Bystrov, G. De Temmerman, M. Aints, M. Kiisk, J. Kozlova, M. Laan, J. Likonen, and A. Lissovski, Erosion of W and mixed W-Al marker coatings exposed to Pilot-PSI plasma, 20th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Aachen, Germany, 21–25 May, 2012 Paper P2-033.

93. J. Likonen, A. Hakola, S. Koivuranta, E. Ahonen, M.I. Airila, E. Alves, N. Barradas, J.P. Coad, A. Widdowson, M. Rubel, S. Brezinsek, and JET- EFDA Contributors, Local deposition of 13C tracer in the JET MKII-HD divertor, 20th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Aachen, Germany, 21–25 May, 2012 Paper P2-036.

94. C.P. Lungu, J. Likonen, A. Hakola, C. Porosnicu, I. Jepu, A.M. Lungu, P. Chiru, Gh. Oncioiu, A. Victor, P. Osiceanu and JET-EFDA Contributors, Characterization of Mixed Materials in Support of the ITER Like Wall, 20th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Aachen, Germany, 21–25 May, 2012 Paper P2-038.

95. M. Mayer, S. Krat, J.P. Coad, A. Hakola, J. Likonen, S. Lindig, A. Widdowson, and JET-EFDA contributors, Erosion at the inner wall of JET during the discharge campaigns 2001–2009, 20th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Aachen, Germany, 21–25 May, 2012 Paper P2-041.

96. I. Tiseanu, M. Mayer, V. Rohde, T. Craciunescu, A. Hakola, S. Koivuranta, J. Likonen, C. Dobrea, A. Sima, ASDEX Upgrade Team, Two-dimensional erosion mapping of metal layers coated on carbon based plasma facing materials, 20th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Aachen, Germany, 21–25 May, 2012 Paper P2-057.

97. A.M. Widdowson, C.F. Ayres, S. Booth, J.P. Coad, D. Ivanova, J. Likonen, M. Mayer, M. Stamp and JET-EFDA contributors, Comparison of JET main chamber erosion with dust collected in the divertor, 20th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Aachen, Germany, 21–25 May, 2012 Paper P2-060.

98. L. Marot, E. Meyer, M. Rubel, D. Ivanova, A. Widdowson, P. Coad, J. Likonen, A. Hakola, S. Koivuranta, G. De Temmerman and JET-EFDA Contributors, Performances of Rh and Mo Mirrors Under JET Exposure, 20th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Aachen, Germany, 21–25 May, 2012 Paper P3-080.

99. D. Ivanova, J. Likonen, A. Widdowson, J.P. Coad, M. Rubel, G. De Temmerman and JET- EFDA Contributors, Assessment of Cleaning Methods for First Mirrors Tested in JET for ITER, 20th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Aachen, Germany, 21–25 May, 2012 Paper P3-094.

100. T. Johnson, A. Salmi, G. Steinbrecher, L.-G. Eriksson, T. Hellsten, L.J. Höök, M. Schneider and ITM-TF Contributors, Library for RF Interactions in Orbit Following Codes, AIP conference proceedings 1406 (2011) 373.

101. S. Syri, T. Kurki-Suonio and V. Satka, Increasing Nuclear Energy at Liberalised Energy Markets – Case Finland. European Energy Conference – E2C, Maastricht, 17–20 April, 2012, European Physical Society, EPS Web of Conferences 1–7 (2012).

102. C. Björkas, D. Borodin, A. Kirschner, R.K. Janev, D. Nishijima, R. Doerner, K. Nordlund, Molecules can be sputtered also from pure metals: sputtering of beryllium hydride by fusion plasma-wall interactions, Proceedings to Theory of Plasma Physics workshop 2012, in press.

8.2 Fusion technology

8.2.1 Publications in scientific journals

103. T. Ahlgren, K. Heinola, K. Vörtler and J. Keinonen, Simulation method for extensive length and time scales of hydrogen, impurities and defects in metals, J. Nucl. Mat. **427** (2012), 152.

104. M. Rieth, S.L. Dudarev, S.M. Gonzalez de Vicente, J. Aktaa, T. Ahlgren, et al., Recent progress in research on tungsten materials for nuclear applications in Europe, Journal of Nuclear Materials, accepted.

105. K. Heinola and T. Ahlgren, Hydrogen retention to impurities in tungsten: a multi-scale study, Journal of Nuclear Materials, submitted.

106. A. Widdowson, C.F. Ayres, S. Booth, J.P. Coad, A. Hakola, K. Heinola, et al., Comparison of JET main chamber erosion with dust collected in the divertor, Journal of Nuclear Materials, submitted.

107. Reux, P. Card, K. Heinola, S. Jachmich, E. Joffrin, et al., Use of disruption mitigation valve in closed loop for routine disruption protection on JET, Fusion Engineering and Design, submitted.

8.2.2 Conference articles – fusion technology

108. H. Saarinen, V. Hämäläinen, J. Karjalainen, T. Määttä, M. Siuko, S. Esqué and D. Hamilton, Simulating and visualizing deflections of a remote handling mechanism, 27th Symposium on Fusion Technology SOFT-27, Liège, Belgium, 24–28 September 2012.

109. V. Lyytikäinen, P. Kinnunen, J. Koivumäki, J. Mattila, M. Siuko, S. Esque and J. Palmer, Divertor cassette locking system remote handling trials with WHMAN at DTP2, 27th Symposium on Fusion Technology SOFT-27, Liège, Belgium, 24–28 September 2012.

110. J. Tuominen, T. Rasi, J. Mattila, M. Siuko, S. Esque and D. Hamilton, Interoperability of Remote Handling Control System Software Modules at DTP2 Using Middle-ware, 27th Symposium on Fusion Technology SOFT-27, Liège, Belgium, 24–28 September 2012.

111. P. Alho and J. Mattila, Breaking down the requirements: reliability in remote handling software, 27th Symposium on Fusion Technology SOFT-27, Liège, Belgium, 24–28 September 2012.

112. J. Väyrynen and J. Mattila, Reliability requirements management for ITER Remote Handling maintenance systems, 27th Symposium on Fusion Technology SOFT-27, Liège, Belgium, 24–28 September 2012.

