VTT PUBLICATIONS 738

Fusion Yearbook
Association EURATOM-TEKES

Annual Report 2009

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Annual Report 2009

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Cover: DTP2 inauguration, photo by Anton Halas

Edita Prima Oy, Helsinki 2010

FOREWORD

The absolute highlight of the Finnish fusion programme in 2009 was the inauguration of the ITER divertor test platform (DTP2) at VTT in Tampere. Top management of Euratom, Fusion for Energy (F4E), ITER IO and VTT took part in the DTP2 opening ceremony. The occasion attracted a great deal of interest in European and Finnish media including a large number of newspapers and major national TV channels.

ITER construction is gradually speeding up as the main procurement arrangements of the major components on the critical path such as magnets, buildings and vacuum vessel are completed and large industrial contracts are in the final stage of preparation. In addition, the ITER site at Cadarache is now ready for the construction to start. However, ITER baseline is still waiting for confirmation from the parties. Regarding F4E the procurements and engineering contracts are advancing well, but the launching of the F4E grants has been slower than expected. The low number of F4E Grants with the decreasing Euratom baseline and EFDA priority funding has been the major problem for the Tekes Association with the programme emphasising the ITER technology.

The emphasis of the Association Euratom-Tekes programme was in the EFDA and JET workprogrammes. Plasma physics and plasma-wall studies were carried at JET (task forces exhaust, transport and diagnostics) and in EFDA task forces “Plasma Wall Interaction” and “Integrated Tokamak Modelling”. The Tekes Association provided a task force leader (transport) and two Tekes scientists were nominated to deputy task force leaders for the ITER-like-wall (ILW) experiments, starting at JET in 2011. Other services for the EFDA and JET include a member in the high level support team for high performance computing and JOC secondees for remote handing of ILW and code integration. Collaboration with the AUG team at IPP Garching is the other important and scientifically productive activity of the Association Euratom-Tekes. Scientific work at JET and AUG includes transport and fast particle physics experiments and modelling, plasma-wall and post-mortem surface studies of divertor tiles.

Theory and modelling work deals with gyrokinetic turbulence simulations, predictive modelling of JET experiments, fast particle physics, edge plasmas and plasma-surface phenomena, molecular dynamics and radiation damage effects in stainless steels with the related code development. Materials research was complemented by mechanical testing of new steels and advanced welding methods.

Diagnostics studies covered upgrading of the JET neutral particle analyser, feasibility studies for micromechanical magnetometer for ITER, smart tile development and laser spectroscopy for erosion and tritium inventory studies.

Finally, I would like to express my most sincere thanks to the scientists and engineers of the Finnish and Estonian Research Units and companies involved for their excellent and dedicated work in fusion physics and technology to provide a valuable contribution to Euratom Fusion Programme and ITER.

Seppo Karttunen
Head of Research Unit, Association Euratom-Tekes

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1. SUMMARY

This Annual Report summarises the fusion research activities of the Finnish and Estonian Research Units of the Association Euratom-Tekes in 2009. The Estonian Research Unit was established by the Agreement between Tekes and the University of Tartu in 2007. The emphasis of the new EFDA is in exploiting JET and co-ordinating physics research in the Associations. In addition, emerging technology and goal oriented training activities are under EFDA. ITER related technology R&D is now 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 Research Unit are divided in the fusion physics under the Contract of Association and EFDA. New R&D Grant work on remote handling for ITER divertor maintenance launched by the Joint Undertaking "Fusion for Energy" started in 2008 and is running to 2010. Finnish companies have been very active in F4E calls. The volume of the CoA (Contract of Association) and EFDA activities decreased by 20% from 2008. The main reason was that the old EFDA technology work was completed by the end of 2008. However, the total R&D volume increased slightly due to a large F4E Grant for DTP2.

The Physics Programme is carried out at VTT Technical Research Centre of Finland, Aalto University School of Science and Technology (until 31.12.2009 Helsinki University of Technology TKK), University of Helsinki (UH) and University of Tartu (Estonia). The research areas of the Physics and EFDA Programme are:

- Heat and particle transport, MHD physics and plasma edge phenomena
- Plasma-wall interactions and material transport in SOL region
- Code development and diagnostics.

Association Euratom-Tekes participated actively in the EFDA JET Workprogramme 2009 and exploitation of JET facilities in experimental campaigns C20–C27. Three persons were seconded to the CCFE operating team, two physicists in codes & modelling and one engineer in remote handling. One person was a Task Force Leader in TF T (transport). One engineer from VTT was seconded to the ITER IO at Cadarache in 2009 (Assembly). Practically all physics activities of the Research Unit are carried out in co-operation with other Associations with the focus on EFDA JET work. In addition to EFDA JET activities, the Tekes Association participated in the 2009 experimental programme of ASDEX Upgrade (AUG).

Staff mobility visits of total 678 days took place in 2009. The visits were hosted by the Associations IPP Garching (233 days, MA Art. 1.2.b collaboration), CCFE Culham (58 days), SCK-CEN Mol (29 days), University of Tartu (28 days) and FOM Rijnhuizen (16 days). Other staff mobility actions were EFDA meetings (PWI, ITM, FT, TGs) meetings (43 days), ITPA meetings (22 days), Goal Oriented Training GOTiT (86 days) and US (160 days) for IEA Large Tokamak experiments and EU-US visits. Tekes (University of Helsinki hosted a visit of 28 days from the Slovakian Association.

The Technology work is carried out at VTT, Helsinki University of Technology TKK (from 2010 Aalto University School of Science and Technology), Tampere University of Technology (TUT) and Lappeenranta University of Technology (LUT) in close collaboration with Finnish industry. The companies with fusion related activities are:

- Fortum (Finnish EFET partner)
- Luvata Pori, Metso, and Hollming Works (VV and in-vessel components)
- Diarc Technology (PFC and coatings)
- Creanex, Hytar and Adwatec (RH technologies and water hydraulics)
- Oxford Instruments Analytical (diagnostics).

Industrial participation is co-ordinated by Tekes. The technology research and development is focused on the remote handling, vessel/in-vessel materials and components plus some activities in physics integration and JET Technology:

- Divertor Test Platform (DTP2) at VTT in Tampere for remote handling of divertor maintenance and development of water hydraulic tools and manipulators
- Development of advanced welding methods and IWR cutting/welding robot
- Application of powder HIP method for fabrication of ITER vessel/in-vessel 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
- Upgrading of the JET NPA diagnostics
- Feasibility study for micromechanical magnetometers.

A major PI/PR occasion was the inauguration of the ITER divertor test platform DTP2 at VTT in Tampere, 29 January 2009. The press conference was carried out in close collaboration with the Commission and attracted the main national TV and radio channels, leading newspapers and was broadly reported by the European media. The Commission was represented by the Euratom Director Octavi Quintana Trias, ITER IO by the Deputy Director General Norbert Holtkamp, Fusion for Energy by the Director Didier Gambier and VTT by the Director General Erkki Leppävuori.

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 high-tech 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) and Staff Mobility Agreement. In 2007, Tekes and the University of Tartu (Estonia) signed an Agreement 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. Juha Lindén. The fusion related industrial activities were co-ordinated by Tekes and Finpro. 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. Seppo Karttunen from VTT. The following institutes and universities participated in the fusion research during 2009:

1. **VTT Technical Research Centre of Finland**
    VTT Materials and Buildings (co-ordination, physics, materials, diagnostics)
    VTT Industrial Systems (remote handling, beam welding, DTP2)
    VTT Microtechnologies and Sensors (diagnostics)
2. **Helsinki University of Technology (TKK; from 2010 the Aalto University School of Science and Technology)**
    Department of Engineering Physics and Mathematics (plasma physics and diagnostics)
3. **University of Helsinki (UH)**
    Accelerator Laboratory (physics, materials)
4. **Tampere University of Technology (TUT)**
    Institute of Hydraulics and Automation (remote handling, DTP2)
5. **Lappeenranta University of Technology (LUT)**
    Institute of Mechatronics and Virtual Engineering (remote handling).

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 three Finnish staff persons in the ITER IO team, in Cadarache and two Finnish staff persons in F4E, in Barcelona.

2.4 Association Steering Committee

The research activities of the Finnish Association Euratom-Tekes are directed by the Steering Committee, which comprises the following members in 2009:

Chairman 2009	Mr. Reijo Munther, Tekes
Members	Mr. Doug Bartlett, EU Commission, Research DG
	Mr. Steven Booth, EU Commission, Research DG
	Mr. Marc Pipeleers, EU Commission, Research DG
	Mrs. Liisa Heikinheimo, VTT
	Mr. Harri Tuomisto, Fortum Oy
	Mr Juha Lindén, Tekes
Head of Research Unit	Mr. Seppo Karttunen, VTT
Head of Estonian RU	Mr. Madis Kiisk, UT, Estonia
Secretary	Mr. Jukka Heikkinen, VTT

The Association Steering Committee (ASC) had a meeting in Tampere, 21 October 2009 including a presentation of the DTP2 project and hardware at VTT. The EFDA Leader Jerome Pamela and Danilo Pacella from EFDA CSU Garching participated in the ASC meeting by video link. Bilateral discussions between Tekes and the Commission took place at VTT in Espoo, 21 September 2009. In the meeting the Commission was represented by Steven Booth and Ruggero Giannella. Yvan Capouet, Eduard Rille and Marc Pipeleers from the Commission participated by a video link.

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.

Chairman	Mr. Jaakko Ihamuotila, Millennium Prize Foundation
Members	Ms. Mirja Arajärvi, Ministry of Education
	Mr. Hannu Juuso, Tekes
	Ms. Anna Kalliomäki, Finnish Academy of Sciences
	Mr. Kimmo Kanto, Tekes
	Mr. Ben Karlemo, Luvata Pori Oy
	Mr. Jari Liimatainen, Metso Oy
	Mr. Reijo Munther, Tekes
	Mr. Juho Mäkinen, VTT
	Mr. Herkko Plit, Teollisuuden Voima Oy
	Mr. Pentti Pulkkinen, Finnish Academy of Sciences
	Mr. Dan-Olof Riska, Helsinki Institute of Physics
	Mr. Jorma Routti, Creative Industries Management Oy
	Mr. Jouko Suokas, VTT
	Mr. Harri Tuomisto, Fortum Nuclear Services Oy
	Ms. Janica Ylikarjula, Confederation of Finnish Industries
Head of research Unit	Mr. Seppo Karttunen, VTT
Secretary	Mr. Pekka Tolonen and Mr. Markus Ranne, Finpro

The national steering committee had one meeting in 2009.

The research activities are steered by three Topical Advisory Groups for 1) physics and diagnostics chaired by Heikki Sipilä and Seppo Nenonen Oxford Instruments Analytical, 2) for materials research chaired by Ilpo Koppinen, Luvata Oy, and 3) for remote handling systems chaired by Olli Pohl, Hytar Oy.

2.6 The Finnish Members in the EU Fusion Committees

Euratom Science and Technology Committee (STC)
Rainer Salomaa, TKK

Consultative Committee for the Euratom Specific Research and Training Programme in the Field of Nuclear Energy – Fusion (CCE-FU)
Reijo Munther, Tekes

Seppo Karttunen, VTT
Juha Lindén, Tekes
Marco Kirm, UT, Estonia
Madis Kiisk, UT, Estonia

EFDA Steering Committee

Juha Lindén, Tekes
Seppo Karttunen, VTT
Madis Kiisk, UT, Estonia

Science and Technology Advisory Committee (STAC)

Rainer Salomaa, TKK

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

Reijo Munther, Tekes
Seppo Karttunen, VTT
Rein Kaarli, MER, Estonia
Ergo Nõmmiste, UT, Estonia

Executive Committee for the Joint European Undertaking for ITER and the Development of Fusion Energy, "Fusion for Energy" (F4E EXE)

Kari Törrönen, Energywave

Other international duties and Finnish representatives in the following fusion committees and expert groups in 2009:

Seppo Karttunen and Reijo Munther are members of the IEA Fusion Power Co-ordinating Committee (FPCC).

Jukka Heikkinen, 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 Conference on Plasma Physics, Helsinki, Finland, July 2013.

Harri Tuomisto is a member of the International Organising Committee, of the Symposium on Fusion Technology (SOFT).

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, Max Planck Gesellschaft.

Salomon Janhunen was nominated to High Level Support Team for HPC-FF.

Jukka Heikkinen is a Comments Editor of Physica Scripta.

Rainer Salomaa is the Tekes administrative contact person in EFDA JET matters.

Hannu Juuso is an Industry Liaison Officer for F4E and Pertti Pale is a consultant for Fusion-Industry matters.

2.7 Public Information Activities

Inauguration of the ITER Divertor Test Facility (DTP2) at VTT in Tampere was the main fusion PI/PR occasion in 2009 (Figure 2.1). It attracted a large number of Finnish and European media including the main national TV channels and newspapers. Over 20 hits in Finnish media were recorded. The press conference was carried out in collaboration with the EU Commission. The presentations were given by Octavi Quintana Trias (Director, Euratom), Norbert Holtkamp (Principal Deputy Director, ITER IO), Didier Gambier (Director, F4E) and Erkki Leppävuori (Director General, VTT). Nearly 100 guests representing Finnish and European research institutes, agencies and industries participated in the inauguration and related seminar and the occasion can be considered as a great success.

Figure 2.1. Press conference during the DTP2 Inauguration at VTT Tampere in January 2009. Bihand table from left: Erkki Leppävuori, VTT, Director General, Octavi Quintana Trias, Euratom, Director, Norbert Holtkamp, ITER IO, Principal Deputy Director, Didier Gambier, Director, F4E and Olli Ernvall, VTT, Communications Director (Photo: Anton Halas).

Helsinki University of Technology (TKK) and VTT Technical Research Centre of Finland proposed to host the EPS Conference on Plasma Physics in Finland in July 2013. EPS Plasma Physics Board accepted the proposal by TKK and VTT. The venue is Dipole Congress Centre in Otaniemi Campus just a few kilometres from the downtown Helsinki. The chair person of the Local Organising Committee is Mrs. Taina Kurki-Suonio (Aalto University, TKK).

The Annual Fusion Seminar of the Association Euratom-Tekes was organised by the Estonian Research Unit and took place in Pärnu, Estonia, 3–4 June 2009. Over 50 scientists and engineers participated in the Seminar. The seminar gave a review of the Finnish and Estonian fusion research activities in 2008–2009. The chairman of the EFDA Diagnostics Topical Group, Tony Donne from FOM Rijnhuizen gave an invited talk on ITER diagnostics and preparations of European contributions. The *Fusion Yearbook 2008*, Annual Report of the Association Euratom-Tekes, VTT Publication **709** (2009) 132 p. was published in the Annual Seminar.

The brochure "*Fusion and Industry together for the Future*" by the EU Commission was translated in Finnish "*Fuusio ja teollisuus palvelevat yhdessä tulevaisuutta*". Finnish industry and fusion technology R&D are well represented in the brochure which will be widely distributed in Finland.

Lecture course "*Introduction to Plasma Physics*" (S. Karttunen) and "*Fusion Technology*" (S. Karttunen, J. Heikkinen and R. Salomaa) were given in the Spring Semester 2009 at the Helsinki University of Technology. Open day on fusion research at VTT was held for high school physics classes on 18 March 2009.

TKK and VTT organised the 3rd Finnish–German Workshop on *Materials Migration in Fusion Devices* in Tervaniemi, Finland, 29–30 January 2009 and in the Finnish–Russian Seminar on *High Temperature Plasma Physics*, Espoo, Finland, 9–11 December 2009.

In addition, several newspaper articles and interviews on fusion energy and ITER were published in 2009.

2.8 Funding and Research Volume 2009

In 2009, the expenditure of the Association Euratom-Tekes was about 4,868 million € including Staff Mobility actions and F4E & ITER contracts (see Figure 2.2). A clear reduction in the CoA and EFDA expenditure is compensated by one large F4E Grant (DTP2) plus a smaller ITER Contract. Still two teams with strong EFDA Technology background (welding and welding robots) were left without contracts in 2009.

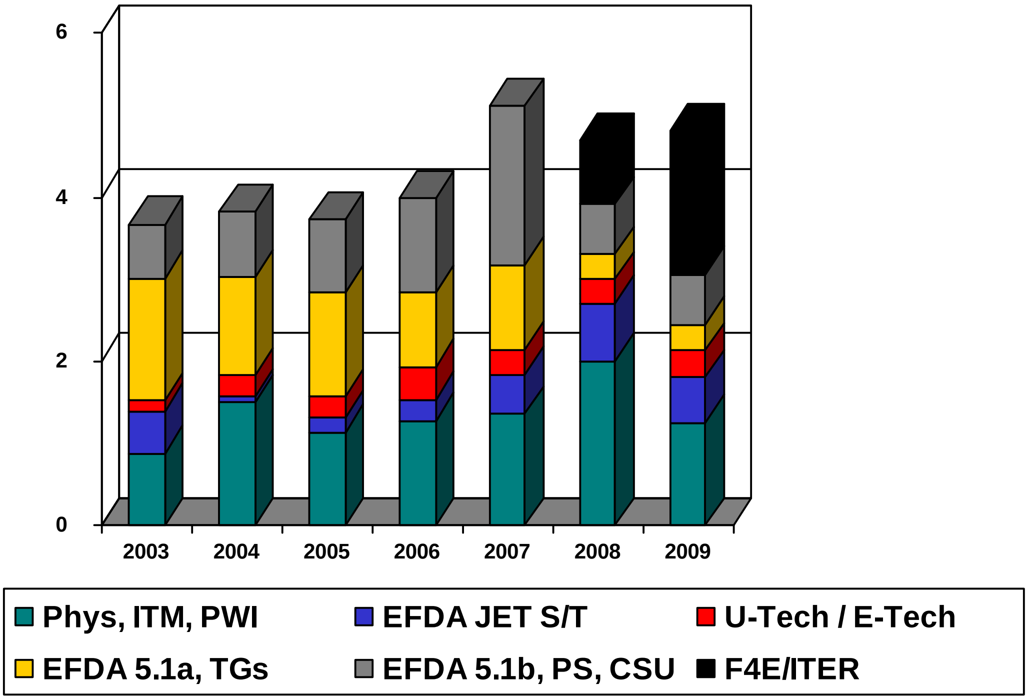


Figure 2.2. Expenditures (in Mio €) of the Association Euratom-Tekes for different physics and technology R&D activities in 2003–2009.

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, TKK, TUT, UH, LUT and UT) and industry. The expenditures were distributed among various activities as following:

- Fusion Physics including Task Forces ITM and PWI 26%
- EFDA JET activities – 11%
- Emerging Technology – 7%
- EFDA Topical Group Tasks – 7%
- Priority Support activities in TF ITM and PWI, TGs Activities and Goal Oriented Training including EFDA Fellowship – 13%
- F4E Grant & ITER contract – 36%
- Staff Mobility expenditure in 2009 was 107 k€.

The total volume of the 2009 activities was about 45 professional man-years.

3. EFDA FUSION PHYSICS AND MATERIALS RESEARCH

Institute: **VTT Technical Research Centre of Finland**

Research scientists: Dr. Seppo Karttunen (Head of Research Unit), Dr. Markus Airila, Dr. Jukka Heikkinen (Project Manager), MSc. Seppo Koivuranta, Dr. Jukka Kyynäräinen, Dr. Jari Likonen (Project Manager), Dr. Pekka Moilanen, Dr. Tuomas Tala (TFL Transport at JET), MSc. Seppo Tähtinen
Visiting scientist: Francisco Ogando (from UNED, Spain)
Student: Elina Kuisma

Institute: **Helsinki University of Technology (TKK; from 2010 the Aalto University School of Science and Technology)**
Department of Applied Physics, Advanced Energy Systems

Research scientists: Prof. Rainer Salomaa (Head), Dr. Pertti Aarnio, MSc. Leena Aho-Mantila, MSc. Otto Asunta, Dr. Mathias Groth, Dr. Antti Hakola, MSc. Salomon Janhunen, MSc. Simppa Jämsä, Dr. Timo Kiviniemi, MSc. Tuomas Koskela, Dr. Taina Kurki-Suonio, MSc. Susan Leerink, Dr. Johnny Lönnroth (JOC secondee), MSc. Markus Nora, MSc. Antti Salmi (JOC secondee), Dr. Marko Santala, Dr. Seppo Sipilä
Students: Joonas Govenius, Eero Hirvijoki, Tuomas Korpilo, Ville Lindholm, Toni Makkonen, Antti Snicker

Institute: **University of Helsinki (UH)**
Accelerator Laboratory

Research scientists: Dr. Tommy Ahlgren, Dr. Carolina Björkas, Dr. Flyura Djurabekova, Dr. Kalle Heinola, Dr. Niklas Juslin, Prof. Juhani Keinonen (Head of Laboratory), prof. Kai Nordlund (Project Manager), MSc. Kenichiro Mizohata, Dr. Helga Timko, Dr. Petra Träskelin and MSc. Katharina Vörtler

Companies: **Diarc Technology, Oxford Instruments Analytical**

Collaborators: **CCFE, IPP Garching, SCK-CEN, University of Tartu and EFDA JET Contributors**

3.1 Introduction

The fusion physics work has been performed in close co-operation between VTT Technical Research Centre of Finland and Helsinki University of Technology (TKK). Participation in the EFDA JET and EFDA Workprogrammes is the first priority in the fusion physics activities of the Association Euratom-Tekes. Physics emphasis in the S/T Order and Notification work related to the experimental campaigns C26–C27 of the JET Workprogramme 2009 and in the AUG programme at IPP Garching in co-operation with other Euratom Associations. Main topics were transport and MHD studies, plasma-wall interactions and diagnostics. Dr. Tuomas Tala from VTT was a Task Force leader for Task Force transport. Two persons were seconded to the CCFE JOC team for the code development work. The fusion plasma simulation groups at VTT and TKK provide an important modelling and support centre in fusion physics, code development and plasma engineering for the European Fusion Programme and ITER.

The second focus activity covers particle exhaust and plasma-wall interaction, related experiments at JET and ASDEX Upgrade, surface analyses of plasma facing materials and samples supported by computer modelling of erosion and material transport in scrape-off-layer (SOL). Advanced coatings, wall diagnostics with smart tiles and plasma processing of materials are carried out in collaboration with industry.

3.2 Energy and Particle Confinement and Transport

3.2.1 The dependence of inward momentum pinch on density peaking using two different experimental techniques on JET

EFDA JET Activity:	JW8-O-TEKE-17 and JW8-N-TEKE-20
Principal Tekes scientist:	T. Tala, Tekes – VTT
Collaboration:	EFDA-JET Contributors

The study of plasma rotation and momentum transport has gained interest over the last few years as rotation is thought to play an important role in the stability of tokamak plasmas. Furthermore, it may affect transport properties via the stabilization of turbulence. A proper understanding of all aspects that affect the rotation in tokamak plasmas, in particular momentum transport and sources of rotation, is therefore important if one wants to make an accurate prediction of the rotation in ITER.

Experiments where the Neutral Beam Injection (NBI) power and torque were modulated at varying frequencies between 6Hz and 12Hz have been performed on JET. Modulation allows us to separate the diffusion and pinch terms which from the steady-state data is impossible. The NBI induced modulated torque has been calculated with TRANSP transport code. Passing ions transfer toroidal angular momentum to the bulk plasma by collisions that is a slow process, whereas trapped ions transfer their momentum by $\boldsymbol{j} \times \boldsymbol{B}$ forces which is practically instantaneous ($\boldsymbol{j}$ denotes displacement current density due to finite banana orbit width and $\boldsymbol{B}$ magnetic field). The amplitudes and phases of these two calculated torque components are shown in Figure 3.1 (left frame) for JET shot no. 73701.

The novel transport modelling methodology adopted in this study to determine the momentum diffusivity and pinch uses the following 3 steps: step 1, calculate the effective ion heat diffusivity $\chi_{i,eff}$; step 2, vary the Prandtl number P_r (the ratio of momentum to ion heat diffusivity) value and its radial profile to fit the simulated phase of the modulated rotation to the experimental phase profile; step 3, vary v_{pinch} to best fit also the simulated amplitude of the modulated toroidal rotation to the experimental data, simultaneously also matching the steady-state. Step 2 leads to a rather precise identification of the acceptable range of P_r values. This resolves the indeterminacy associated with the analysis of only the steady-state profile, as the latter can be reproduced by an unlimited number of possible combinations for χ_ϕ and v_{pinch} yielding the same $\chi_{\phi,eff}$. Once P_r is identified, step 3 allows us to identify v_{pinch} needed to reproduce the steady-state rotation and amplitude with the chosen P_r value.

Figure 3.1 shows the need to have an inward pinch in order to reproduce the amplitude and phase of the modulated toroidal rotation. The case with the low Prandtl number and without the pinch (Figure 3.1 centre frame) has far too high predicted phase values while the case with the high Prandtl number and pinch (Figure 3.1 right frame) has the phase values much closer to those of the experiments. The same conclusion can be drawn from the 2nd harmonic data. Results from several JET shots using this technique have demonstrated the existence of a significant inward momentum pinch (of the order of 20 m/s) and Prandtl numbers between 0.5 and 2. As the next step, the parametric dependencies of the pinch and Prandtl numbers were studied. The momentum transport theory predicts that the magnitude of the inward pinch depends most strongly on density gradient length R/L_n (density peaking factor). The experimental results using the NBI modulation technique show that indeed in plasmas with larger R/L_n the pinch is also larger, the dimensionless pinch number Rv_{pinch}/χ_ϕ increasing roughly from 4 to 8 when going from $R/L_n = 1$ to $R/L_n = 4$.

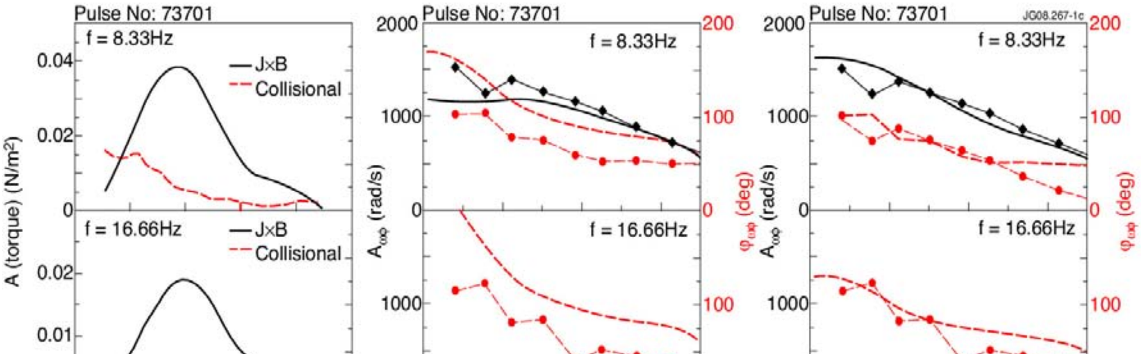


Figure 3.1. (Left frame) Different components of the modulated torque for JET shot no. 73701 for 1st harmonic (upper frame) and 2nd harmonic (lower frame). (Centre frame) Experimental amplitude (black solid with squares) and phase (red dashed with squares) and simulated amplitudes $A_{\omega,\phi}$ (black solid) and phases $\varphi_{\omega,\phi}$ (red dashed) of modulated ω_ϕ with $P_r = 0.25$ and $v_{pinch} = 0$ for 1st harmonic and 2nd harmonic. (Right frame) Experimental amplitude (black solid with squares) and phase (red dashed with squares) and simulated amplitudes $A_{\omega,\phi}$ (black solid) and phases $\varphi_{\omega,\phi}$ (red dashed) of modulated ω_ϕ with $P_r \approx 1$ and v_{pinch} increasing radially from 0 (centre of the plasma) up to 25m/s at $\rho = 0.8$ for 1st harmonic and 2nd harmonic.

In addition to NBI modulation technique, an independent method to study the pinch and Prandtl number was performed. It is based on the rotation database that contains entries from various operational scenarios for which the average rotation and momentum source and transport properties are determined in steady-state phases of the discharge. An estimation of the momentum pinch was made for all entries in the JET rotation database by assuming that $\chi_\phi = \chi_i$ and the difference between the measured $\chi_{\phi,\mathrm{eff}}$ and $\chi_{i,\mathrm{eff}}$ is due to the momentum pinch. The analysis shows values for H-mode discharges the pinch values range from $0.3\mathrm{m/s} < v_{\mathrm{pinch}} < 17\mathrm{m/s}$, the pinch numbers being approximately $2 < Rv_{\mathrm{pinch}}/\chi_\phi < 10$. This is illustrated in Figure 3.2. An increasing trend with the peaking of the density profile R/L_n was found. This result is very consistent with that found using the NBI modulation technique. Having two completely independent methods yielding similar results makes the extrapolation of the toroidal rotation profile with respect to density profile peaking R/L_n to ITER much more robust.

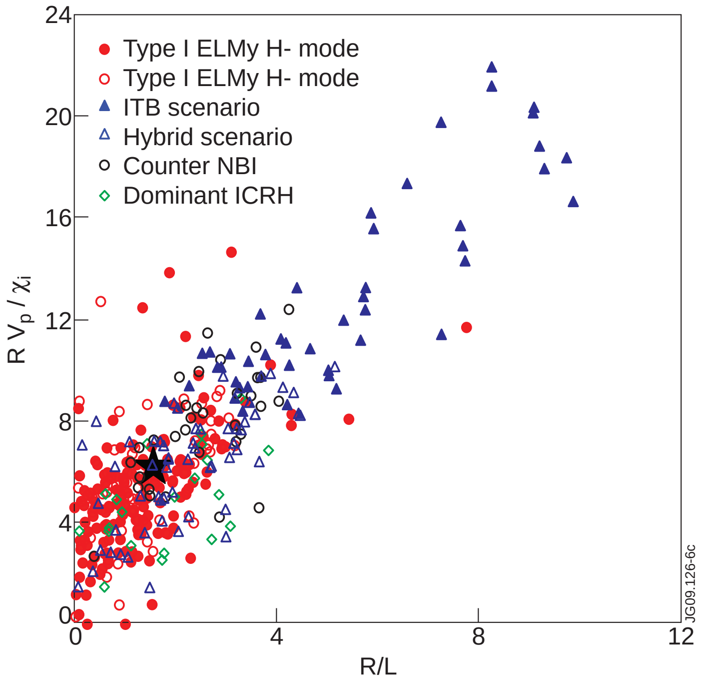


Figure 3.2. The normalised pinch velocity, RV_p/χ_i calculated for the entire JET rotation database for various operational scenarios, under the assumption that $\chi_\phi = \chi_i$ plotted versus the normalised inverse density gradient length R/L_n. Note that all parameters in the JET rotation database are determined at $\rho = 0.5$ (averaged from $\rho = 0.2–0.7$).

3.2.2 Identity physics experiment on internal transport barriers between JET and JT-60U

EFDA Activity:	JW8-O-TEKE-17 and IEA Large Tokamaks IA
Principal Tekes scientist:	T. Tala, Tekes – VTT
Collaboration:	EFDA-JET Contributors

Internal transport barriers or ITBs in fusion plasmas are a phenomenon where turbulence driven transport is locally reduced, causing an improvement in the confinement properties. ITBs are considered as a possible way to enhance the energy confinement in

Advanced Tokamak scenarios that aim to provide fully non-inductive operation of ITER at moderate plasma current but at high pressures. The study of transport barriers may also give insight in the physics of turbulence and transport in fusion plasmas in general. Different physical mechanisms are thought to enable the formation of transport barriers. The mechanism in one device may differ from that in others, making a comparison of observations not always easy. Hence, for the first time a series of experiments have been carried out at Japanese JT-60U tokamak and JET in order to find common characteristics and differences in the process of ITB formation, with the aim to improve the understanding of the physics behind the triggering and sustainment of transport barriers.

In order to study the impact of plasma rotation and rotational shear on ITBs between JET and JT-60U, a series of discharges with identical plasma profiles, but with different plasma rotation were performed by balancing the NBI torque on JT-60U and varying toroidal field ripple on JET. In Figure 3.3.a, a rough overview is given of the obtained maximum ITB strength and rotation properties of the various JET and JT-60U cases. Firstly, the dimensionless Mach number, i.e. the plasma rotation normalised to the thermal velocity, is used to characterise the rotation. Clearly a large variation in Mach numbers was obtained. Before comparing the observations in JT-60U and JET it is important to have a clear definition of an ITB. Here the steepness of the ion temperature profile caused by the ITB is defined by ρ^*_{Ti}, i.e. the ratio of the ion Larmor radius at the sound speed and the ion temperature gradient length. A value of $\rho^*_{Ti} > 0.014$ is the criterion used to identify an ITB for both JET and JT-60U.

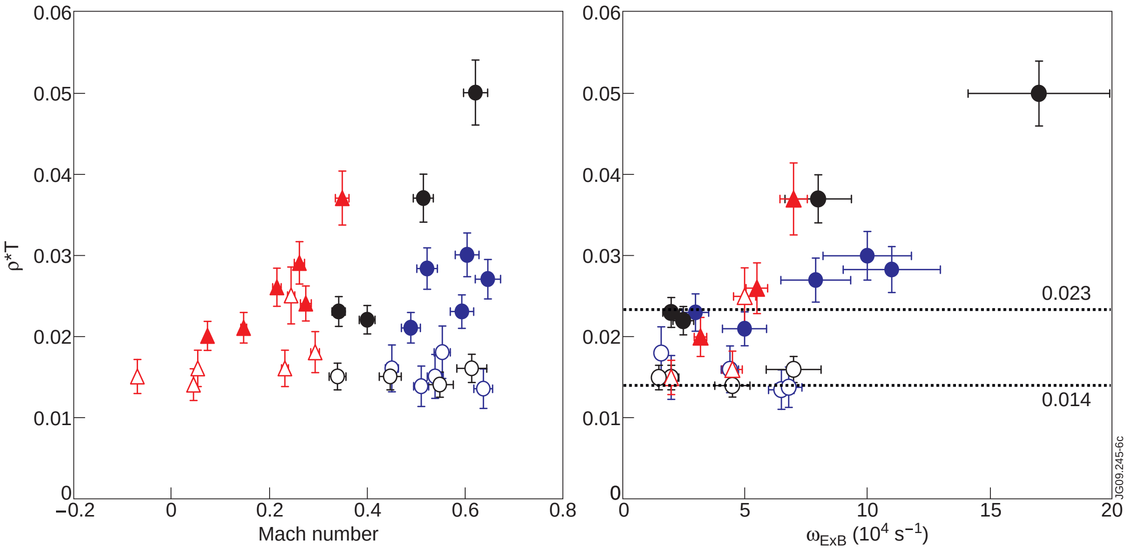


Figure 3.3. a) The value of ρ^*_{Ti} plotted versus the central Mach number for various JT-60U (red triangles) and JET (black/blue dots) cases. b) The same data but plotted versus the rotational shear, ω_{ExB} in the vicinity (radial) of the ITB. The open symbols show the values at the time the ITB is triggered, while the close symbols are at the time of maximum ITB strength.