113. T. Pinna and R. Tuominen, Outlines of RAMI Guidelines for DEMO Systems, 11th International Probabilistic Safety Assess-ment and Management Conference & The Annual European Safety and Reliability Conference, Helsinki, Finland, 25–29 June 2012.

8.2.3 Research reports – fusion technology

114. M. Airila and S. Karttunen (eds.), Fusion Yearbook – Association Euratom-Tekes Annual Report 2011, VTT Science **7** (2012).

115. P. Kinnunen, V. Lyytikäinen, V. Takalo. Technical specification of the CLS tooling. Divertor RH design updates and DTP2 Phase 2 Testing. Tampere 2012. 36 p.

116. H. Mäkinen, H. Saarinen. Performance of the refurbished SCEE, Divertor RH design updates and DTP2 Phase 2 Testing. Tampere 2012. 15 p.

117. P. Valkama, P. Kinnunen. Design Description Document. Divertor RH design updates and DTP2 Phase 2 Testing. DDD Diagnostic Rack End-Effector. Tampere 2012. 41 p.

118. P. Valkama, P. Kinnunen. Design Description Document. Divertor RH design updates and DTP2 Phase 2 Testing. Tampere 2012. 34 p.

119. P. Valkama, J. Alanen, H. Mäkinen, K. Salminen, V. Takalo, Management of Requirements, Divertor RH design updates and DTP2 Phase 2 Testing. Tampere 2012. 21 p.

120. M. Saarinen, J. Kortelainen, T. Niemeläinen, L. Heikkilä, T. Nurminen, H. Saarinen, J. Karjalainen, A. Muhammad, J. Alanen, S. Rantala, Demonstration Report. Divertor RH design updates and DTP2 Phase 2 control system demonstrations. Tampere 2012. 240 p.

121. M. Saarinen, J. Kortelainen, T. Niemeläinen, L. Heikkilä, J.Tuominen, H. Saarinen, J. Karjalainen, A. Muhammad, S Rantala, J. Alanen, M. Viinikainen, A. Aaltonen, Control System Specification. Divertor RH design updates and DTP2 Phase 2 Testing. Tampere 2012. 214 p.

122. H. Mäkinen, H. Saarinen, Performance of the refurbished SCEE, Divertor RH design updates and DTP2 Phase 2 Testing. Tampere 2012. 15 p.

123. H. Saarinen, J. Tuominen. Divertor RH design updates and DTP2 Phase 2 Testing. Tampere 2012. 12 p.

124. R. Tuominen and T. Ahonen, WP12-DTM02-REL-D04: RAMI assessment methodology for DEMO. EFDA_D_2GDFNJ.

125. T. Ahonen and R. Tuominen, WP12-DTM02-REL-D05: Evaluation of RAMI tools for DEMO. EFDA_D_2HCYBN.

126. J. Järvenpää, M. Siuko and V. Takalo, VTT & Labate C, ENEA: Applicability of the ITER divertor maintenance scheme to the DEMO divertor. Tampere 2012, 49 p.

8.3 Doctoral and graduate theses

127. A. Salmi, Fast ions and momentum transport in JET tokamak plasmas, Doctoral dissertation, Aalto University School of Science, Espoo 2012. VTT Science **10**.

128. S. Leerink, Gyrokinetic full-f transport simulations of ohmic FT-2 tokamak discharges, Doctoral dissertation, Aalto University School of Science, Espoo 2012.

129. R. Shuff, Development of Remote Handling Pipe Jointing Tools for ITER, Doctoral dissertation, Tampere University of Technology, Tampere, 2012.

130. L. Zhai, Modelling and Robust Control of Hydraulic Manipulators, Doctoral dissertation, Tampere University of Technology, Tampere, 2012.

131. J. Koivumäki, Virtual Decomposition Control of a Hydraulic Manipulator, Master of Science Thesis, Tampere University of Technology, Tampere, 2012.

132. V. Lyytikäinen, Development of Divertor Cassette Locking Tool Prototypes according to Remote Handling Requirements, Master of Science Thesis, Tampere University of Technology, Tampere, 2012.

133. J. Tuominen, The Remote Handling Control System of a 6 DOF Water Hydraulic Manipulator at Divertor Test Platform 2, Master of Science Thesis, Tampere University of Technology, Tampere, 2012.

8.4 Publications of the Estonian Research Unit

8.4.1 Publications in scientific journals

134. P. Paris, A. Hakola, K. Bystrov, G. De Temmerman, M. Aints, M. Kiisk, J. Kozlova, M. Laan, J. Likonen, and A. Lissovski, Erosion of W and mixed W-Al marker coatings exposed to Pilot-PSI plasma, Journal of Nuclear Materials, accepted.

135. A. Malaquias, V. Philipps, A. Huber, A. Hakola, J. Likonen, J. Kolehmainen, S. Tervakangas, M. Aints, P. Paris M. Laan, A. Lissovski, S. Almaviva, L. Caneve, F. Colao, G. Maddaluno, M. Kubkowska, P. Gasior, H.J. van der Meiden, A.R. Lof, P.A. Zeijlmans van Emmichoven, P. Petersson, M. Rubel, E. Fortuna, and Q. Xiao, Development of ITER Relevant Laser Techniques for Deposited Layer characterization and Tritium Inventory, Journal of Nuclear Materials, accepted.

8.4.2 Conference articles

136. V. Philipps, A. Malaquias, A. Hakola, G. Maddaluno, P. Gasior, M. Laan, H. van der Meiden, M. Rubel, S. Almaviva, L. Caneve, F. Colao, N. Gierse, A. Huber, B. Schweer, M. Zlobinski, A. Czarnecka, M. Kubowska and P. Petersson, Development of Laser Based Techniques for In-situ Characterization of the First Wall in ITER and Future Fusion Devices, 24th IAEA Fusion Energy Conference, San Diego, USA, 8–13 October, 2012 Paper EX/P5-14.

137. P. Paris, A. Hakola, K. Bystrov, G. De Temmerman, M. Aints, M. Kiisk, J. Kozlova, M. Laan, J. Likonen, and A. Lissovski, Erosion of W and mixed W-Al marker coatings exposed to Pilot-PSI plasma, 20th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Aachen, Germany, 21–25 May, 2012 Paper P2-033.