The Mach number may, however, not be the relevant parameter. In Figure 3.3.b the ITB strength ρ^*_{Ti} is plotted versus the rotational shear ω_{ExB}, calculated with the JETTO code assuming neoclassical poloidal rotation. Similar values of rotational shear are found in JT-60U and JET. The figure shows that ITBs are always triggered, independently of the rotational shear ($1 \cdot 10^4 s^{-1} < \omega_{ExB} < 2 \cdot 10^5 s^{-1}$). Moreover, weak ITBs ($0.014 < \rho^*_{Ti} < 0.023$) can always be found in plasmas with reversed magnetic shear. This suggests that overall rotational shear, is not the dominant factor in the triggering of these transport barriers. But strong ITBs ($\rho^*_{Ti} > 0.023$) only develop in JT-60U and JET plasmas that have sufficient rotational shear, i.e. $\omega_{ExB} > 4\text{–}5 \cdot 10^4 s^{-1}$ in the vicinity of the ITB location. This result indicates that although ITBs will be triggred easily in ITER, it may be challenging to sustain strong ITBs in ITER where the toroidal rotation gradient may be significantly smaller than that in JET and JT-60U.

3.2.3 Dependence of plasma performance on the characteristics of the H-mode pedestal

EFDA Activity:	JW8-O-TEKE-17 and JW8-N-TEKE-20
Principal Tekes scientist:	J. Lönnroth, Tekes – TKK
Collaboration:	EFDA-JET Contributors

The sensitivity of the MHD stability of the pedestal to small changes in the pedestal plasma profiles has been studied. It has been demonstrated that very different stability outcomes easily fit within the error bars of even the best available plasma profile data. It has been shown that the MHD stability of the pedestal and, hence, the level of achievable pressure gradient within the pedestal depend sensitively on the shapes of the pressure gradient profile and the toroidal current density profile, the latter of which follows indirectly from the former. Stability is, in particular, sensitive to the radial location of the maximum pressure gradient. The further inside the separatrix the maximum pressure gradient is located, the larger a level of pressure gradient does the plasma appear to be able to sustain.

Figure 3.4 shows the main result of this study, a cluster of marginally unstable plasmas. The figure contains the radial profiles of the pressure, normalized pressure gradient and self-consistently calculated toroidal current density of five plasmas derived from the plasma profiles of JET discharge 73247, all of which are marginally unstable. The toroidal current density profiles have been evolved to a steady state by running the 1.5D core transport code JETTO interpretatively with respect to the given plasma profiles. MHD stability analysis has then been carried out with the ideal linear MHD stability code MISHKA-1. The figure shows that the further inside the separatrix the maximum pressure gradient is located, the larger a level of pressure gradient can the plasma sustain. Because of diagnostic limitations, it is, however, difficult to verify the proposed trend in experimental data.

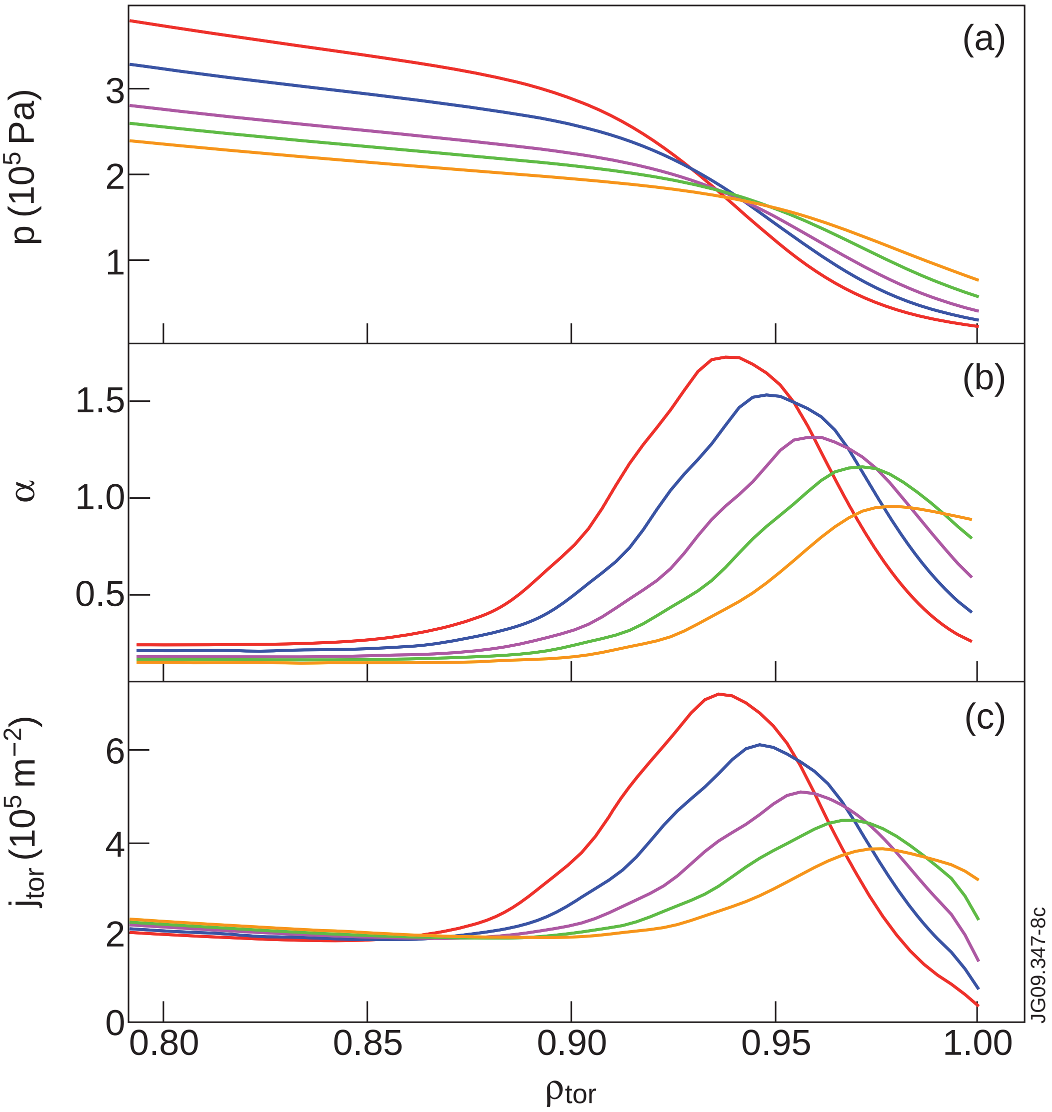


Figure 3.4. Radial profiles of (a) total pressure, (b) normalized pressure gradient α, (c) toroidal current density derived from the plasma profiles of JET pulse 73247 and found to be marginally unstable. The profiles in the figure have been obtained by multiplying the original electron density, electron temperature and ion temperature profiles by equal factors and applying equal radial shifts to them. The most inward location of the pressure gradient maximum corresponds to the measured experimental location in pulse 73247. The corresponding level of pressure gradient in the figure exceeds the experimental level. The four other sets of profiles correspond to radial shifts of 0.5 cm, 1.0 cm, 1.5 cm and 2.0 cm inwards in outer midplane co-ordinates. The profiles have been plotted as a function of ρ_{tor}, the square root of the normalized toroidal flux.

The study also reveals a couple of other trends. The further inside the separatrix the maximum pressure gradient is located, the wider are the eigenfunctions of the unstable modes and the lower does the toroidal mode number of the most unstable mode appear to be. The latter trend appears to be less robust, however, because the most unstable mode number depends strongly on the distribution of rational surfaces, i.e. on the safety factor *q*.

3.2.4 Implications of pedestal MHD stability limits on the performance of ITER Scenario 2

EFDA Task Force ITM:	WP09-ITM-09
Principal Tekes scientist:	J. Lönnroth, Tekes – TKK
Collaboration:	EFDA-JET Contributors

The implications of pedestal MHD stability limits on the fusion performance of ITER Scenario 2 plasmas have been studied under the auspices of the ITER Scenario Modelling Group of the EFDA Integrated Tokamak Modelling (ITM) Task Force. Scenario 2 is the baseline ELMy H-mode scenario for ITER operation. Using JETTO, predictive transport simulations corresponding to ITER Scenario 2 plasmas have been set up based on data gathered from the ITER Organization and the ITER Team preceding it. The marginally stable level of pedestal pressure gradient has been determined by running MISHKA-1 on a series of transport simulations with varying levels of pedestal pressure gradient. The marginally stable level has then been used in predictive transport simulations aiming to predict the achievable fusion power in Scenario 2. The pedestal width has been predicted with the EPED1 pedestal model by P. Snyder *et al.*, Nucl. Fus **49** (2009), in which it scales as $\beta_{pol}^{1/2}$. Transport has been modelled with the theory-based GLF-23 transport model. The simulations indicate that it will probably be very difficult, if not impossible, to reach a projected fusion power enhancement factor of $Q = 10$ in ITER Scenario 2, the baseline scenario. The result may thus have significant consequences.

3.2.5 Quiescent H-Mode operation at AUG

Research scientists:	T. Kurki-Suonio, Tekes – TKK
Collaboration:	ASDEX Upgrade Team

Edge Localized Modes (ELMs) are characteristic for high-performance H-mode plasmas. Unfortunately, ELMs can provide unacceptably high power loads (tens of MW) to plasma-facing components and thus are a potential threat for the successful operation of a fusion reactor. In a so-called Quiescent H-mode (QHM), however, the ELMs are replaced by a more benign, continuous edge MHD activity that can still provide the necessary particle exhaust from the fuel plasma. QHM operation was first observed at the DIII-D tokamak, US, but it has also been reproducibly produced at ASDEX Upgrade.

Originally QHM operation was only obtained with counter-injected neutral beams. Such operation is unlikely to be reactor relevant because it leads to high, localized heat loads to the wall directly from the beams. However, in 2008 DIII-D serendipitiously encountered QHM operation with co-injected beams re-raising hopes for ELM-free operation of fusion plasmas. This motivated re-trying QHM operation with co-injection also at ASDEX Upgrade.

In the fall 2009, after carefully consulting Keith Burrell at DIII-D, we attempted QHM operation with co-injected neutral beams at ASDEX Upgrade. Low density is known to be a prerequisite for QHM, so in two separate sessions right after boronisation we carried out several shots varying such external factors as beam direction, safety factor and ECRH, the last being highly controversial: edge ECRH lowers the collisionality but, at the same time, it has been found to trigger ELMs. In these shots the target edge density value of 2×10^{-19} m^{-3} could not be reached but remained at least twice as high. Consequently, also the target temperature could not be achieved and the collisionality remained probably too high for QHM operation. However, significant changes in the ELM behaviour were observed, some shots exhibiting even ELM-free phases albeit classical ones where the density continuously rises. Also MHD signatures typical of QHM operation were observed, but this activity was probably too weak to maintain steady state density.

In conclusion it appears that the reason for the different edge MHD behaviour between DIII-D and ASDEX Upgrade lies in the different wall pumping: DIII-D still has carbon walls with high pumping capability thus allowing lower densities than ASDEX Upgrade that, over the years, has been converted to a full-tungsten machine in preparation for ITER.

3.2.6 Gyrokinetic simulation of plasma edge

EU Activity:	DEISA
Research scientists:	J. Heikkinen, Tekes – VTT S. Janhunen, T. Kiviniemi and S. Leerink, Tekes – TKK

The ultimate objective of this project is the proposition of plasma configurations with enhanced confinement properties in comparison to the current ones. Turbulence has been found to be a principal factor leading to the confinement leaks detected in actual tokamak devices. Reducing plasma turbulence is therefore a main goal for tokamak designs, especially when having in mind long operation cycles, like ITER and the following devices in the way to a commercial reactor.

In L-H transition of the edge transport, a transport barrier is created by external heating which is presently considered as an important part of reactor plasma operation. The enhanced confinement regimes resulting from flow shear stabilization of turbulence are of considerable scientific interest; systems seldom self-organize to a higher energy state, with reduced turbulence and transport, when an additional source of free energy is applied. Such a self-organization together with ion orbit effects may well be responsible for the L-H transition, but the very mechanism behind it is still uncovered.

In the present work, a global 5D full *f* gyrokinetic particle-in-cell simulation code ELMFIRE is used. The particle orbits are solved in time in the toroidal configuration in a 5-dimensional phase space, and a 3D electrostatic potential solver is included to capture turbulence that arises from ***ExB*** convective cells in the presence of pressure gradient and toroidicity in the plasma, resulting in enhanced transport. Being a particle code solving for the full distribution of electrons and ions in 5D phase space, it breaks new ground in gyrokinetic turbulence modelling. Electron parallel acceleration and ion polarization motion are solved for implicitly.

Longer simulations (up to 500 μs) for the ASDEX Upgrade pre-pedestal region were achieved and were important in order to see the orbit effect and transport relaxation with more realistic parameters. Importance of proper heating model was pointed out in determining time behaviour of transport coefficients. This was further analysed to strive towards steady heat flow conditions from the core to edge regions. It was found that no clear sign of L-H transition was in the simulations. On the other hand, the short simulation time with the accompanying effects from the initial conditions still complicate the simulation effort. In a smaller tokamak, FT-2, the confinement transition was seen and turbulence was well characterized with the experimental measurements by the Doppler reflectometry.

3.2.7 ELMFIRE simulations of TEXTOR turbulence and comparison with experiment

EFDA TG Activity:	WP09-TGS-01
Research scientists:	J. Heikkinen, Tekes – VTT S. Janhunen and T. Kiviniemi, Tekes – TKK
Collaboration:	TEXTOR Team

The aim of this task is to compare the first principle gyrokinetic ELMFIRE simulations to the experimental studies of plasma turbulence in Textor tokamak. Textor is very suitable for ELMFIRE simulations due to its circular geometry, relatively small size but relevant power. At Textor, a set of edge turbulence diagnostics exists such as 35 keV Li-beam which has proven its density profile and turbulence measurement capability in the 0.1% relative fluctuation amplitude range and microsecond timescale. Other diagnostics include reflectometry, supersonic He-beam, thermal Li-beams, probes. Very recently fast beam poloidal scanning can resolve the poloidal movement of structures at least on the millisecond timescale. In order to extent the simulation time long enough, simulation was focused on the cm region at the plasma outer confinement region (r/a > 0.8) which already requires significant amount of computing power. Spatial resolution of the simulation is more accurate than in experimental measurements as the Larmor radius needs to be resolved.

The full f nonlinear gyrokinetic particle-in-cell code ELMFIRE was used to simulate the Ohmic case for TEXTOR measuring the density fluctuation amplitudes, spectra and -temporal correlation function. From correlation analysis in time and poloidal direction the velocity of turbulent structures was estimated. In the simulation this roughly corresponds to the ***ExB*** velocity indicating that for this case there is no significant phase velocity involved. This was further confirmed using GS2 code. In the experimental measurements there is some indication of the inclination of turbulent structures but it is not yet sure if this due to radial propagation of the fluctuations or inclination of the eddy itself. The preliminary wavelet analysis shows inclination in qualitative agreement with experiments but the origin of the inclination is not yet explained.

3.3 Energetic Particle Physics

3.3.1 Simulations of fast ion losses for ITER with 3D wall

EFDA TG Activity:	WP08-09-DIA-01
Research scientists:	T. Kurki-Suonio and T. Koskela, Tekes – TKK
Collaboration:	M. Garcia-Munoz and ASDEX Upgrade Team

In 2009, the modelling of fast ion losses in ITER reported in T. Kurki-Suonio *et al.*, Nuclear Fusion **49** (2009) was continued in order to obtain reliable results even in the presence of non-periodic perturbations. These perturbations are expected to be found in ITER due to the Test Blanket Modules (TBMs), which contain a significant amount of ferritic material. Figure 3.5 shows how the presence of the TBM bends the normally straight flux surfaces.

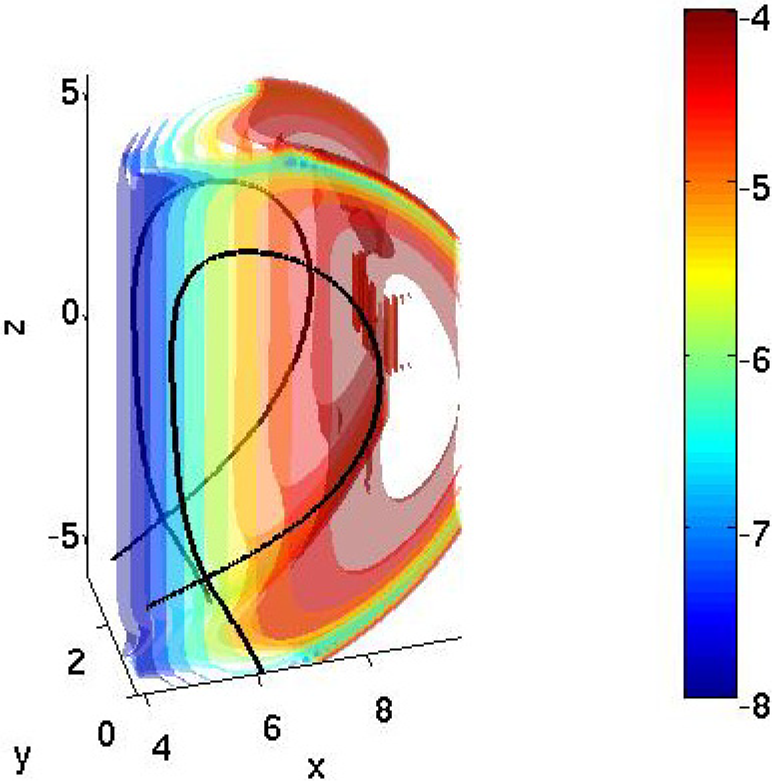


Figure 3.5. Iso-surfaces of the toroidal magnetic field Bphi. The TBM can be seen on the right hand side of the x-axis where it has been modelled by rectangular blocks.