138. A. Malaquias, V. Philipps, A. Huber, A. Hakola, J. Likonen, J. Kolehmainen, S. Tervakangas, M. Aints, P. Paris M. Laan, A. Lissovski, S. Almaviva, L. Caneve, F. Colao, G. Maddaluno, M. Kubkowska, P. Gasior, H.J. van der Meiden, A.R. Lof, P.A. Zeijlmans van Emmichoven, P. Petersson, M. Rubel, E. Fortuna, and Q. Xiao, Development of ITER Relevant Laser Techniques for Deposited Layer characterization and Tritium Inventory, 20th International Conference on Plasma Surface Interactions in Controlled Fusion Devices, Aachen, Germany, 21–25 May, 2012 Paper P2-91.

8.4.3 Research reports

139. M. Laan, P. Paris, Dependence of LIBS profiles on laser fluence, EFDA meeting on dust and tritium management, Culham, UK, JET, 23–24 February 2012.

140. A. Hakola, A. Lissovski, J. Karhunen, M. Aints, M. Laan, J. Likonen, P. Paris, Results and analysis from LIBS laboratory measurements in TEKES in deuterium doped Be samples, Emerging technologies – Dust and Tritium Management; 3–4 September, 2012, Garching.

141. P. Paris, LIBS laboratory measurements of deuterium doped samples, Emerging technologies – Dust and Tritium Management, 3–4 September 2012, Garching.

142. M. Laan, Selection of spectral lines for depth profiles (Al/W/C on W) and Plasma plume temperature (Al/W/C on W), Dust and Tritium Management, Videomeeting Nov, 11, 2012.

143. M. Laan, M. Aints, A. Hakola, J. Karhunen, J. Likonen, A. Lissovski, P. Paris, Laser induced plasma spectroscopy, EFDA Work Programme 2011 Emerging Technologies & System Integration, Dust and Tritium Management, Task WP11-ETS-DTM-01-05/TEKES/BS, Task WP11-ETS-DTM-01-05-02/TEKES/PS, Final report.

144. P. Paris, A. Hakola, K. Bystrov, G. De Temmerman, M. Aints, I. Jõgi, M. Kiisk, J. Kozlova, M. Laan, J. Likonen, and A. Lissovski, Analysis of samples exposed to Pilot–PSI Plasma, Euratom-TEKES Annual Fusion Seminar; Tartu; 29–30 May 2012.

8.4.4 Doctoral and graduate theses

145. K. Piip, Spatially Resolved Characteristics of Laser-Induced Plasma in Case of W target, University of Tartu, Tartu 2012.

Appendix A: Introduction to Fusion Energy

Energy demand is increasing

Most projections show world energy demand doubling or trebling in the next 50 years. This derives from fast population growth and rapid economic development. Energy sources that are not yet fully tapped include biomass, hydropower, geothermal, wind, solar, nuclear fission and fusion. All of them must be developed to meet future needs. Each alternative has its advantages and disadvantages regarding the availability of the resource, its distribution globally, environmental impact, and public acceptability. Fusion is a good candidate for supplying base-load electricity on a large scale. Fusion has practically unlimited fuel resources, and it is safe and environmentally sound.

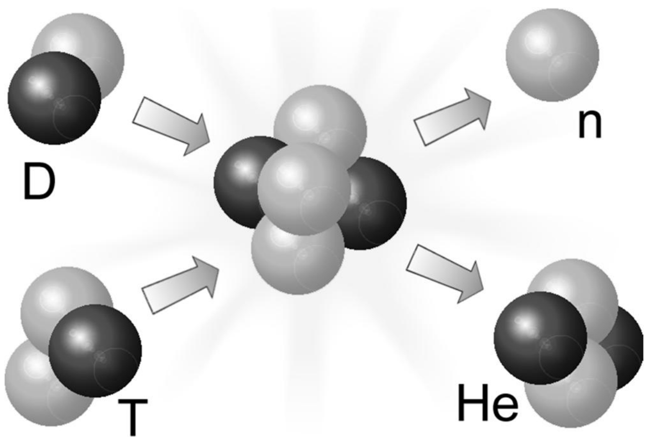

Figure A.1. In a fusion reaction, Deuterium (D) and Tritium (T) fuse together forming a Helium nucleus (^{4}He) and releasing a large amount of energy which is mostly carried by a neutron (n).

What is fusion energy?

Fusion is the energy source of the sun and other stars, and all life on Earth is based on fusion energy. The fuels burned in a fusion reactor are hydrogen isotopes, deuterium and tritium. Deuterium resources are practically unlimited, and tritium can be produced from lithium, which is abundant. The fusion reactions occur only at very high temperatures. For the deuterium-tritium reaction, fuel temperatures over 100 million °C are required for sufficient fusion burn. At these temperatures, the fuel gas is fully ionised plasma. High temperatures can be achieved by injecting energetic particle beams or high power radio-frequency (RF) waves into the plasma. The hot plasma can be thermally isolated from the material walls by strong magnetic fields, which form a "magnetic bottle" to confine the fuel plasma. With a sufficiently large plasma volume, much more energy is released from fusion reactions than is required to heat and confine the fuel plasma, i.e., a large amount of net energy is produced.

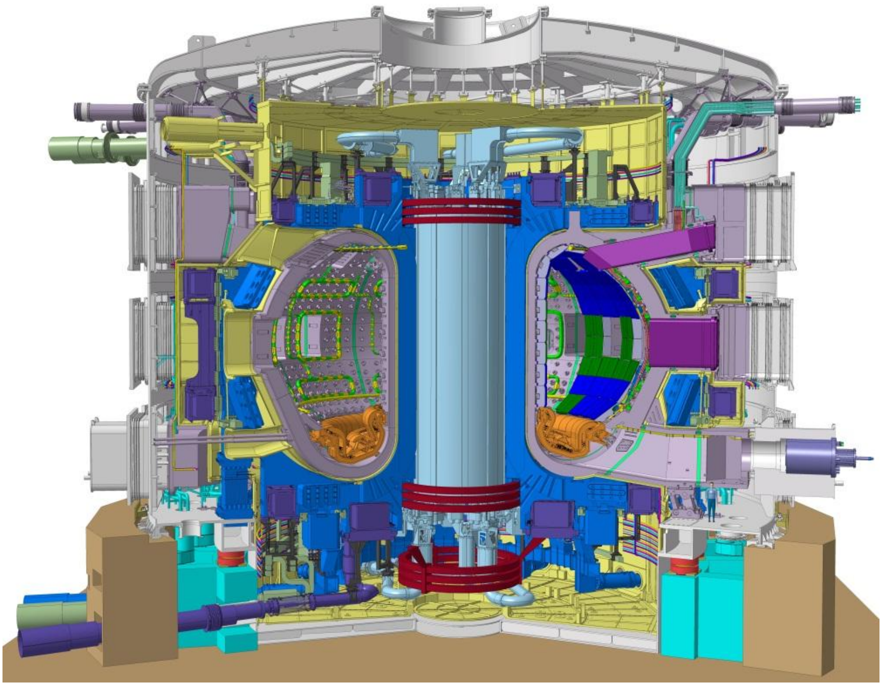

Figure A.2. A cutaway of the ITER Tokamak, produced by the ITER Design Office in January 2013. Credit © ITER Organization, http://www.iter.org/

The European fusion programme

Harnessing fusion energy is the primary goal of the Euratom Fusion Programme in the 7th Framework Programme. The reactor orientation of the programme has provided the drive and the cohesion that makes Europe the world leader in fusion research. The world record of 16 megawatts of fusion power is held by JET device, the Joint European Torus.

Euratom Fusion Associations are the backbone of the European Fusion Programme. There are 27 Associations from the EU countries and Switzerland. The multilateral European Fusion Development Agreement (EFDA) between all Associations and Euratom takes care of overall physics co-ordination in Europe, facilitates the joint exploitation of the JET facilities and emerging fusion technologies.

A new organisation "The Joint European Undertaking for ITER and the Development of Fusion Energy", "Fusion for Energy" (F4E) was established in 2007 and came fully operational in 2008. The main task of Fusion for Energy is to provide European in-kind contributions for ITER including component and system procurements, services and technology R&D for ITER. In addition, Fusion for Energy manages DEMO design activities and the European Broader Approach activities in collaboration with Japan.

ITER International Fusion Energy Organisation

To advance significantly beyond the present generation of fusion devices, a next step device, enabling the investigation of burning plasma in near-reactor conditions, is needed. This will be done in the global ITER project ("iter" is "way" in Latin), which is the joint project of EU, Japan, Russian Federation, United States, China, India and South Korea. The ITER parties agreed in 2005 to site ITER in Europe (Cadarache, France) and the ITER International agreement was signed by the parties in Elysée Palace hosted by the President of France Jacques Chirac, Paris, on 21 November 2006. ITER started as an international legal entity from 27 November 2007. The director general of ITER is Osamu Motojima and head of the ITER project is Remmelt Haange. At the end of 2011 the project staff was about 500 persons. The total number of personnel will be close to 600.

Figure A.3. Seventeen metres below the surface of the platform, the concrete basemat, retaining walls, and seismic pads of the Seismic Isolation Pit are in place to protect the buildings and the equipment from ground motion in the case of an earthquake. Credit © ITER Organization, http://www.iter.org/

Appendix B: Institutes and Companies

Research Institutes and Companies

Tekes – The Finnish Funding Agency for Technology and Innovation
Kyllikinportti 2, Länsi-Pasila
P.O. Box 69, FI-00101 Helsinki, Finland
Tel. +358 10 191 480; fax +358 9694 9196
www.tekes.fi

Juha Lindén	juha.linden@tekes.fi
Kari Koskela	kari.koskela@tekes.fi
Hannu Juuso	hannu.juuso@tekes.fi

Finnish Fusion Research Unit of the Association Euratom-Tekes

VTT Materials for Power Engineering
Otakaari 3A, Espoo and Kemistintie 3, Espoo
P.O. Box 1000, FI-02044 VTT, Finland
Tel. +358 20 722 111; fax +358 20 722 6390
www.vtt.fi

Tuomas Tala	tuomas.tala@vtt.fi
Jukka Heikkinen	jukka.heikkinen@vtt.fi
Jari Likonen	jari.likonen@vtt.fi

VTT Production Systems
Tuotantokatu 2, Lappeenranta
P.O. Box 17021, FI-53851 Lappeenranta, Finland
Tel. +358 20 722 111; fax +358 20 722 2893

Veli Kujanpää	veli.kujanpaa@vtt.fi

VTT System Engineering
Tekniikankatu 1, Tampere
P.O. Box 1300, FI-33101 Tampere, Finland
Tel. +358 20 722 111; fax +358 20 722 3495

Jorma Järvenpää	jorma.jarvenpaa@vtt.fi
Mikko Siuko	mikko.siuko@vtt.fi

VTT Sensors
Tietotie 3, Espoo
P.O. Box 1000, FI-02044 VTT, Finland
Tel. +358 20 722 111; fax +358 20 722 7012

Jukka Kyynäräinen	jukka.kyynarainen@vtt.fi

Aalto University (AU)
School of Science
Department of Applied Physics
P.O. Box 14100, FI-00076 AALTO, Finland
Tel. +358 9 4511; fax +358 9 451 3195
physics.aalto.fi
Mathias Groth mathias.groth@aalto.fi
Taina Kurki-Suonio taina.kurki-suonio@aalto.fi
Rainer Salomaa rainer.salomaa@aalto.fi

Tampere University of Technology (TUT)
Institute of Hydraulics and Automation
Korkeakoulunkatu 2, P.O. Box 589, FI-33101 Tampere, Finland
Tel. +358 3115 2111; fax +358 3115 2240
www.iha.tut.fi
Matti Vilenius matti.vilenius@tut.fi
Jouni Mattila jouni.mattila@tut.fi

Lappeenranta University of Technology (LUT)
Laboratory of Machine Automation
Skinnarilankatu 34, P.O. Box 20, FI-53851 Lappeenranta, Finland
Tel. + 358 5 621 11; fax +358 5 621 2350
www.lut.fi
Heikki Handroos heikki.handroos@lut.fi

University of Helsinki (UH)
Accelerator Laboratory
P.O. Box 43, FI-00014 University of Helsinki, Finland
Tel. +358 9 191 40005; fax +358 9 191 40042
www.beam.helsinki.fi
Juhani Keinonen juhani.keinonen@helsinki.fi
Kai Nordlund kai.nordlund@helsinki.fi