The orbit following Monte Carlo code ASCOT was used to calculate the fast ion power loads on the ITER first wall in reference operating scenario 4. Discrete, three-dimensional vacuum magnetic background, calculated by K. Shinohara *et al.*, Fusion Engineering and Design **84** (2009) and the ITER 2-D equilibrium were used as background data. The vacuum field includes the magnetic ripple and the local magnetic perturbations caused by the three TBMs. A fully three-dimensional ITER wall model is used, where protruding wall elements such as port limiters can be simulated.

The wall distribution of the peak heat fluxes was compared between a 2-D wall with no limiters, a 3-D wall with two limiters placed at equatorial ports 8 and 17 and a 3-D wall with poloidal limiters between each port. The absence of limiters leads to hot spots on the first wall tiles corresponding to the ripple period, while the limiters are found to receive the bulk of the fast ion flux thus protecting the regular wall tiles.

In order to benchmark the simulations to experiments, there has been collaboration with Dr. M. Garcia-Munoz at IPP Garching. A 3-D wall model for ASDEX Upgrade has been obtained from Dr. Lunt and then processed for use in ASCOT. Also a synthetic FILD-diagnostic has been developed into the code. With the improvements, ASCOT is able to model the signal measured by the FILD operating at AUG. Preliminary results have been obtained from simulations of NBI prompt losses, but further work is required to obtain definite results.

3.3.2 Simulation of fast particle population and comparison with experiments

EFDA TG Activity:	WP08-09-TGS-01
Research scientists:	T. Kurki-Suonio, S. Jämsä and O. Asunta, Tekes – TKK
Collaboration:	ASDEX Upgrade Team

This EFDA task called for *a comparison of several techniques for confined alpha particles at a present device... the comparison should include a number of diagnostics from the following set: CTS, FIDA, high resolution neutron spectroscopy, gamma spectroscopy, and NPA.* ASDEX Upgrade has four (CTS, FIDA, high resolution neutron spectroscopy and NPA). Furthermore, the measurements of confined fast ion population can be supplemented by the FILD diagnostic, which gives time-resolved information on the energy and pitch angle of the lost ions.

An ASDEX Upgrade scenario for alpha particle simulation experiments where the capabilities of all involved diagnostics can be best exploited was developed in concert with the ASDEX Upgrade team. The tool-chain to produce input data to ASCOT was refurbished to be more flexible and quicker. Benchmarking of ASCOT simulations against NPA measurements continued and a synthetic FILD diagnostic was introduced to ASCOT. Fast ion distributions for ASDEX Upgrade were calculated with ASCOT and compared to earlier CTS measurements and to the fresh FIDA-diagnostics M. Salewski *et al*., "*Comparison of fast ion collective Thomson scattering measurements at ASDEX Upgrade with numerical simulations*", Nucl. Fusion (accepted for publication). The CTS was off-line during the 2009 campaign, and the actual simulation experiments were not performed in the full extent, but preliminary shots intended also for NPA and FIDA studies were done.

3.4 Theory and Modelling for ITER and Code Development

Research scientists:	J. Heikkinen, Tekes – VTT O. Asunta, S. Janhunen, T. Kiviniemi, S. Leerink, J. Lönnroth, A. Salmi, A. Snicker and S. Sipilä, Tekes – TKK

3.4.1 Diagnostic development and cross verification of IMP#4 codes (ELMFIRE)

EFDA Task Force ITM: WP09-ITM-IMP4

Good diagnostic tools in plasma microturbulence codes are relevant for understanding plasma behavior in the simulations but also for studying the accuracy of the numerical models used in the codes, and the development of a unified diagnostics is an integral part of IMP#4 collaboration. In line with the ITM requirements, diagnostic capabilities of ELMFIRE have recently been improved by a nonequispaced Fourier transform and new plasma diagnostics of intrinsic quantities such as plasma rotation, convective and conductive fluxes, velocity-space distributions for heat flux, and vorticity. Many of these and other quantities are assembled in a grid directly from the particle distribution function as velocity moments but some parameters, such as vorticity, are constructed from direct evaluation of derived fluid quantities. In addition to the new diagnostics, considerable effort has been put to improve the visualization of the diagnostic data. Interfacing the diagnostics of the code into the ITM Consistent Physical Object format applicable for the Kepler environment is underway.

In addition to the ITM requirements, a bootstrap current calculation has been implemented. The bootstrap current diagnostic enables to compare parallel current profile produced by ELMFIRE with the analytical neoclassical models, i.e., Sauter model and Hirshman-Sigmar full matrix formulation together with Shaing viscosity coefficients. Preliminary results show good agreement for the bootstrap current between ELMFIRE simulations and the neoclassical models.

The ITM IMP#4 benchmark (based on DIII-D) case for core turbulence codes has been investigated further, and the role of particle fluxes in conjunction with Boltzmann distributed (adiabatic) electrons in suppressing turbulence through unmitigated radial electric field growth in the absence of collisions has been assessed.

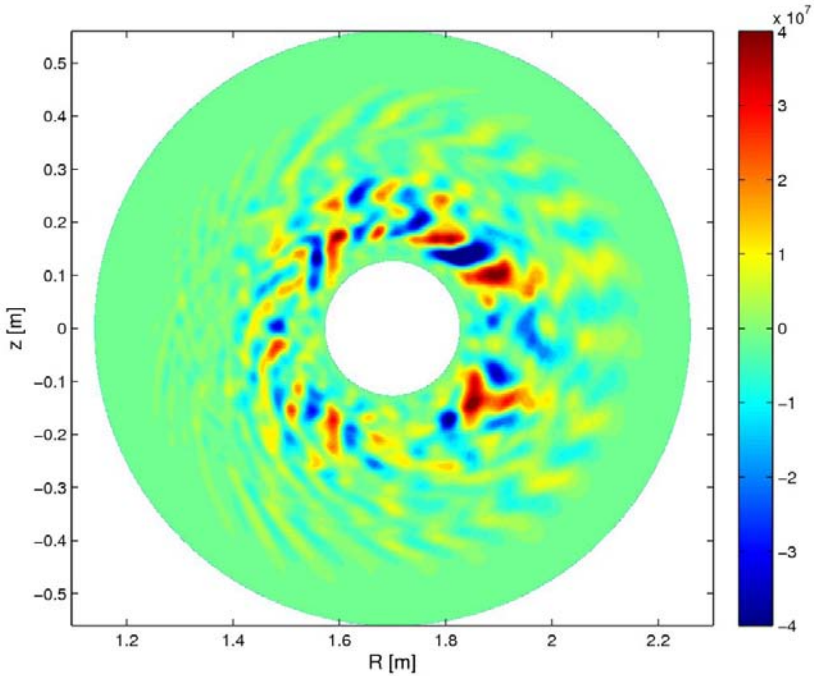


Figure 3.6. Radial heat flux obtained from ELMFIRE for the IMP#4 test case promptly after saturation of turbulent flow.

3.4.2 Gyrokinetic model for pedestal simulation

EFDA TGS Activity: WP09-TGS-02

The goal of this task is to extent the full f gyrokinetic codes ELMFIRE to the pedestal region. A major change that is needed to implement the pedestal region in the ELMFIRE code is the implementation of a more complex magnetic field background. Efforts on coupling the ELMFIRE code to a magnetic field solver are ongoing. However, after learning the CPU costs of the use of the magnetic solver the ELMFIRE code is also simultaneously studying the implementation of an analytical solution for the magnetic field including the pedestal and SOL (Boozer, Phys. Fluids **27** (1984)).

To check whether the accuracy of the ELMFIRE code, as programmed in the core version, is good enough for the pedestal analytical benchmark cases were done in cooperation with Dr. P. Catto from the Massachusetts Institute of Technology. A flux surface averaged simulation with constant ion and electron temperature profiles and a hyperbolic tangent pedestal profile for electron and ion density was performed. For these specific parameters there is an exact solution for the radial electric field where the pressure gradient should exactly cancel the potential gradient. When initializing the particles in their orbits with an radial electric field close to the analytical solution it was found that the radial electric field was indeed settling at the exact known analytical solution, indicating that the accuracy of the ELMFIRE code is good enough for the pedestal region. However when the value of the initialized electric field value was taken far from the analytical solutions the boundaries were getting unstable, leading to big instabilities. For pedestal simulations, therefore, the radial electric field will always have to be initialized reasonably close to its neoclassical value.

3.4.3 Gyrokinetic code benchmarking and validation

Experimental validation of the ELMFIRE code is performed in cooperation with the Ioffe institute in St Petersburg. Turbulence spectra of density fluctuations measured with Doppler Reflectometry at the FT-2 tokamak are compared to full f nonlinear gyrokinetic simulations by means of a synthetic Doppler reflectometry diagnostic.

The experimental and synthetic power spectrum of the Doppler reflectometer show good agreements in both the Doppler shift as well as the width of the power spectrum, indicating comparable rotation and spreading of the turbulence. The averaged radial electric field is shown to closely follow the neoclassical Hazeltine Hinton value and Geodesic Acoustic mode are clearly identified by the width of the spectra.

A benchmark effort between the ELMFIRE code and the full f gyrokinetic code XGC is ongoing. The XGC code and the ELMFIRE code are based on two different gyro kinetic approaches. The XGC code uses an explicit scheme for the polarization density where the ELMFIRE code relies on a implicit scheme. Benchmarking the two approaches would be an important check. To study the two approaches as good as possible it was chosen to use the most simple benchmark case. To do this however the analytical magnetic field model and the implicit kinetic electron model used in ELMFIRE code have to be implemented into the XGC code. The implementation is ongoing.

3.4.4 ELMFIRE development

The upgrade of the ELMFIRE code for the SOL region is ongoing. Significant effort has been done in order to construct an appropriate grid to treat the pedestal-SOL interface. An important development project was launched to test the conservation of toroidal angular momentum in ELMFIRE simulations. The validity of lower order gyrokinetic models has been recently challenged by theoreticians, and it is of interest to check for it with the ELMFIRE code.

3.4.5 ELM module to JETTO

EFDA Task Force ITM: WP09-ITM-IMP2

Development work on an ELM module for the European Transport Solver (ETS) has been carried out under the auspices of EFDA Task Force Integrated Tokamak Modelling. The new package relies heavily on ELM models used in the 1.5D core transport code JETTO provided by JET. These models have been in active use for many years already. The package includes simple *ad hoc* models, in which transport is enhanced arbitrarily in a specified region upon the violation of a critical pressure gradient or current density limit, but also slightly more sophisticated models, in which the ELM times, ELM amplitude and ELM duration are calculated self-consistently from a simple model of instability. At the end of 2009, the status of the work is that it is still awaiting formal agreement on the transfer of the modules involved.

3.4.6 ASCOT to ITM standards

EFDA Task Force ITM: WP09-ITM-IMP4

In 2009, the orbit-following Monte Carlo code ASCOT was installed on the EFDA-ITM Gateway computing platform. Work was initiated to make ASCOT compliant with the ITM input/output data standards. Importing data to the code as Consistent Physical Object (CPO) data structures was partially implemented, and a 2D equilibrium magnetic field was successfully read from the CPO data tree. The code for importing other necessary inputs such as plasma and neutral data was written, but testing had to be postponed as actual data was not yet available. The work will continue in 2010.

3.4.7 SOFI to Gateway

EFDA Task Force ITM: WP09-ITM-IMP5

The single-orbit-following implement SOFI was installed on the EFDA-ITM Gateway. As with ASCOT, the 2D equilibrium magnetic field was successfully read from the CPO, but the complete orbit CPO is needed for thorough testing of the implement.

3.4.8 ASCOT 3D NBI source

EFDA Task Force ITM: WP09-ITM-IMP5

The 3D NBI source module from ASCOT was separated into a stand-alone program that runs on the EFDA-ITM Gateway computers. A major part the work in 2009 was discussing and agreeing on the input and output data structures (CPOs) utilized by all the NBI source codes under the ITM framework. During 2009 the NBI-related CPOs were finalized and parts of the code importing the CPOs was written. Once all the input/output CPOs are available, the module will be rendered fully CPO-based.

3.4.9 Improvements to ASCOT code

EFDA Task Force ITM: WP09-ITM-IMP3

Microturbulence related diffusion coefficient: In MHD quiescent plasmas fast ion transport has been assumed to be dominated by neoclassical effects. However, NBI (Neutral Beam Injection) current drive experiments with the ASDEX Upgrade (AUG) tangential beams failed to demonstrate the predicted levels of off-axis current [S. Günter *et al*., Nucl. Fusion **47** (2007)], which led to questioning this assumption. The subsequent theoretical work has revealed that, unlike previously believed, microturbulence can induce additional transport of not just the bulk plasma but also the fast ions.

A theory-based model for anomalous diffusion due to microturbulence [T. Hauff, *et al.*, Phys. Rev. Lett. **102** (2009)] was included to ASCOT. The model has gone through intensive testing and is now ready for simulating the above mentioned AUG current drive experiments.

Full orbit integration: Until now, the fast ions has been traced using guiding centre simulations, see e.g. [1] and references therein, in which the fast gyration of the charged particle around the magnetic field line is averaged out. In the presence of a strong magnetic field ripple, the gradient length of the magnetic field becomes comparable to the Larmor radius of the fast ion breaking the guiding centre approximation. This also gives rise to some phenomena not seen in the guiding centre simulation. Moreover, near the 3D wall elements guiding centre simulations may be inaccurate.

To study these effects, ASCOT was enhanced by the full orbit integration procedure. At the hear of the procedures the leap frog Boris method which is used to advance the particle's velocity and location in time, as seen in Figure 3.7. Taking the finite Larmor effects into account by full orbit integration comes with a significant cost – the CPU consumption with the full orbit calculation is roughly 50 to 100 times (depending on several details) that of the guiding centre calculation. This makes it impossible to follow a large ensemble of fast ions throughout the whole slowing down process, i.e. around a 0.1 s, using the full orbit procedure.

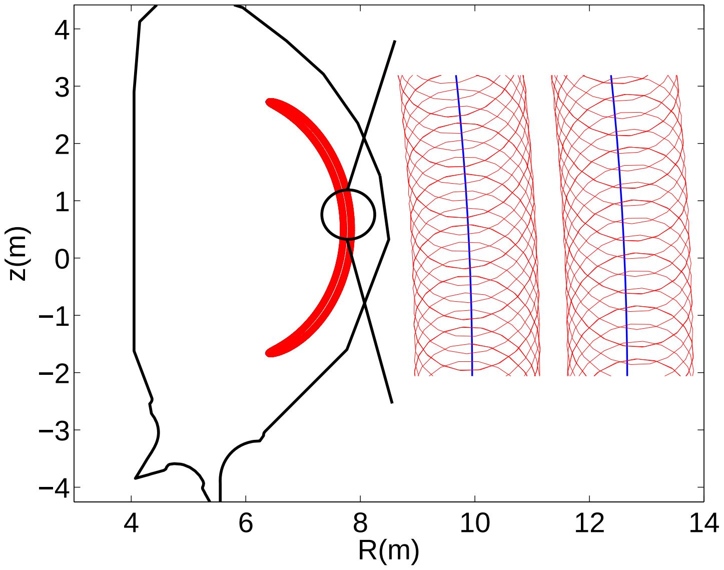


Figure 3.7. Trace of a 3.5 MeV alpha-particle with an initial pitch angle -0.3767. The magnetic background of ITER discharge # 585 was used. Guiding centre trace is in blue and full orbit trace in red.

During last year, the procedure was used to compare the ITER power loads calculated with the full orbit procedure to the earlier guiding centre simulations. It was found that the wall loads differ significantly in the presence of unmitigated magnetic field ripple whereas for optimized ripple scenarios the guiding centre simulation gives an accurate output.

Magnetic islands: ASCOT has been used to quantitative analysis of fast ion losses for several experiments. So far ASCOT has neglected the influence of all MHD instabilities. During last year, ASCOT was enhanced to include a magnetic perturbation causing magnetic island structures. The effect of magnetic islands is added to the equations of motion in the magnetic coordinates as additional terms including the magnetic perturbation [2]. The islands are allowed to rotate slowly, while the induced electric field is, at the moment, neglected.

The implementation has been tested by, e.g., plotting Toroidal Poincaré plots, see Figure 3.8 and will be applied to study fast ion losses in several experiments, especially ASDEX Upgrade and ITER. ASCOT, with its improved capabilities, serves as a perfect tool for these studies.