Estonian Research Unit of the Association Euratom-Tekes

University of Tartu (UT)
Institute of Physics
Riia 142
51014 Tartu, Estonia
Tel. +372 742 8493; fax +372 738 3033
www.fi.tartu.ee
Madis Kiisk madis.kiisk@fi.tartu.ee
Marco Kirm marco.kirm@ut.ee

Industrial Companies

Company: **ABB Oy**
Technology: Power and automation
Contact: ABB Oy, P.O. Box 184, FI-00381 Helsinki, Finland
Tel. +358-10-2211; fax +358-10-2222 287
Ralf Granholm, ralf.granholm@fi.abb.com

Company: **Adwatec Oy**
Technology: Water cooling systems for high power electronics (low, medium and high voltage).
Contact: Adwatec Oy, Artturintie 14H, FI-36220 Tampere, Finland
Tel. +358 3 389 0860; fax +358 3 389 0861
www.adwatec.com
Arto Verronen, arto.verronen@adwatec.com

Company: **Aspocomp Oy**
Technology: Electronics manufacturing, thick film technology, component mounting (SMT), mounting of chips (COB) in mechanical/electrical micro systems (MEMS) and multi-chip modules (MCM), PWB (or also called PCB), sheet metal manufacturing and assembly.
Contact: Aspocomp Oy, Yrittäjäntie 13, FI-01800 Klaukkala, Finland
Tel. +358 9 878 01244; fax +358 9 878 01200
www.aspocomp.com
Markku Palmu, markku.palmu@aspocomp.com

Company: **CLS-Engineering Oy**
Technology: Preliminary engineering, implementation, engineering, field and electrification engineering, manufacturing of automation cabinets and switchgear, programming, installation, testing, and maintenance services
Contact: CLS-Engineering Oy, Hakunintie 21, FI-26100 Rauma, Finland
Tel. +358 201 549 400; fax +358 201 549 401
www.cls-engineering.fi
Tom Holmström, tom.holmstrom@cls-engineering.fi

Company: **Comatec Group (Engineering bureau Comatec Ltd)**
Technology: Engineering design for machinery and industrial equipment. Mobile machinery, production equipment, transportation equipment as well as pressure equipment and boiler plant engineering. Our offering comprises of concept services, project design and management services, design services and expert services.

Contact: Comatec Group, Kalevantie 7C, FI-33100 Tampere, Finland
Tel. +358 29 000 2000
www.comatec.fi
Miikka Riittinen, miikka.riittinen@comatec.fi

Company **Creanex Oy**
Technology: Remote handling, teleoperation and walking platforms.
Contact: Creanex Oy, Nuolialantie 62, FI-33900 Tampere, Finland
fax +358 33683 244, GSM +358 50 311 0300
www.creanex.com
Timo Mustonen, timo.mustonen@creanex.com

Company: **Delfoi Oy**
Technology: Telerobotics, task level programming
Contact: Delfoi Oy, Vänrikinkuja 2, FI-02600 Espoo, Finland
Tel. +358 9 4300 70; fax +358 9 4300 7277
www.delfoi.com
Heikki Aalto, heikki.aalto@delfoi.com

Company: **DIARC-Technology Oy**
Technology: Coatings for plasma facing components. Deuterium doped coatings for hydrogen migration and erosion studies in fusion machines. Cleaning techniques for first wall components.
Contact: DIARC-Technology, Kattilalaaksontie 1, FI-02330 Espoo, Finland
Tel. +358 10 271 2030; fax +358 10 271 2049
www.diarc.fi
Jukka Kolehmainen, jukka.kolehmainen@diarc.fi

Company: **Elektrobit Microwave Oy**
Technology: Product development, test solutions and manufacturing for microwave and RF- technologies, high-tech solutions ranging from space equipment to commercial telecommunication systems
Contact: Teollisuustie 9A, FI-02700 Kauniainen, Finland
Tel. +358 40 344 2000, fax +358 9 5055 547
www.elektrobit.com
Marko Koski, marko.koski@elektrobit.com

Company: **Elomatic Oy**
Technology: Design and other services for manufactures of machinery and equipment. We are involved in our customer´s R&D: in projects, product design and production development.
Contact: Elomatic Oy, Kangasvuorentie 10, FI-40320 Jyväskylä, Finland
Tel. +358 14 446 7111; fax +358 14 446 7123
www.elomatic.com
Timo Martikainen, timo.martikainen@elomatic.com

Company:	**Etteplan Oyj**
Technology:	Etteplan is a specialist in industrial equipment engineering and technical product information solutions and services. Our customers are global leaders in their fields and operate in areas like the automotive, aerospace and defence industries as well as the electricity generation and power transmission sectors, and material flow management.
Contact:	Terveystie 18, FI-15860 Hollola, Finland Tel: +358 10 307 1010

Company:	**Fortum Power and Heat Oy**
Technology:	Nuclear Engineering
Contact:	P.O. Box 100, FI-00048 Fortum, Finland Tel. + 358 10 4511 www.fortum.com Reko Rantamäki, reko.rantamaki@fortum.com

Company:	**Hollming Works Oy**
Technology:	Mechanical engineering, fabrication of heavy steel and stainless steel structures, design for manufacturing
Contact:	Puunaulakatu 3, P.O. Box 96, FI-28101 Pori, Finland Tel. +358 20 486 5040; fax +358 20 486 5041 www.hollmingworks.com Mika Korhonen, mika.korhonen@hollmingworks.com

Company:	**Hytar Oy**
Technology:	Remote handling, water hydraulics
Contact:	Ilmailukatu 13, P.O. Box 534, FI-33101 Tampere, Finland Tel. +358 3 389 9340; fax +358 3 389 9341 Olli Pohls, olli.pohls@avs-yhtiot.fi

Company:	**Instrumentti-Mattila Oy**
Technology:	Designs and manufacturing of vacuum technology devices
Contact:	Valpperintie 263, FI-21270 Nousiainen, Finland Tel +358-2-4353611, fax +358-2-431 8744 www.instrumentti-mattila.fi Veikko Mattila, veikko.mattila@instrumentti-mattila.fi