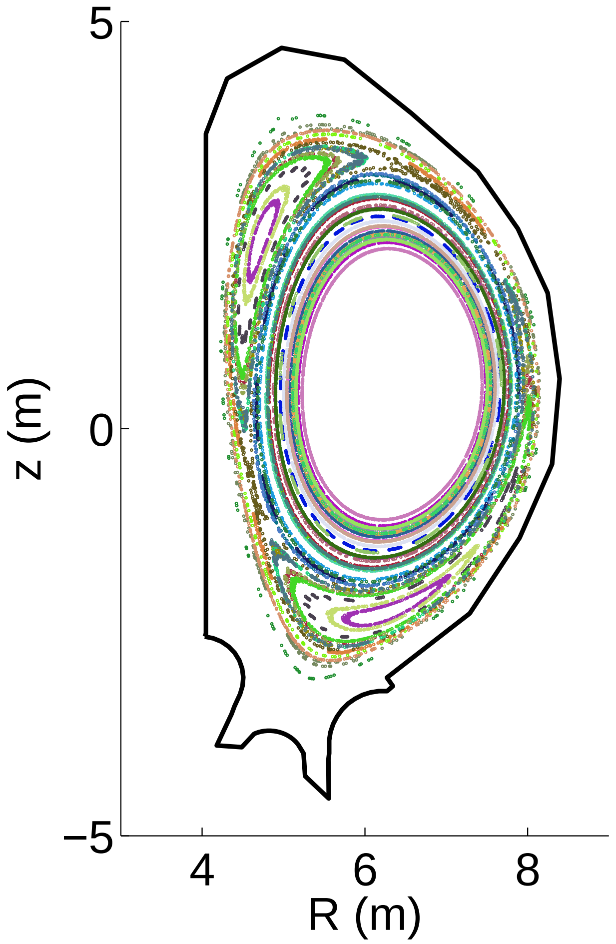
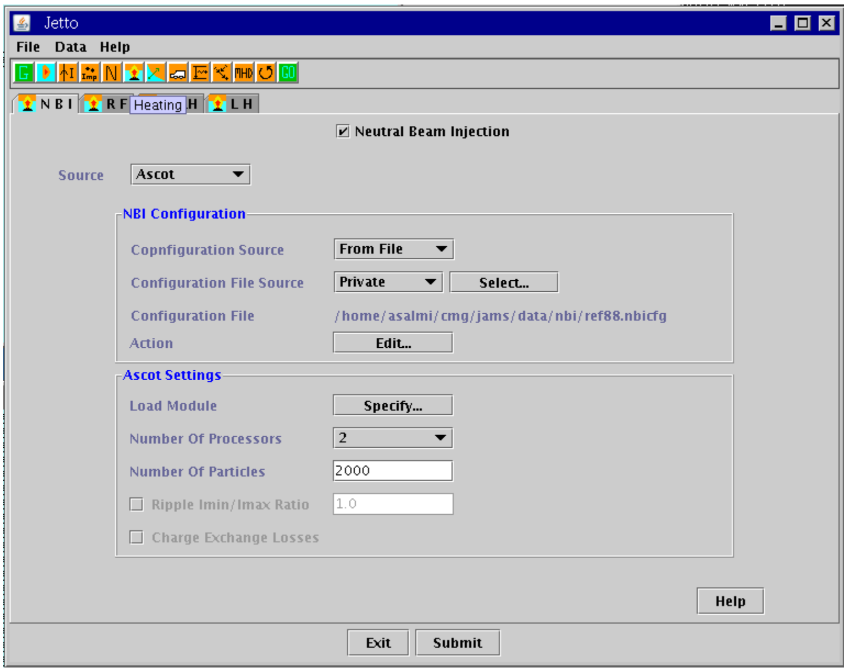


Figure 3.8. A Poincaré plot of a (2,1) magnetic islands in ITER.

JETTO-ASCOT integration: Within the JET code integration project the following additions and enhancements were made into the JINTRAC transport code:

- Including ASCOT internal NBI birth profile generator
- Adding eqdsk support
- Creating an automatic PPF reading routine for experimental NBI configuration (time dependent).



☑ Neutral Beam Injection

Source: Ascot

NBI Configuration

Copnfiguration Source: From File

Configuration File Source: Private

Configuration File: /home/asalmi/cmg/jams/data/nbi/ref88.nbicfg

Ascot Settings

Number Of Processors: 2

Number Of Particles: 2000

☐ Ripple Imin/Imax Ratio: 1.0

☐ Charge Exchange Losses

Figure 3.9. NBI heating panel in JAMS with ASCOT selected.

In practise the first two items provide the possibility for ITER modelling with ASCOT. Previously only JET could be simulated. The inclusion of PPF reading together with ASCOT internal NBI birth profile generator allow simulating complete JET discharges similar to what can be done with TRANSP. This option has been made simple to use and it requires no other user input. However, at the same time, it gives full flexibility by allowing users to generate their custom waveforms and NBI settings. NBI deposition calculations are also improved since previous and some times severe JAMS/PENCIL/ EIRENE limitations that would easily produce wrong deposition profiles are now removed.

JAMS now includes an option to use the experimental and time dependent NBI settings directly from the PPF system. User can also make a custom file of his/her choosing with full flexibility. This option is general and can be implemented also in PENCIL, EIRENE or any other NBI heating module but currently is only available with ASCOT.

The new module has been benchmarked against PENCIL and good agreement was found both in beam alignment and deposition. Shine through fractions were also compared and found similar in both codes. Small deviations could be understood and together with deposition they show that ASCOT cross sections are a slightly smaller than in PENCIL.

Improved equations of motion in ASCOT: The equations of motion used in the two distinct coordinate systems of ASCOT have been improved. The Cartesian equations of motion were re-derived based on exactly the same Hamiltonian as those derived for the Boozer coordinate system, and the capability of relativistic treatment of test particles was added to the equations of motion in the Boozer system. Thus, the two sets of equations of motion have been rendered exactly consistent with each other.

3.4.10 High level support team for HPC-FF

Collaboration within the HLST (high level support team) framework has been initiated, and a significant amount HPC-FF resources have been obtained for development and investigations with ELMFIRE. Tekes association provides one person to the HLST team (Salomon Janhunen) from 2010.

3.5 Power and Particle Exhaust, Plasma-wall Interaction

3.5.1 Overview

Our extensive activities in the field of particle exhaust and plasma-wall interaction during 2009 ranged from co-ordination of experiments at ASDEX Upgrade and JET tokamaks to surface analyses of plasma-exposed samples and computer modelling of erosion as well as global and local migration of materials in plasma. We begin this section with task reports focusing on surface analyses of JET and ASDEX Upgrade samples (including specific modelling) and continue with more modelling-intensive task reports. Experiments on local carbon migration at ASDEX Upgrade relate closely to our modelling work and are reported together with modelling.

3.5.2 Material transport and erosion/deposition in the JET torus

EFDA-JET task:	JW9-FT-3.51
Research Scientists:	Jari Likonen, Antti Hakola and Seppo Koivuranta, Tekes-VTT and TKK Juhani Keinonen and Kenichiro Mizohata, Tekes-UH Paul Coad and Anna Widdowson, JET-CCFE Jukka Kolehmainen, Tapani Haikola and Anna Tervakangas, DIARC Technology Inc.
Collaboration:	EFDA-JET Contributors

Background: Since 2001 an extensive analysis program is going on under JET Task Force Fusion Technology to investigate wall tiles using various surface analysis techniques. Erosion/deposition, retention of hydrogen isotopes and material transport 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, 2005–2007). 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 period, with heavy deposition at the inner divertor but just small net erosion at the outer divertor. Analyses of the tiles removed from JET during every shutdown form the basis of our knowledge on the plasma-wall interaction mechanisms at JET.

In 2009, a set of divertor and upper dump plate tiles (removed in 2007), inner wall guard limiter tiles (IWGL, removed in 2004), and a set of test mirror samples were characterized using Secondary Ion Mass Spectrometry (SIMS) and optical microscopy. The work has been done in close collaboration with JET under the JET Task Force Fusion Technology.

Main results in 2009: The main emphasis in 2009 was in the completion of post-mortem surface analyses of divertor tiles removed in 2007. In addition, retention of D in the divertor and wall tiles removed in 2004 and migration of ^{13}C in the Scrape-Off Layer (SOL) have been investigated.

The analysed divertor tiles LBT, 7, 8 and B turned out to be clean. Tiles 7, 8 and B from the outer divertor have clearly been eroded by plasma and by energetic charge exchange neutrals (CXN) in the case of tile B. The analysed tiles were not coated with a marker layer before exposure, but previous analyses have shown that all tiles 7 removed in 2004 had a deposition band near the centre of the tile. Tile 7 analysed in 2009 must have had the same deposition band after 2004 operations, but the tile was clean after 2007 operations.

The upper dump plate tiles from the top of the vessel analysed in 2009 were exposed in 1994–2007. These tiles have not been analysed in previous FT tasks. There is some speculation about plasma interaction with the dump plate region especially when plasmas have high elongation. SIMS and optical microscope analyses have indicated that there is some deposition in the dump plate region but the tiles have only a thin co-deposited layer with a thickness of a few microns.

In 2009, the post-mortem surface analysis of tiles removed in 2004 was completed. A set of IWGL tiles was analysed and the retention of D in the divertor and wall tiles during 2001–2004 operations was determined. Post-mortem surface analysis of the IWGL tiles from near the centre and bottom of the limiter showed similar deposition pattern as observed for the IWGL tiles removed in 2001. Tile 3X11L located near the centre of the limiter exhibited net erosion on the tangency region but there is an area of strong deposition further from the centre. Tile 3X11R showed deposition near the tangency region. Deposition was clearly found on the left-hand side near the bottom of the limiter (3X17L), whereas the right-hand side tile 3X17R was located in a net erosion zone.

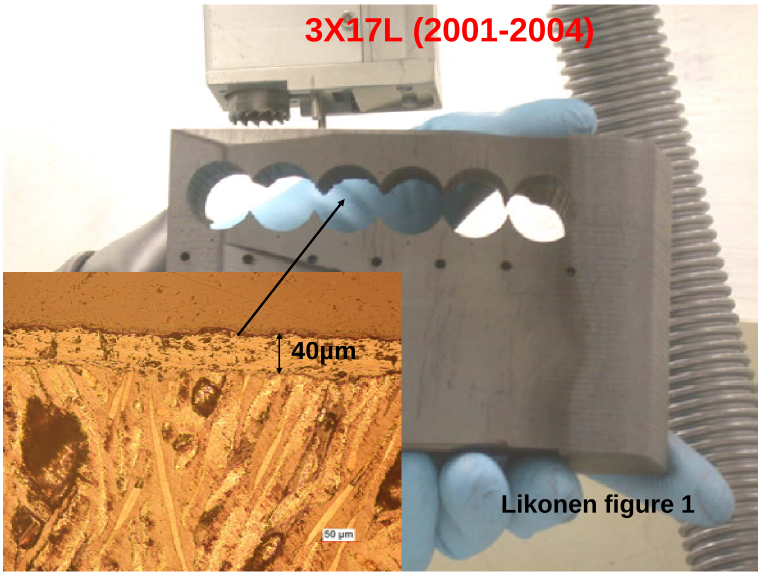


Figure 3.10. JET IWGL tile after exposure at JET and optical microscope image of a cross-section sample.

During the MkII-SRP phase in 2001–2004 the total D input was 1 800 g. The measured amount of retained D (excluding the IWGL limiters) is about 66 g which corresponds to a retention of 4% of the D input. The majority of the retention has earlier been found on the inner floor tile 4 and in the inner louvre area. Very thick deposits have been found on the sloping part of outer floor tile 6 and the D inventory in this area is also very significant. In 2009, the D amount was estimated to be 27g on the IWGL limiter arrays and the overall D inventory is 93 g which is 5% of the total D input during the 2001–2004 operations.

Metallic mirrors will be important components for optical diagnostics and imaging systems at ITER. Changes in their properties, such as in reflectivity, will influence the quality and the reliability of the detected signals. At JET, a program to assess the degradation of the mirror surfaces as a result of the exposure to plasma has been initiated. During the shutdown in 2004, several mirrors were installed in the shadowed regions at the inner and outer divertor corners, in the SRP wedge under the LBT tile, and at two positions at the outer mid-plane. A total of 11 mirror test samples removed in the 2007 shutdown were analysed in 2009. The mirror samples were installed at 4 different locations and recessed at distances from 0 to 45 mm into tubes. All the samples from the divertor have deposits on the front face of the mirror the thicknesses decreasing as a function of the recess. In some cases partial spalling of the film was observed. The cleanest samples were the ones unrecessed at the outer mid-plane, whilst the recessed samples did have a small amount of deposit on them.

At the end of the C19 campaign in 2007, Task Force E carried out an experiment to provide specific information on material transport and SOL flows observed at JET. $^{13}CH_4$ was injected in 2007, into the plasma boundary near the mid-plane adjacent to the lower hybrid antenna in the last day of discharges using one type of discharge only. In the case of 2007 experiment, ^{13}C was deposited mainly on tile 1, but the amount is smaller than in the 2001 experiment. The highest amount of ^{13}C on the outer divertor was found at the centre of tile 7 and below the strike point. A second set of tiles 7 and 8 were analysed in 2009. In both cases the ^{13}C deposition pattern was similar to that obtained in previous FT task. LBT and B tiles contained very little ^{13}C but there was, however, some ^{13}C deposition on the upper dump plate area.

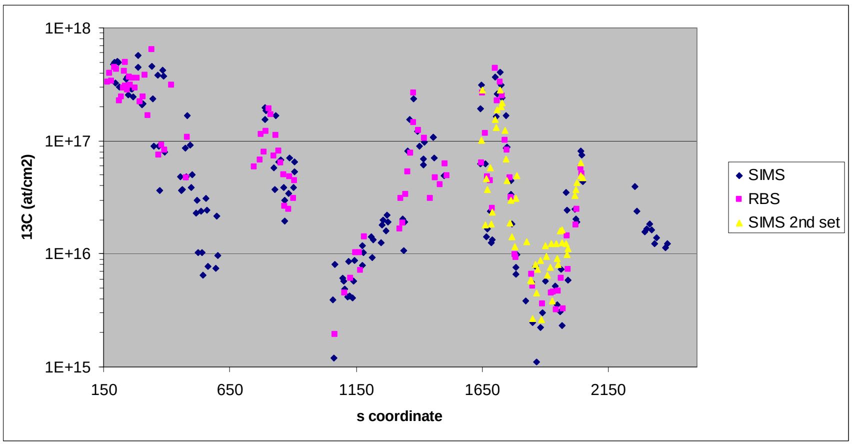


Figure 3.11. Surface density of ^{13}C (at/cm^2) on the divertor tiles as a function of the poloidal s coordinate and measured with SIMS and Rutherford backscattering (RBS).

3.5.3 Erosion and deposition in ASDEX Upgrade: analysis of erosion probes and marker tiles

EFDA PWI tasks:	WP09-PWI-01-02, WP09-PWI-04-01, WP09-PWI-04-04, WP09-PWI-05-01, and WP09-PWI-07-04
Principal investigators:	A. Hakola, Tekes – TKK J. Likonen and S. Koivuranta, Tekes – VTT
Collaboration:	K. Krieger, M. Mayer, R. Neu and V. Rohde, ASDEX Upgrade Team, IPP Garching, T. Haikola, J. Kolehmainen and S. Tervakangas, DIARC-Technology Inc.

Introduction: Our group has studied erosion of plasma-facing components and deposition of material on them in ASDEX Upgrade since 2002. For these investigations, special marker coatings have been prepared on selected divertor and main-chamber tiles, and each coated set of tiles has been exposed to plasma during a whole experimental campaign. The erosion of the coatings and the composition of layers deposited on them have been determined using post-mortem ion-beam techniques such as Nuclear Reaction Analysis (NRA), Rutherford Backscattering (RBS), and Secondary Ion Mass Spectrometry (SIMS), both at VTT and at IPP Garching. In addition, the migration of carbon has been studied with the help of global ^{13}C injection experiments at the end of four experimental campaigns, in 2003, 2004, 2005, and 2007. The poloidal deposition profile of ^{13}C on the marker tiles or on standard tungsten-coated ASDEX Upgrade wall tiles has been determined using SIMS. Modelling of the obtained results has been going on since 2008.

Main results in 2009: In 2009, a set of marker tiles, removed from the lower divertor of ASDEX Upgrade after the 2008 experimental campaign, was analyzed using SIMS. The main goals were to determine the deposition of different elements (B, C, D, and W) on the W coatings (thickness 200–1 500 nm) and on uncoated graphite areas of the tiles, to study erosion of the W coatings, and to investigate formation of mixed W–C layers on the tiles. For all these purposes, depth profiles of H, D, B, ^{12}C, ^{13}C, and W were recorded from samples drilled from the tiles. Figure 3.12 shows the poloidal cross section of the ASDEX Upgrade torus and locations of the analyzed marker tiles (in red).

On the W-coated areas, deuterium had been accumulated close to the inner strike point and in areas with either noticeable deposition or a damaged W coating due to arcing (tiles 6A and 6B). The largest carbon deposits were observed in the same regions indicating that deuterium had been co-deposited with carbon and mainly in the inner divertor. Boron, for its part, showed a different poloidal deposition profile with peaks in the arcing tiles 6A and 6B but also in many of the outer-divertor tiles. Furthermore, on the uncoated graphite areas, the deposition profiles of B and D were completely different from the corresponding curves for the W coatings. The graphite stripes were also observed to have been covered with a re-deposited W layer, especially close to the inner and outer strike points.

Erosion was most noticeable in the vicinity of the outer strike and in the arcing zone of the inner divertor. For areas with net deposition, also layers with a varying W/C ratio could be identified, up to three such layers in the inner strike-zone samples. The erosion studies were supplemented by exposing one marker probe (see Figure 3.13) to ASDEX Upgrade plasma in June 2009 and determining the erosion of its W, Ni, and Al stripes. The results indicated that the parts closest to plasma had been eroded by < 10 nm as Figure 3.13 shows. The experiment was also numerically modelled with the ERO code. The simulations revealed significant variations in the erosion yields between the different marker materials when equal exposure to the plasma was assumed. The non-negligible erosion of the W surface observed in the experiment was in contradiction to the simulation results, possibly indicating a fast ion contribution in the plasma.

In 2009, the migration and subsequent deposition of ^{13}C was studied by determining the poloidal deposition profile on uncoated graphite areas of lower-divertor marker tiles, removed from the ASDEX Upgrade torus after the 2007 ^{13}C injection experiment (see Figure 3.12. The ^{13}C profile was totally different from the corresponding distribution on W-coated tiles as one can notice from Figure 3.14. For the W-coated tiles, the deposition was stronger in the inner divertor while in the outer divertor, the deposition was barely distinguishable from the background. In contrast, on the graphite areas the deposition was comparable both at the inner and outer divertors and the determined surface densities were locally 10–100 times higher than on W.

For the 2010 AUG campaign, regions of different surface roughness have been realized on four full-size outer strike-point tiles at IPP and then coated by DIARC-Technology Inc: two of the tiles with a W layer and the remaining two with a Mo layer. The thicknesses of the coatings range from 2–5 µm. In addition, two outer-strike-point tiles have been coated for re-erosion studies: one of the tiles has 2–3 µm thick W and W+5-% Ta stripes, the other one 2–5 µm thick Al, Cr, Mo, and W stripes. Also six new erosion probes have been prepared and coated with C, Al, Ni, and W marker stripes.

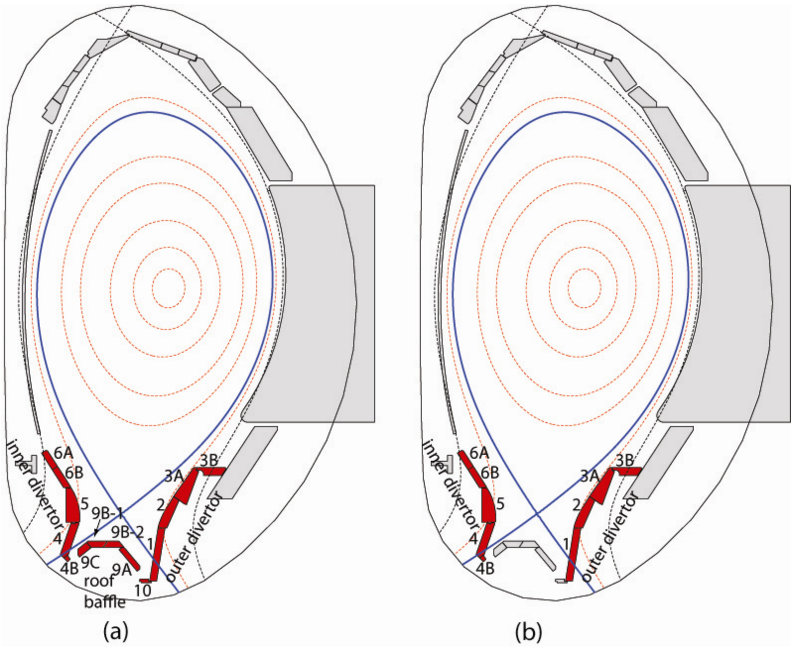
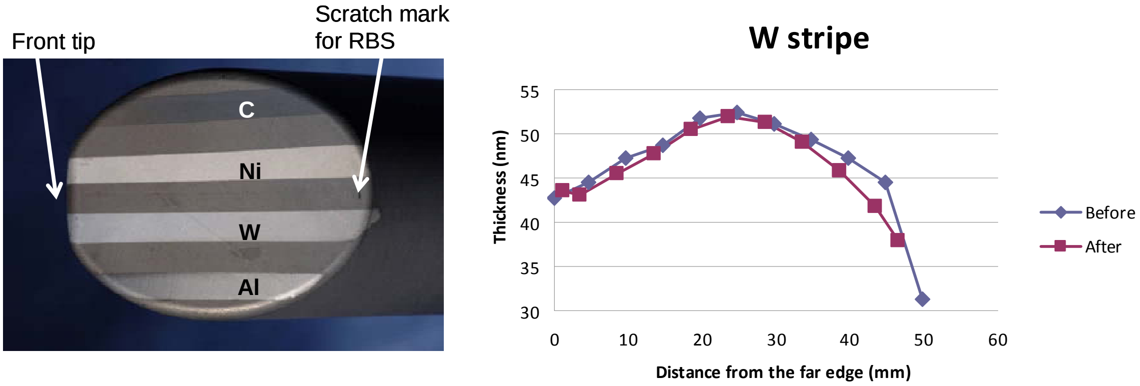


Figure 3.12. Poloidal cross section of the ASDEX Upgrade torus and locations of the analyzed marker tiles (red) of the (a) 2007 and (b) 2008 campaigns.



(a) (b)

Figure 3.13. (a) Photograph of the erosion probe after its plasma exposure in 2009. (b) Thickness of the W stripe on the erosion probe as a function of the distance from the far edge of the probe before and after plasma exposure.

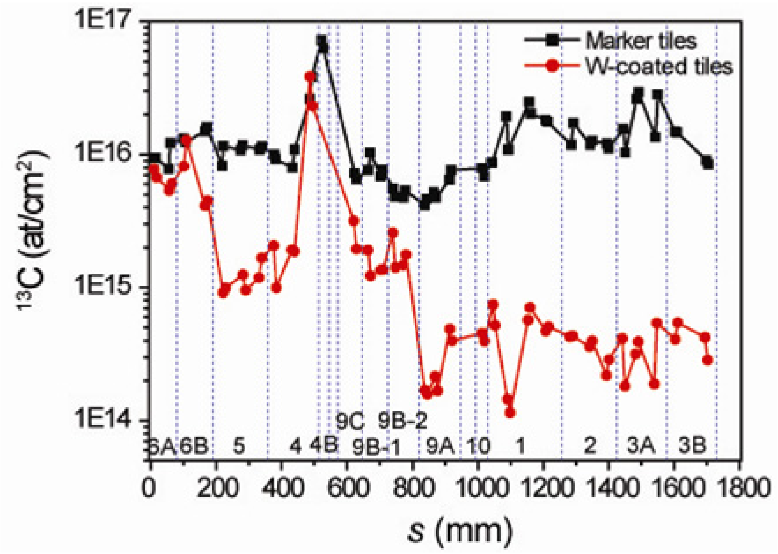


Figure 3.14. Surface density of ^{13}C on the W-coated tiles (red circles) and on the uncoated graphite areas (black squares) of the 2007 marker tiles.

3.5.4 Predictive EDGE2/EIRENE and SOLPS simulations of heat flux fall-off width

EFDA Fellowship:	WP08-FRF-TEKES/Groth
Principal investigator:	M. Groth, Tekes – TKK
Collaboration:	S. Wiesen, JET/FZ Jülich D. Coster, M. Wischmeier and A. Chankin, IPP Garching and EFDA-JET Contributors

Introduction: Within the framework and training programme of my EFDA Fellowship I carried out numerical studies of the divertor power deposition using the fluid edge codes EDGE2D/EIRENE and SOLPS. The simulations were run on grids derived from equilibrium reconstructions from JET and ASDEX Upgrade, respectively. By varying the upstream density the simulations were diagnosed for heat loads to the outer divertor target plate, and the fall-off width was calculated from the heat flux profiles. Simulations were run including carbon impurities, and fluid and Monte Carlo neutrals. In support of these activities I visited JET/Culham Science Centre in July and September 2009, and IPP Garching in November 2009.

Principal results in 2009: The EDGE2D/EIRENE and SOLPS codes are two of the most sophisticated edge fluid codes available to-date. Both code packages include the Monte Carlo code EIRENE to adequately describe the spatial and velocity distributions of neutrals in ionising plasma. Assuming Maxwellian plasma behaviour, the codes calculate the 2-D distribution of plasma parameters density, temperature, and electric fields, as well as the parallel-**B** and perpendicular-**B** particle and heat fluxes, for the scrape-off layer and pedestal regions. Plasma-wall interaction is accounted for by assuming physical and chemical sputtering, and the transport of impurities is followed within the computational domain, including ionisation and recombination.

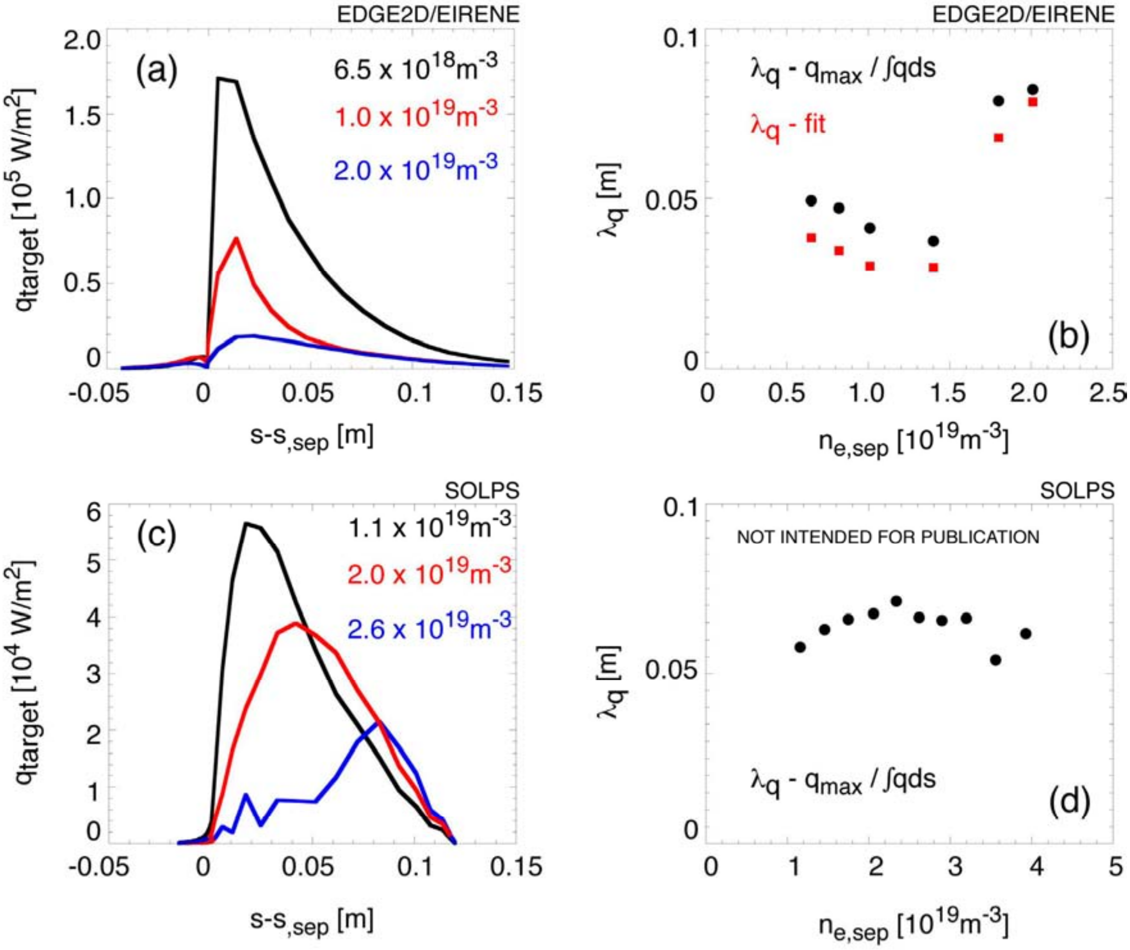


Figure 3.15. Radial heat flux profiles (a, c) and heat flux fall-off lengths (b, d) at the outer divertor target calculated with EDGE2D/EIRENE for JET (a, b) and with SOLPS for ASDEX-Upgrade (c, d). The fall-off lengths for the EDGE2D/EIRENE simulations were calculated using the ratio of peak heat flux over the integral power load ($q_{max}/\int q ds$), and exponential fits to the heat flux profiles in the SOL near the separatrix (λ_q - fit). For SOLPS only the former technique was used, since the profiles do not fall off exponentially. These results are intended for illustration, and not intended for publication.

For both EDGE2D/EIRENE and SOLPS simulations, as the upstream density is increased the peak heat flux is reduced, and the peak moves radially outward into the far scrape-off layer. The fall-off length derived from EDGE2D/EIRENE simulations for JET is of the order 5 cm at the outer divertor target, which is approximately 5 mm mapped to the outer midplane. This finding is consistent with earlier results from JET reported by Fundamenski *et al*. The simulations indicate that at low-to-medium density the heat flux width decrease with upstream density, while at higher density, close to the detachment of the outer divertor plasma, the width increases again. Simulations with the SOLPS for ASDEX Upgrade show a significantly stronger effect of radially shifting the peak heat flux toward the far SOL when raising the upstream density. The width of the heat flux profiles at the outer target for the density range investigated is invariant on the upstream density. Simulations including impurities show a stronger reduction of the heat flux to the divertor target, since power is radiated before impacting the target, but the derived heat flux fall-off widths remain approximately the same as those calculated without impurities. Further studies are to be carried out to study the effect of power crossing the separatrix, radial diffusivities, and recycling coefficients assumed at the target.

3.5.5 Local carbon deposition in tracer injection experiments of JET

EFDA-JET Order:	JW8-O-TEKE-17
Principal investigators:	M. Airila, Tekes – VTT M. Groth, Tekes – TKK
Collaboration:	P. Coad and A. Widdowson, CCFE S. Brezinsek, A. Kirschner, D. Matveev and S. Wiesen, FZ Jülich and EFDA-JET Contributors

Introduction: Tracer injection experiments in tokamaks provide information on material migration and deposition under controlled constant plasma conditions. It is customary to use the natural isotope ^{13}C of carbon as the tracer. In plasma devices with carbon plasma-facing components it can be distinguished from substrate ^{12}C in post-mortem surface analyses. The use of the same tracer has been also successfully continued in ASDEX Upgrade after the transition to all-tungsten wall. The principal carbon migration can be investigated by injecting a tracer-containing molecule such as $^{13}CD_4$ from a net erosion zone.

Carbon migration in plasma is a complex process starting from physical or chemical erosion of the surface by particle bombardment, followed by successive ionization and transport under the influence of electromagnetic forces, plasma flow, thermal forces and diffusion. Finally, the eroded or injected particles are deposited on the plasma-facing surfaces, where re-erosion may occur, leading to migration into remote areas. The diagnostic capabilities for studying the details of this process are limited: The density distributions of impurity species in the plasma can be obtained in situ by spectroscopy, and the final tracer distribution on plasma-facing components can be measured ex situ by e.g. ion beam techniques. Interpretation of the measurements requires computer simulations.

We have modelled the local transport process in the vicinity of the divertor surface with using a chain of different codes: 1) Plasma fluid code EDGE2D coupled to the Monte

Carlo neutrals code Eirene to find a background plasma solution, 2) The 3D Monte Carlo impurity transport code ERO for impurity tracing in the plasma and 3) The 3D-GAPS code for material deposition studies in gaps and shadowed areas, recently developed at FZJ Julich, Germany. In 2009 this simulation work was directed to the 2004 and 2007 injection experiments of JET.

Local deposition on plasma-wetted and shadowed surfaces in the 2004 injection experiment: In the 2004 tracer experiment of JET, $^{13}CH_4$ was injected into H-mode plasma at the outer divertor through 48 injectors distributed around the torus. Deposition measurements and spectroscopy are available from this experiment, which provides a possibility to benchmark the physics models of ERO. However, there are considerable experimental uncertainties, e.g., leakage of the tracer gas away from the injector, which make precise quantitative comparison difficult.

In ERO modelling, Edge2D/Eirene fluid plasma solutions for inter-ELM and ELM-peak phases were used as plasma backgrounds. Local 2D deposition patterns at the vertical outer divertor target plate were obtained for comparison with post-mortem surface analyses. Our previous modelling indicates that enhanced re-erosion of deposited carbon layers is essential in explaining the amount of local deposition (see Figure 3.16). ERO also provides emission profiles for comparison with radially resolved spectroscopic measurements. The modelling of the emission profiles was separated to two parts: intrinsic emission was obtained by imposing an atomic carbon flux from the private-flux region that ionizes and radiates upon reaching the dense separatrix plasma. The extrinsic emission due to the methane injection was then combined to the intrinsic emission with the ratio of intrinsic and extrinsic fluxes as a free parameter. It turned out that this model can not provide a satisfactory match the measured emission profiles.

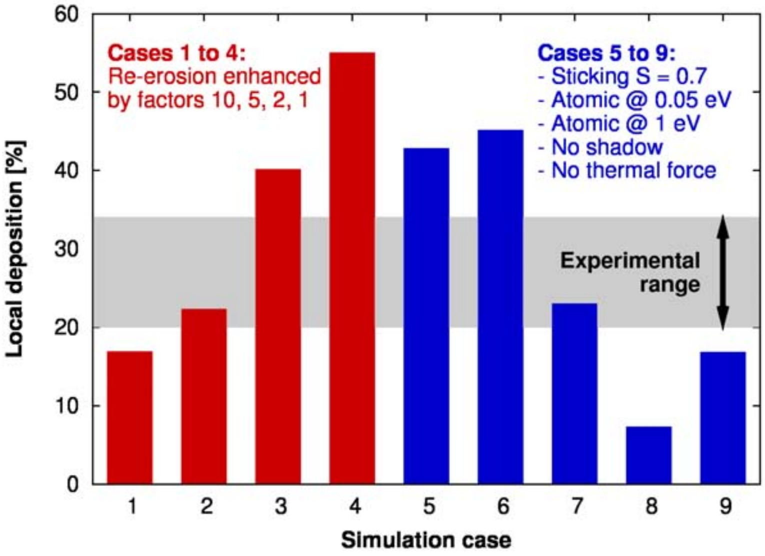


Figure 3.16. Local deposition with different values of the re-erosion enhancement factor f_{re} (red bars) and for various cases with other modelling assumptions (blue bars). Case 1: reference case (shadow and thermal force included, molecular injection, $S = 0$, $f_{re} = 10$). Match to experiment is achieved with $f_{re} = 2.5–7$. Cases 2 to 4: as reference but $f_{re} = 5, 2, 1$, respectively. Case 5: as reference but $S = 0.7$. Cases 6 and 7: as reference but atomic injection at 0.05 and 1 eV, respectively. Case 8: as reference but without shadow. Case 9: as reference but without thermal force.