Company:	**Japrotek Oy Ab**
Technology:	Design and manufacturing of stainless steel and titanium process equipment such as columns, reactors and heat exchangers
Contact:	Japrotek Oy Ab, P.O. Box 12, FI-68601, Pietarsaari, Finland Tel +358-20 1880 511, fax +358-20 1880 415 www.vaahto.fi
Ulf Sarelin	ulf.sarelin@vaahto.fi

Company: **Jutron Oy**
Technology: Versatile electronics manufacturing services
Contact: Jutron Oy, Konekuja 2, FI-90630 Oulu, Finland
Tel +358-8-555 1100, fax +358-8-555 1110
www.jutron.fi
Keijo Meriläinen, keijo.merilainen@jutron.fi

Company: **Kankaanpää Works Oy**
Technology: Mechanical engineering, fabrication of heavy stainless steel structures including 3D cold forming of stainless steel
Contact: Kankaanpää Works Oy, P.O. Box 56, FI-38701 Kankaanpää, Finland
Tel. +358 20 486 5034; fax +358 20 486 5035
www.hollmingworks.com
Jarmo Huttunen, jarmo.huttunen@hollmingworks.com

Company: **Kempower Oy**
Technology: Designs and manufacturing of standard and customised power sources for industrial and scientific use
Contact: Hennalankatu 39, P.O. Box 13, FI-15801, Lahti, Finland
Tel +358-3-899 11, fax +358-3-899-417
www.kempower.fi
Petri Korhonen, petri.korhonen@kempower.fi

Company: **Luvata Pori Oy**
Technology: Superconducting strands and copper products.
Contact: Luvata Pori Oy, Kuparitie, P.O Box 60, FI-28101 Pori, Finland
Tel. +358 2 626 6111; fax +358 2 626 5314
Ben Karlemo, ben.karlemo@luvata.com

Company: **Mansner Oy Precision Mechanics**
Technology: Precision mechanics: milling, turning, welding, and assembling. From stainless steels to copper.
Contact: Mansner Oy, Yrittäjäntie 73, FI-03620 Karkkila, Finland
Tel. +358 20 7862 367; fax +358 20 7862 363
www.mansner.com
Sami Mansner, sami.mansner@mansner.fi

Company: **Marimils Oy**
Technology: Evacuation guiding systems and emergency lighting.
Contact: Marimils Oy, Pohjantähdentie 17, FI-01451 Vantaa, Finland
Tel. +358 207 508 615; fax +358 207 508 601
www.marimils.com
Juha Huovilainen, juha.huovilainen@marimils.fi

Company:	**Marioff Corporation Oy**
Technology:	Mist fire protection systems
Contact:	Marioff Corporation Oy, P.O. Box 25, FI-01511 Vantaa, Finland Tel. +358 9 8708 5342; fax +358 9 8708 5399 www.hi-fog.com Pekka Saari, pekka.saari@marioff.fi
Company:	**Metso Oyj** **Metso Engineered Materials and Components**
Technology:	Steel castings, special stainless steels, powder metallurgy, component technology/ engineering, design, production and installation
Contact:	Metso Engineered Materials and Components, P.O. Box 306, FI-33101 Tampere, Finland Tel. +358 20 484 120; fax +358 20 484 121 www.metsomaterialstechnology.com Jari Liimatainen, jari.liimatainen@metso.com
Company:	**Oxford Instruments Analytical**
Technology:	Plasma diagnostics, vacuum windows
Contact:	Nihtisillankuja, P.O. Box 85, FI-02631 Espoo, Finland Tel:+358 9 329411, fax +358 9 23941300 www.oxford-instruments.com Seppo Nenonen, seppo.nenonen@oxinst.fi
Company:	**Patria Oyj**
Technology:	Defence and space electronics hardware and engineering
Contact:	Patria Oyj, Kaivokatu 10, FI-00100 Helsinki, Finland Tel +358-2-435 3611, fax +358-2-431 8744 www.patria.fi Tapani Nippala, tapani.nippala@patria.fi
Company:	**Platom Oy**
Technology:	UF_6 handling equipment, process modelling and radioactive waste management.
Contact:	Platom Oy, Jääkärinkatu 33, FI-50130 Mikkeli, Finland Tel. +358 44 5504 300; fax +358 15 369 270 www.platom.fi Miika Puukko, miika.puukko@platom.fi
Company:	**Powernet Oy**
Technology:	Design and manufacturing of custom design power supplies, AC/DC, DC/DC, DC/AC in power ranges from 100–3200W.
Contact:	Powernet Oy, Martinkyläntie 43, FI-01720 Vantaa, Finland Tel. +358-10-2890-700; fax +358-10-2890-793 Harry Lilja, harry.lilja@powernet.fi

Company: **PPF Projects Oy**
Service: Tekes Industrial Activation Project, ITER
Contact. Kaunismäentie 7B, FI-28800 Pori, Finland
Tel. +358 50 40 79 799, +358 2 648 2030
fusion.ppf.fi
Pertti Pale, pertti.pale@ppf.fi

Company: **Prizztech Oy**
Role: Industry activation and support
Contact: Pohjoisranta 11D, PL 18, FI-28101 Pori, Finland
Tel. +358 44 710 5336
www.prizz.fi
Leena Jylhä, leena.jylha@prizz.fi

Company: **Pöyry Finland Oy**
Technology: Global consulting and engineering expert within the Pöyry Group serving the energy sector. Core areas: nuclear energy, hydro-power, oil & gas, renewable energy, power & heat, transmission & distribution.
Contact: P.O. Box 93, Tekniikantie 4 A, FI-02151 Espoo, Finland
Tel. +358 10 3311
www.poyry.com
Miko Olkkonen, miko.olkkonen@poyry.com

Company: **Rados Technology Oy**
Technology: Dosimetry, waste & contamination and environmental monitoring.
Contact: Rados Technology Oy, P.O. Box 506, FI-20101 Turku, Finland
Tel. +358 2 4684 600; fax +358 2 4684 601
www.rados.fi
Erik Lehtonen, erik.lehtonen@rados.fi

Company: **Rejlers Oy**
Technology: Services for industry, energy, building & property and infra customers. Core expertise: electricity and automation, mechanical engineering, plant engineering, FE modelling and analysis. Also more comprehensive project deliveries as turn-key basis.
Contact: Rejlers Oy, P.O. Box 194, FI-50101 Mikkeli, Finland
Tel: +358 20 7520 700; fax +358 20 7520 701
www.rejlers.fi
Seppo Sorri, seppo.sorri@rejlers.fi