Carbon migration into tile gaps and shadowed areas can be modelled with the 3D-GAPS code. In collaboration with FZ Jülich, we extended the modelling 2004 tracer experiment to include the gap between divertor tiles 7 and 8 as well as the shadowed area on the front surface of tile 7. For this the simulation geometry in ERO was upgraded to include realistic tile shapes and the interface between plasma and the shadow. The simulations were carried out iteratively by launching the test particles first at the bottom of the gap with 3D-GAPS, tracing escaping particles in plasma with ERO, and finally calculating the gap deposition of returning particles with 3D-GAPS. By extending ERO simulations until the surface reaches its equilibrium concentrations, we included also the contribution of particles re-eroded from plasma-wetted surfaces. Preliminary results indicate that a significant fraction of the injection can be deposited in the gap, but detailed comparison to the measured deposition is still ongoing.

Deposition during the 2007 L-mode detachment experiment: Also the 2007 L-mode detachment experiment included methane injection (without isotope labelling) and post mortem deposition analysis. A toroidal profile and several poloidal profiles have been measured. The estimate of deposited amount of carbon (about 1/3 of injection) was based on the assumption that the deposited layer would contain deuterium and carbon in proportions of 1:1. Outer strike point was located at the LBSRP tile at the bottom of divertor and the injection location was at the outer strike point. The discharges detached gradually and the injection was performed into the detached phase.

We initiated the deposition modelling with ERO by assuming a uniform plasma background and scanning density and temperature over the relevant ranges suggested by the uncertainties in the local measurements. This scan yields local deposition fractions for some parameter combinations. However, this simplified model does not yield correct toroidal decay for the same densities and temperatures. We will refine the modelling by employing Edge2D/Eirene for a more realistic plasma background.

3.5.6 Transport and deposition of ^{13}C in the ASDEX Upgrade outer divertor: experiments and SOLPS/ERO modelling

EFDA Task Force PWI:	WP09-PWI-04-01
Principal investigator:	L. Aho-Mantila, Tekes – TKK
Collaboration:	M. Wischmeier, D. Coster and K. Krieger, ASDEX Upgrade Team, IPP Garching and A. Kirschner, FZ Jülich

Introduction: Local transport of carbon has been investigated in the ITER-relevant, vertical target configuration of ASDEX Upgrade by injecting ^{13}C methane into the scrape-off layer from two poloidally separated locations along the tungsten-coated outer target. After repetitions of identical discharges, the relevant divertor tiles have been promptly removed from the torus for nuclear reaction ion-beam analysis of the ^{13}C re-deposition layer thickness. For interpretation of the observed local deposition, numerical modelling is carried out using the SOLPS and ERO codes. Current research efforts concentrate on a series of well-diagnosed low-confinement mode experiments in 2007–2009, which form an extensive data set for model validation.

Main results in 2009: Numerical modelling focused on the 2007 L-mode experiment in normal AUG field configuration. The steady-state scrape-off layer plasma background was simulated with the combined 2D fluid plasma – Monte Carlo neutrals code package SOLPS5.0, with the objective of reproducing all available diagnostics data. In 2009, cross-field drift terms were activated in these simulations, which improved the correspondence with experiments significantly. The ERO code was then used to calculate the 3D trajectories of the injected hydrocarbons, including dissociation, transport of ions and neutrals in the given SOLPS plasma background, and the subsequent re-deposition and re-erosion steps.

The modelled background plasma determines the location of dissociation and ionization, the frictional and thermal forces on the impurity ions, and cross-field drifts due to electric fields. In 2009, the effect of each of these physical mechanisms on ^{13}C transport and local deposition in the outer divertor was identified in simulations. For the first time, the full 2D electric field predicted by SOLPS was included in the ERO simulations, resulting in significantly improved correspondence between the modelled and measured ^{13}C re-deposition layers, see Figure 3.17. Due to the ***ExB*** drift, there is net poloidal transport from the scrape-off layer towards the separatrix, and the re-deposition efficiencies increase by a factor of 2. These results underline the importance of considering drift effects in both ERO and SOLPS simulations.

The AUG experimental series was successfully continued in 2009 with ^{13}C injection into L-mode divertor plasma in reversed magnetic field configuration. The results will be used to validate the integrated SOLPS/ERO simulations when the direction of the ***ExB*** drift is reversed. In addition, further characterization discharges were performed, including Langmuir probe measurements of plasma temperature, density and flow velocity along the outer midplane, to verify the plasma conditions in the 2007 forward field experiment.

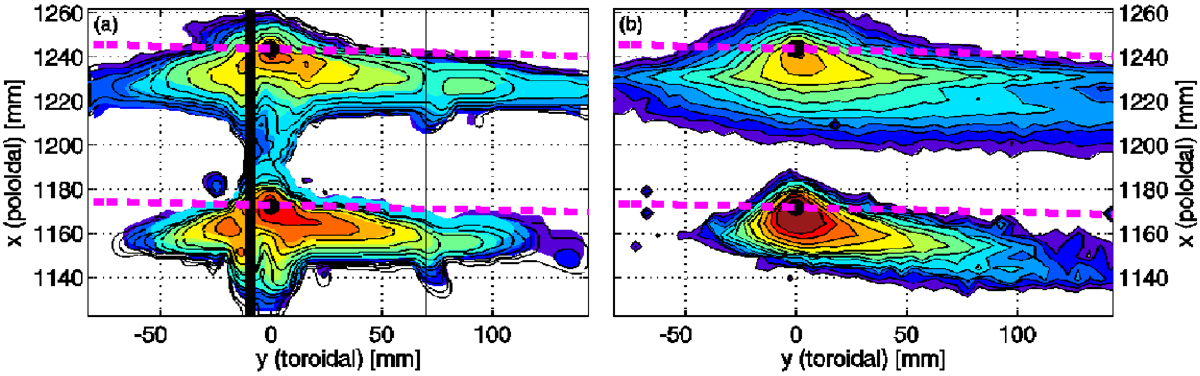


Figure 3.17. Local ^{13}C deposition patterns measured with nuclear reaction analysis (a) and simulated with the ERO code, using background plasma parameters from SOLPS simulations (b). Magnetic field lines are drawn with the dashed magenta lines. The vertical black lines in (a) represent the tile gaps.

3.5.7 OEDGE Simulations of the 2007 ASDEX Upgrade ^{13}C injection experiment

EFDA PWI tasks:	WP09-PWI-04-02
Principal investigators:	T. Makkonen, T. Kurki-Suonio, M. Groth, L. Aho-Mantila and A. Hakola, Tekes – TKK J. Likonen, Tekes – VTT
Collaboration:	K. Krieger, IPP Garching

Introduction: Our group has carried out OEDGE simulations of the 2007 ^{13}C injection experiment at ASDEX Upgrade. In the experiment, isotopically labeled methane was injected into the torus from the outer midplane during 11 identical L-mode lower single null discharges at the end of the 2007 ASDEX Upgrade campaign. The subsequent deposition of ^{13}C on W-coated wall tiles and uncoated graphite areas of specially coated marker tiles, all removed from approximately the same poloidal cross section of the torus, was determined using SIMS. The obtained results have been discussed in Chapter 3.3.3.

Main results in 2009: The OEDGE code is a combination of three separate codes: OSM, EIRENE, and DIVIMP. The DIVIMP part models transport of impurities in a given plasma background. The first step in the modelling is generating the plasma background; in OEDGE this is accomplished by the coupled onion skin model (OSM) solver and the neutral Monte Carlo code EIRENE. To simulate the 2007 ^{13}C injection experiment, Langmuir probe data from the discharge #22575 was used as an input for the OSM solver 22 in OEDGE. At the outer midplane, the generated temperature was in a good agreement with experimental data but the density was two or three times lower than the measured values at worst. Also, the poloidal plasma flow in the main SOL is significantly lower than measurements from various tokamaks suggest.

Considering the deposition of the injected carbon, only approximately 10% of the injected amount was found experimentally on the main chamber and divertor walls. Only a small number of ^{13}C deposition measurements were taken along tiles from the upper divertor, introducing further uncertainties about the total amount deposited in this region. Because of these reasons, the deposition on the heat shield, the PSL and limiter regions, the outer lower divertor, the roof baffle, and the inner lower divertor was normalized to 100% for comparison to the simulations.

In the experiment, isotopically labeled methane was puffed at the outer midplane into the SOL, where it dissociated and ionized. In the simulations, the source of ^{13}C was approximated as a point source of singly charged ^{13}C ions. The effects of changing the injection location and the diffusion coefficient along with the importance of an extended computational grid were studied. The main results were that (1) uncertainties about the injection location, diffusion coefficient, and the computational grid can be approximated by one single variable, the perpendicular transport time, and that (2) simulations with the generated plasma background cannot reproduce the measured ^{13}C deposition. Here, the perpendicular transport time represents the time ^{13}C ions stay in the SOL.

The poloidal plasma flow profile was identified as the most probable source of the mismatch, and in order to test the importance of flows, simulations were carried out with a background that had a flow field imposed in an ad hoc manner. Such simulations resulted in a reasonable match to the experimental deposition data as illustrated in Figure 3.18.

The primary approach of improving the agreement between the measured and simulated ^{13}C deposition profiles is generating more realistic background plasmas using more sophisticated OSM solvers in OEDGE or edge fluid codes, such as SOLPS.

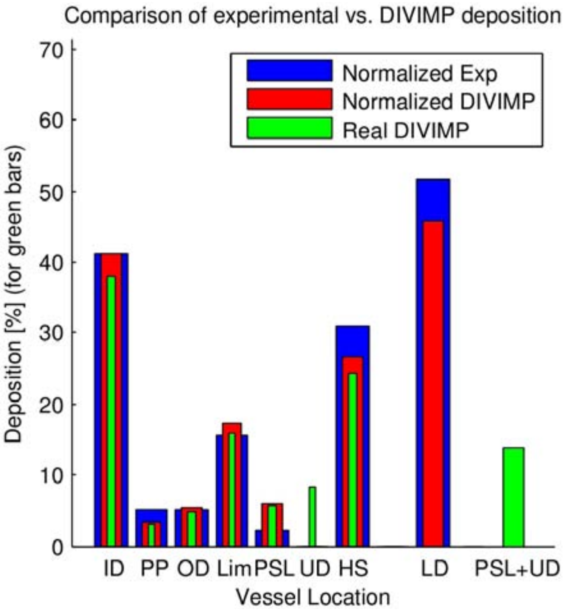


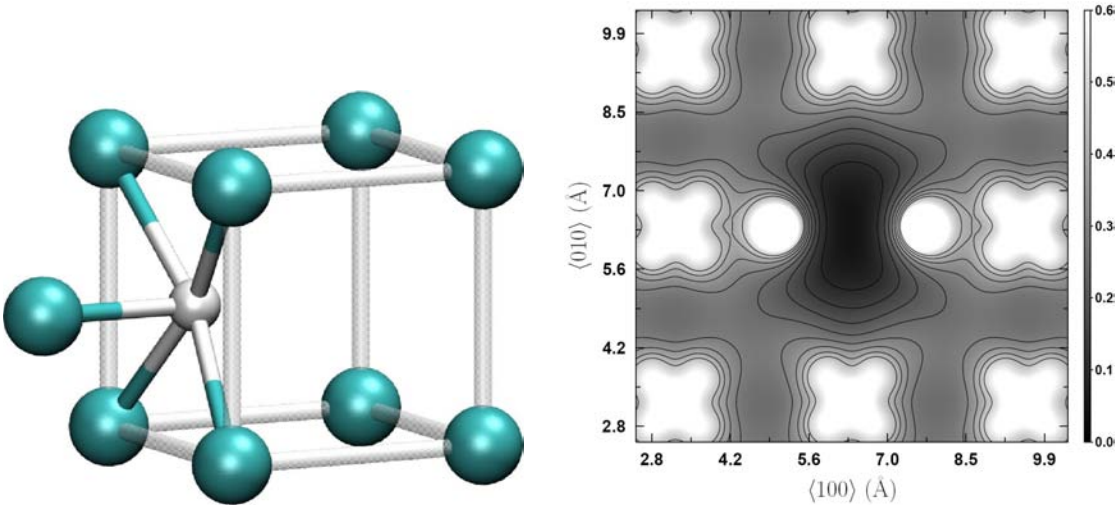
Figure 3.18. Large scale deposition for a simulation run with the imposed flow field plasma background. ID = inner lower divertor, PP = roof baffle (private plasma region), OD = outer lower divertor, Lim = limiter, PSL = passive stabilizer loop, UD = upper divertor, HS = heat shield, LD = lower divertor in total.

3.5.8 MD simulations Hydrogen trapping in Tungsten

EFDA PWI tasks:	WP09-PWI-05
Principal investigator:	Kalle Heinola, Tekes – University of Helsinki

The hydrogen (H) trapping properties to tungsten (W) monovacancy and self-intersitial atom (SIA) were studied using the first-principles calculations based on density functional theory. Since the H atom is a light-mass particle and therefore has a high vibrational energy, the quantum mechanical vibration effects cannot be neglected. Therefore, the hydrogen trapping energies were obtained by taking into account the zero-point energies of the vibrating H atom. Moreover, in the fusion device conditions impurities such as rhenium (Re) and osmium (Os) are formed in bulk W due to the high flux of fusion reaction neutrons leading to the transmutation of a W atom into Re and further into Os. Results for the trapping energies of hydrogen to a Re and Os impurity atom in W were calculated for the first time.

According to our calculations the lowest energy site for H in a W monovacancy is the distorted octahedral site (O) (see Figure 3.19.a. There the H atom is bound to its nearest W atom, which is located outside the monovacancy. Secondary bondings are with the W atoms at the boundaries of the monovacancy. Due to the strong H-nearest neighbour W atom bonding, two H atoms do not form a H_2 molecule in the monovacancy, but stay separated from each other at the distorted O-sites (see Figure 3.19.b). This arrangement corresponds to the ground states of H. The energetically most favorable positions for additional H atoms were found to be at the O-sites forming triangle, tetrahedron, square pyramid, and square bipyramid for 3, 4, 5, and 6 H atoms, respectively.



a) b)

Figure 3.19. a) The H atom in its ground state at the distorted octahedral site in a W monovacancy. b) The charge densities of two H atoms at their lowest energy states bonding to their nearest neighbouring W atoms viewed on the (001) plane. No H_2 molecules are formed inside the monovacancy at room temperature.

The de-trapping energies for 1–6 H atoms from a W monovacancy were found to be 1.60, 1.57, 1.39, 1.28, 1.17 and 0.64 eV, respectively. The energies for the 5th and 6th H atom refer to approximative release temperatures of ~400 K and ~230 K, respectively. This leads to an important conclusion that a W monovacancy can trap up to five H atoms at room temperature.

The W SIA is a quasiparticle by nature extending over three displaced W atoms in forward and backward <111> direction. In Figure 3.20 is presented the SIA configuration distorted by the presence of the H atom. The H trapping energy to the SIA was found to be low (~0.6 eV), so a single SIA does not trap hydrogen at room temperature. However, the interstitial Re and Os atom was found to trap H with release temperatures slightly above room temperature. In other words, the formation of interstitial Re and Os can enhance the hydrogen retention in W. The substitutional Re and Os were not found to trap H at room temperature.

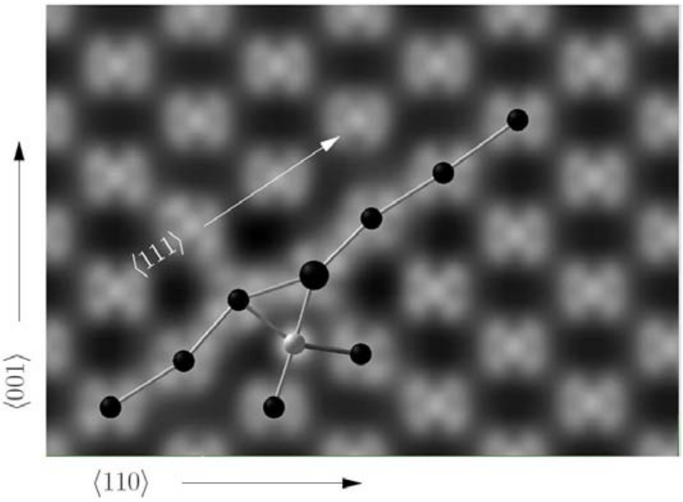


Figure 3.20. The distortion of the <111> SIA quasiparticle produced by the H atom (light coloured sphere) in the presence of the W adatom (larger dark sphere).

3.5.9 MD simulations of sputtering of pure Beryllium and mixed Be-C layers

EFDA PWI tasks:	WP09-PWI-07
Principal investigators:	Kai Nordlund, Carolina Björkas, Niklas Juslin and Katharina Vörtler, Tekes – University of Helsinki
Collaboration:	SCK-CEN

Chemical sputtering of Be due to D plasma bombardment: Due to its low Z and oxygen gettering abilities, beryllium has been chosen as first wall armour material for the future fusion reactor ITER. As plasma facing material (PFM), Be will have to withstand not only the plasma heat, but also the bombardment of hydrogen isotopes and other impurities in the plasma. Critical Be related issues, which are still lacking complete understanding, include formation of mixed materials originating from different PFMs in the reactor and tritium retention.