Company: **Rocla Oyj**
Technology: Heavy Automated guided vehicles
Contact: Rocla Oyj, P.O. Box 88, FI- 04401 Järvenpää, Finland
Tel +358 9 271 471, fax +358 9 271 47 430
www.rocla.fi
Pekka Joensuu, pekka.joensuu@rocla.com

Company: **Selmic Oy**
Technology: Microelectronics design and manufacturing, packaging technologies and contract manufacturing services.
Contact: Selmic Oy, Vanha Porvoontie 229, FI-01380 Vantaa, Finland
Tel: +358 9 2706 3911; fax +358 9 2705 2602
www.selmic.com
Patrick Sederholm, patrick.sederholm@selmic.com

Company: **Space Systems Finland Ltd.**
Technology: Safety critical systems development; safety assessments and qualification of systems for use in nuclear power plants.
Contact: Kappelitie 6 B, FI-02200 Espoo, Finland
Tel. +358 9 6132 8600; fax +358 9 6132 8699
www.ssf.fi
Timo Latvala, timo.latvala@ssf.fi

Company: **Solving Oy**
Technology: Heavy automated guided vehicles. Equipment for heavy assembly and material handling based on air film technology for weights up to hundreds of tons.
Contact: Solving Oy, P.O. Box 98, FI-68601 Pietarsaari, Finland
Tel. +358 6 781 7500; fax +358 6 781 7510
www.solving.fi
Bo-Göran Eriksson, bo-goran.eriksson@solving.fi

Company: **SWECO Industry Oy**
Technology: Consulting and engineering company operating world-wide, providing consulting, engineering and project management services for industrial customers in plant investments, product development and production.
Contact: Valimotie 9, P.O. Box 75, FI-00381 Helsinki, Finland
Tel. +358 20 752 6000
Kari Harsunen, kari.harsunen@sweco.fi

Company: **Tampereen Keskustekniikka Oy**
Technology: Product development, design, production, marketing, and sales of switchgear and controlgear assemblies.
Contact: Hyllilänkatu 15, P.O. Box 11, FI-33731 Tampere, Finland
Tel. +358-3-233 8331
www.keskustekniikka.fi
Reijo Anttila, reijo.anttila@keskustekniikka.fi

Company: **Tankki Oy**
Technology: Production and engineering of stainless steel tanks and vessels for use in different types of industrial installations
Contact: Oikotie 2, FI-63700 Ähtäri, Finland
Tel. +358 6 510 1111, fax +358 6 510 1200
Jukka Lehto, jukka.lehto@tankki.fi

Company: **TVO Nuclear Services Oy**
Technology: Nuclear power technologies; service, maintenance, radiation protection and safety.
Contact: Olkiluoto, FI-27160 Eurajoki,
Tel. + 358 2 83 811; fax +358 2 8381 2109
www.tvons.fi
Mikko Leppälä, mikko.leppala@tvo.fi

Company: **TP-Konepajat Oy / Arelmek Oy**
Technology: Heavy welded and machined products, DTP2 structure
Contact: PO Box 23, FI-33701 Tampere, Finland
Tel. +358 40 8318001
www.tpyhtio.fi
Jorma Turkki, jorma.turkki@tpyhtio.fi

Company: **Oy Woikoski Ab**
Technology: Production, development, applications and distribution of gases and liquid helium
Contact: Voikoski, P.O. Box 1, FI-45371 Valkeala, Finland
Tel. +358-15-7700700 fax +358-15-7700720
www.woikoski.fi
Kalevi Korjala, kalevi.korjala@woikoski.fi

Company: **ÅF-Consult Oy**
Technology: Design, engineering, consulting and project management services in the field of power generation and district heating. EPCM services.
Contact: FI-02600 Espoo, Finland
Tel +358 40 348 5511, fax +358 9 3487 0810
www.afconsult.com
Jarmo Raussi, jarmo.raussi@afconsult.com

Series title and number

VTT Science 30

Title	**Fusion Yearbook** **Association Euratom-Tekes Annual Report 2012**
Author(s)	Markus Airila & Antti Salmi (eds.)
Abstract	This Annual Report summarises the fusion research activities of the Finnish and Estonian Research Units of the Association Euratom-Tekes in 2012. The emphasis of the work coordinated by EFDA was in ITER Physics, PPPT and the ITM Task Force. Other EFDA activities in 2012 were carried within EU Topical Groups, Emerging Technology and in Goal Oriented Training. In addition, a significant fraction of Tekes activities was directed to F4E grants and ITER contracts. Fusion physics work is carried out at VTT, Aalto University, University of Helsinki and University of Tartu. The main activities are plasma experiments in collaboration with tokamak laboratories, modelling with related code development, and diagnostics related to the main European fusion facilities JET and AUG. In particular, Association Euratom-Tekes focused on (i) Heat and particle transport and fast particle studies, (ii) Plasma-wall interactions and material transport in the scrape-off layer, and (iii) Code development and diagnostics. The Association participated in the EFDA JET Workprogramme 2012, including C29-30 experiments with the ITER-like wall, diagnostics development and code integration. Three physicists were seconded to the JET operating team and one to EFDA CSU. The Association participated also in the 2012 experimental programme of ASDEX Upgrade at IPP and the analysis of DIII-D and C-Mod data. Technology work is carried out at VTT, AU, Tampere University of Technology (TUT) and Lappeenranta University of Technology (LUT) in close collaboration with Finnish industry. Industrial participation is co-ordinated by Tekes. The technology research and development includes the DTP2 facility at VTT Tampere, materials and joining techniques, vessel/in-vessel components, magnetic diagnostics by micromechanical magnetometers for ITER, upgrading of the JET NPA diagnostics, Power Plant Physics and Technology (PPPT) activities, plasma facing materials issues, erosion/re-deposition and material transport studies and development of coating techniques. Association Euratom-Tekes is involved in Goal-Oriented Training in Remote Handling project, coordinated by Tampere University of Technology. In July 2013 Aalto University will organize the 40th EPS Plasma Physics Conference in Espoo.
ISBN, ISSN	ISBN 978-951-38-7995-2 (Soft back ed.) ISBN 978-951-38-7996-9 (URL: http://www.vtt.fi/publications/index.jsp) ISSN-L 2242-119X ISSN 2242-119X (Print) ISSN 2242-1203 (Online)
Date	May 2013
Language	English, Finnish abstract
Pages	180 p. + app 13 p.
Name of the project	FU-KOORD 12-13
Commissioned by	Tekes, Euratom
Keywords	Nuclear fusion, fusion energy, fusion research, fusion physics, fusion technology, fusion reactors, fusion reactor materials, ITER remote handling, Euratom
Publisher	VTT Technical Research Centre of Finland P.O. Box 1000, FI-02044 VTT, Finland, Tel. +358 20 722 111

Fusion Yearbook

This Annual Report summarises the fusion research activities of the Finnish and Estonian Research Units of the Association Euratom-Tekes in 2012.

Fusion physics work is carried out at VTT, Aalto University, University of Helsinki and University of Tartu. The main activities are plasma experiments in collaboration with tokamak laboratories, modelling with related code development, and diagnostics. The Association participated in the EFDA JET Workprogramme 2012, including C29-30 experiments with the ITER-like wall, diagnostics development and code integration, as well as in the 2012 experimental programme of ASDEX Upgrade at IPP and the analysis of DIII-D and C-Mod data.

Technology work is carried out at VTT, Aalto University, Tampere University of Technology and Lappeenranta University of Technology in close collaboration with Finnish industry. Industrial participation is co-ordinated by Tekes. The technology research and development includes the DTP2 facility at VTT Tampere, materials and joining techniques, vessel/in-vessel components, magnetic diagnostics by micromechanical magnetometers for ITER, upgrading of the JET NPA diagnostics, Power Plant Physics and Technology (PPPT) activities, plasma facing materials issues, erosion/re-deposition and material transport studies and development of coating techniques.

ISBN 978-951-38-7995-2 (Soft back ed.)
ISBN 978-951-38-7996-9 (URL: http://www.vtt.fi/publications/index.jsp)
ISSN-L 2242-119X
ISSN 2242-119X (Print)
ISSN 2242-1203 (Online)

Julkaisun sarja ja numero
VTT Science 30

Nimeke	**Fuusio-vuosikirja** **Euratom-Tekes-assosiaation vuosikertomus 2012**
Tekijä(t)	Markus Airila & Antti Salmi (eds.)
Tiivistelmä	Tähän vuosikirjaan on koottu Suomen ja Viron fuusiotutkimusyksiköiden vuoden 2012 tulokset ja saavutukset. Työ on tehty Euratom-Tekes-assosiaation puitteissa. EFDAn koordinoima työ keskittyi ITERin fysiikkaan, DEMOn fysiikkaan ja tekniikkaan (power plant physics and technology, PPPT) ja integroituun mallinnukseen (integrated tokamak modelling, ITM). EFDA-työtä tehtiin vuonna 2012 myös EU:n ajankohtaisten aiheiden työryhmissä (topical groups), uusien teknologioiden alalla (emerging technology) ja uusien asiantuntijoiden koulutuksessa (goal oriented training in remote handling, GOTRH). F4E-organisaation myöntämällä rahoituksella ja ITER-sopimuksilla on ohjelmassa merkittävä osuus. Fysiikan tutkimusta tehdään VTT:llä, Aalto-yliopistossa, Helsingin yliopistossa sekä Tarton yliopistossa, ja se keskittyy plasmakokeisiin yhteistyössä tokamaklaboratorioiden kanssa ja niiden mallinnukseen. Assosiaation erityisiä painopistealueita ovat (i) Lämmön ja hiukkasten kuljetus ja nopeiden hiukkasten fysiikka, (ii) Plasma–seinämä-vuorovaikutukset ja materiaalien kulkeutuminen kuorintakerroksessa sekä (iii) Simulointiohjelmistojen kehitys ja diagnostiikka. Vuonna 2012 Euratom-Tekes-assosiaatio osallistui EFDA-JETin koekampanjoihin C29-30, diagnostiikan kehitykseen ja simulointiohjelmien integrointiin. Kolme fyysikkoa toimi JETin käyttöorganisaatiossa ja yksi EFDAn tukiorganisaatiossa (close support unit, CSU). Lisäksi assosiaatio osallistui ASDEX Upgrade -tokamakin vuoden 2012 koeohjelmaan sekä DIII-D- ja C-Mod-tokamakien tulosten analysointiin. Teknologiatyötä tekevät VTT, Aalto-yliopisto, TTY ja LTY tiiviissä yhteistyössä suomalaisen teollisuuden kanssa. Yritysten osallistumista koordinoi Tekes. Kehitettäviin teknologioihin kuuluvat DTP2-laitteisto VTT:llä Tampereella, materiaalit ja niiden liitostekniikat, tyhjiökammioon liittyvät komponentit, MEMS-pohjaisten diagnostiikkojen kehitys ITERin magneettikenttien mittausta varten, JETin NPA-diagnostiikan päivitys, osallistuminen PPPT-tutkimukseen, ensiseinämän materiaalit, eroosion, deposition ja materiaalien kulkeutumisen tutkimus sekä pinnoitteiden kehittäminen. Heinäkuussa 2013 Aalto-yliopisto järjestää EPS:n plasmafysiikan konferenssin Dipolissa Espoossa.
ISBN, ISSN	ISBN 978-951-38-7995-2 (nid.) ISBN 978-951-38-7996-9 (URL: http://www.vtt.fi/publications/index.jsp) ISSN-L 2242-119X ISSN 2242-119X (painettu) ISSN 2242-1203 (verkkojulkaisu)
Julkaisuaika	Toukokuu 2013
Kieli	Suomi, englanninkielinen tiivistelmä
Sivumäärä	180 s. + liitt. 13 s.
Projektin nimi	FU-KOORD 12-13
Toimeksiantajat	Tekes, Euratom
Avainsanat	Nuclear fusion, fusion energy, fusion research, fusion physics, fusion technology, fusion reactors, fusion reactor materials, ITER remote handling, Euratom
Julkaisija	VTT PL 1000, 02044 VTT, puh. 020 722 111