During plasma-wall interaction experiments, BeD molecules have been seen to erode in the JET fusion reactor and in the linear divertor plasma simulator PISCES-B facility indicating that a chemical sputtering effect is present when Be is subject to deuterium plasma bombardment. Chemical sputtering has not been thoroughly investigated in Be, but the mechanism is nonetheless important and must be taken into account when assessing, for instance, the reactor lifetime, plasma contamination and mixed material formation. The bonding of hydrogen isotopes to Be also increases the tritium retention in the first wall, making the use of tritium removal techniques more crucial.

Since erosion is an atomic level mechanism, Molecular Dynamics (MD) simulations are a suitable tool for studying it. The simulations are, however, limited in time and space which means that exact experimental conditions cannot be reproduced. The fluxes in the simulations are inevitably several orders of magnitudes larger and thermal effects (diffusion and surface relaxations) are also not perfectly modelled due to the short time scales in the simulations. Despite this, simulations are able to give insight into many experimentally observed phenomena.

The deuterium plasma impact on Be was simulated with the MD code PARCAS using the recent Be-H potential developed by us (version Be-H I). Also, as a compliment to the simulations, experiments were performed in the PISCES-B facility at UCSD (by D. Nishijima and R. Doerner). During these investigations, Be targets were exposed to a deuterium plasma and the resultant plasma-material interactions were spectroscopically investigated.

The fraction of Be atoms that are sputtered as BeD molecules in the simulations and experiments in this work is plotted in Figure 3.21. At low energies, the simulated fraction is about 100% for almost all surfaces in the simulation, meaning that no single Be atoms are sputtered. At higher energies the BeD fraction is smaller. The same trend is seen in the experiments, with the fraction going from about 80% at low energies to about 40% at energies above 70 eV.

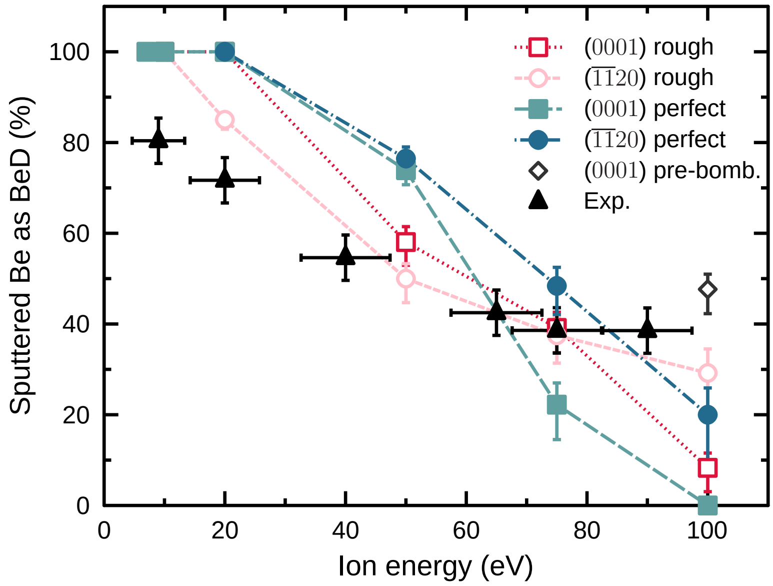


Figure 3.21. The fraction of Be atoms sputtered as BeD molecules after Be exposure to a D plasma. Both simulated and experimental data are shown. Two different orientations of the Be surface and both initially rough and perfect surfaces were used in the simulations

Although 7–10 eV D ions are not expected to be able to erode atoms from a surface, they readily do so here since the D atoms at the surface weaken the surface binding of Be atoms, making them easier targets for sputtering. If an incoming ion then enters the region between the surface Be and its neighbouring Be, and in that way breaks their bonds, it loosens the Be atom's binding further and it can easily be sputtered away with one (or more) of its D neighbours to form a BeD molecule. This so called swift chemical sputtering mechanism (which is illustrated in Figure 3.22) has been observed in covalently bonded material, like C and hydrogenated amorphous Si, but not previously in metals.

The experimental observation that BeD molecules are sputtered when Be is exposed to a D plasma was thus explained by the simulations. The chemical effects were seen to be considerable, since the simulations show that 100% of the sputtered Be atoms come out in BeD molecules at low (7–20 eV) ion energies, and the experimental fraction was seen to decrease from about 80% to 40% over the 9–90 eV energy range. This ion energy dependency was ascribed to changes in the amount of D neighbours to surface Be atoms. This, in turn, is due to larger penetration depths of the D ions at high energies. It was also shown that contrary to previous notion, metals can also sputter chemically.

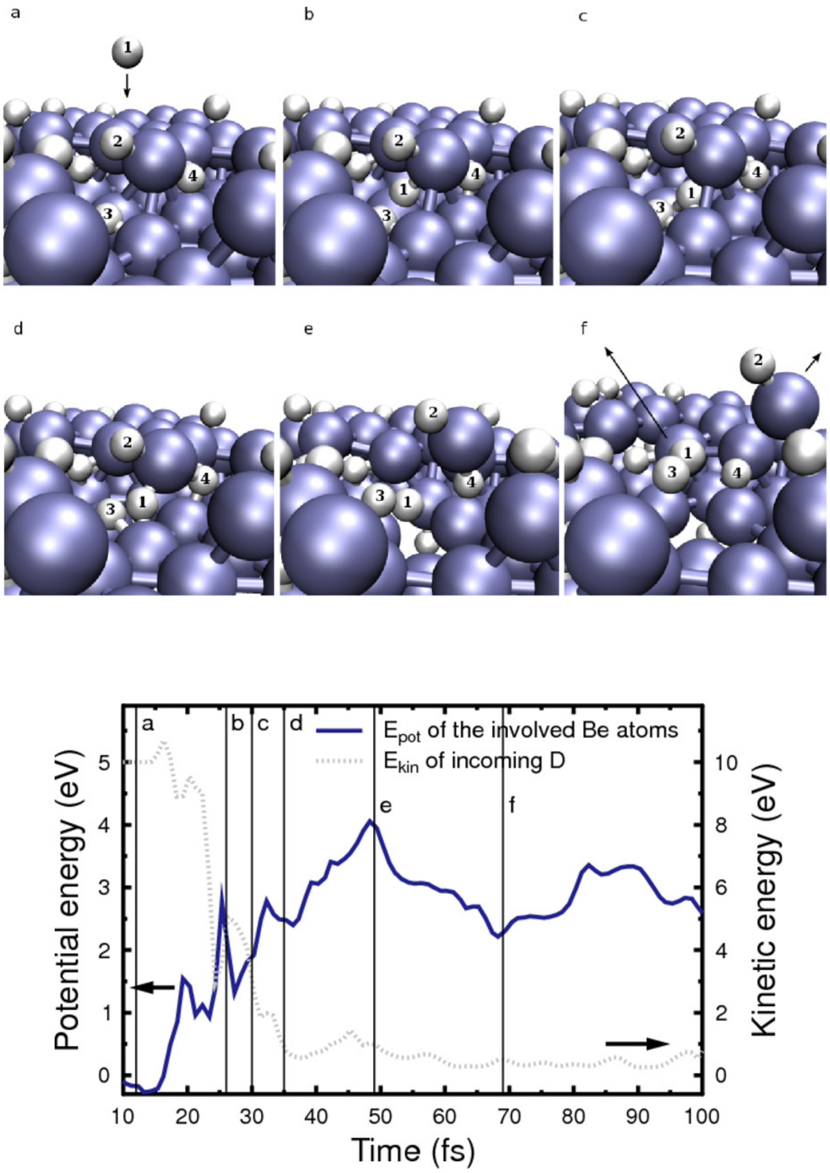


Figure 3.22. An illustration of a sputtering event. The upper part of the figure shows snapshots of the situation at six different times during the process. The D ions are represented by the small light grey spheres and the Be atoms are the larger dark spheres. The graph in the lower part illustrates the kinetic energy of the incoming D ion (dotted line) and the potential energy of the Be atoms that are initially bonded with the sputtered Be atom (solid line). The initial potential energy of these is chosen as zero level energy. The times corresponding to the snapshots are indicated with vertical lines in the graph and the arrows in the last snapshot (f) show in which direction the sputtered D_2 and BeD molecules are moving.

Sputtering of mixed BeC-layers: The current material choice for the next generation fusion reactor ITER is beryllium for the first wall and carbon and tungsten in the divertor region, hence, mixed layers of these materials are expected. The rate, location and extent of the creation of mixed layers are by no means fully known, nor is the sputtering of these materials. Carbide formation on beryllium surfaces has, however, been observed to mitigate not only the pure beryllium but also the pure carbon sputtering yields. As an attempt to gain an atomic level insight into the sputtering process of Be_2C, we have simulated cumulative bombardment of Be_2C surfaces using molecular dynamics (MD).

As in the pure Be case, the BeD molecule sputtering is noteworthy. Other interesting molecules which we found to be sputtered are BeD_2 and CD_3. Overall, very few hydrocarbons and only one methane molecule CD_4 were eroded. Preferential sputtering of Be was observed.

The sputtering mechanism for the most-part of the molecular sputtering at low energies was identified as the swift chemical sputtering. The sputtering yield of the mixed BeC layers was seen to be lower than the pure Be yield (see Figure 3.23), as observed in experiments.

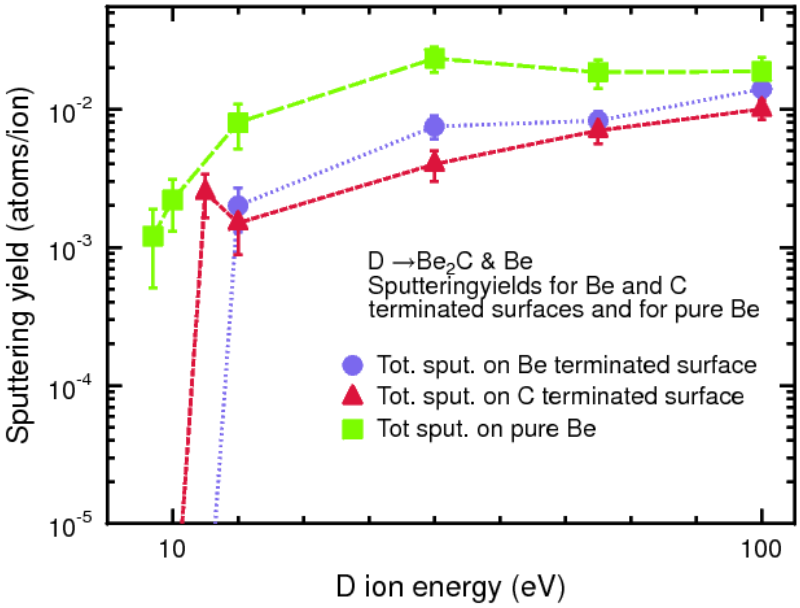


Figure 3.23. The sputtering yield of Be_2C and pure Be due to D bombardment.

A many body bond-order potential of Tersoff-type have been developed for the Be-W system. This potential is able to capture the intermetallic hexagonal Laves phase, Be_2W, and the $Be_{12}W$ phase is also stable. The potential is compatible with the earlier Be-C-W-H-potentials, meaning that simulations of systems containing the first wall material Be, divertor materials W and C, as well as, plasma particles are feasible.

The data obtained in the Be, Be_2C and BeW molecular dynamics simulations are to be used in the Monte Carlo impurity transport code ERO. The MD calculated D reflection probabilities (shown in Figure 3.24 for Be_2C) and sputtering yields will replace the less sophisticated, homogeneous material mixing surface models and we will determine the importance of using accurate plasma-wall parameters.

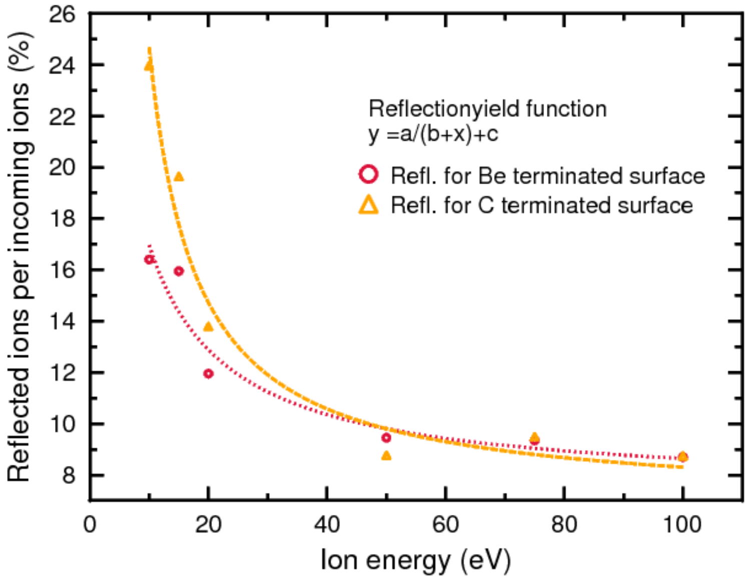


Figure 3.24. The D reflection (per cent) for C and B determined Be_2C surfaces.

3.6 Plasma Diagnostics

3.6.1 Upgrading JET NPA detectors

EFDA JET Activity:	JW6-OEP-TEKE-13 and JW6-NEP-TEKE-17
Principal Tekes scientist:	M. Santala, Tekes – TKK
Collaboration:	Helsinki Institute of Physics, VTT Microelectronics, Jyväskylä University, Helsinki University of Technology and Ioffe Institute, St. Petersburg and CCFE JOC

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 diagnostic hardware as well as all data collection electronics has been supplied to JET by Ioffe Institute, St. Petersburg.

Presently, thin CsI(Tl) detectors coupled to photomultipliers are used to detect the ions in the NPAs. These detectors are limited due to slow response of CsI(Tl), their background sensitivity and poor energy resolution. Major drawbacks are that it is not possible to distinguish between alphas and deuterons in a single detector, and that in high fusion power experiments it is difficult to distinguish between signal and background.

JET EP2 diagnostic project: NPA detector upgrade: In the JET EP2 project, thin silicon detectors have been developed using SOI technology. Earlier, the detectors have been designed and prototypes manufactured and their physics performance has been proven. Tekes is the leading Association in this project and the collaboration has involved Helsinki Institute of Physics, VTT Microelectronics, Jyväskylä University, Helsinki University of Technology and Ioffe Institute in St. Petersburg.

From the physics point-of-view the performance of the detectors (Figure 3.25) meets the goals that were laid out in the beginning of the project. Detection of protons and alphas over a wide energy range was demonstrated and the pulse-height response is narrow enough to permit separation of different ion species based on their pulse height spectra. Weak sensitivity to gamma ray background was demonstrated in laboratory. However, several detectors did exhibit excessive leakage current during tests.

During year 2009 the Phase I of detector development was extended to perform additional tests on the detectors to analyse the leakage problems. Although the leakage current of the reverse-biased detectors has been found to be generally low, several of the detectors exhibited large and creeping leakage current during beam tests. This has raised concerns over long-term viability of the detectors.

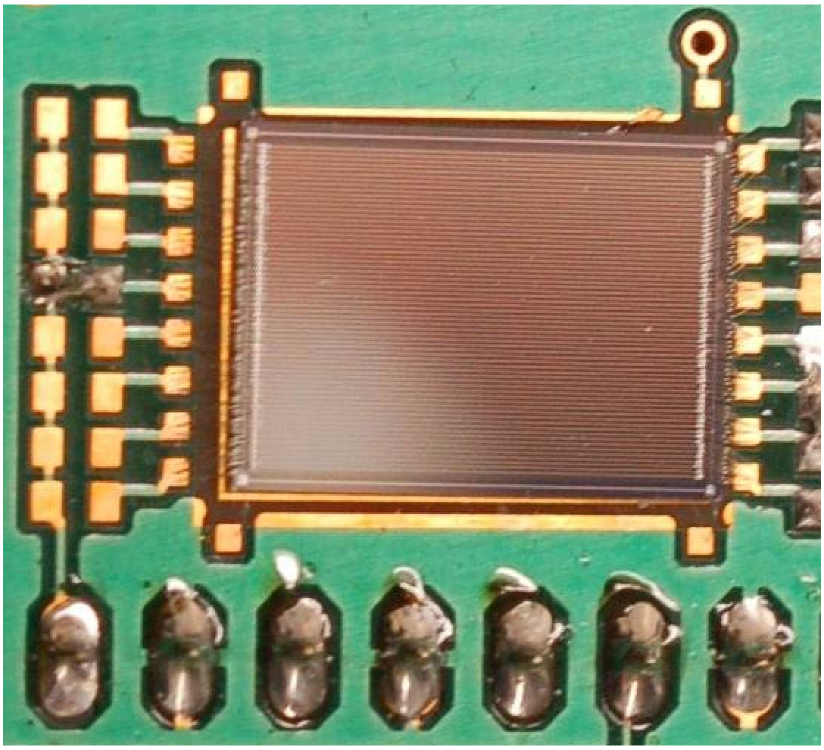


Figure 3.25. Detector bonded to a test PCB.

A systematic testing of existing detector prototypes was carried out to find out if the increase in leakage current is a common issue. A probe card which allows simultaneous contact to all the strips was used (Figure 3.26) to measure the leakage current of unbonded detectors. Initially an increase was observed, however, over longer periods the current reaches a maximum and starts to decrease (Figure 3.27). Similar behaviour was observed also after bonding the detectors. It was deemed that these currents are not large enough to cause serious problems with the diagnostic upgrade.

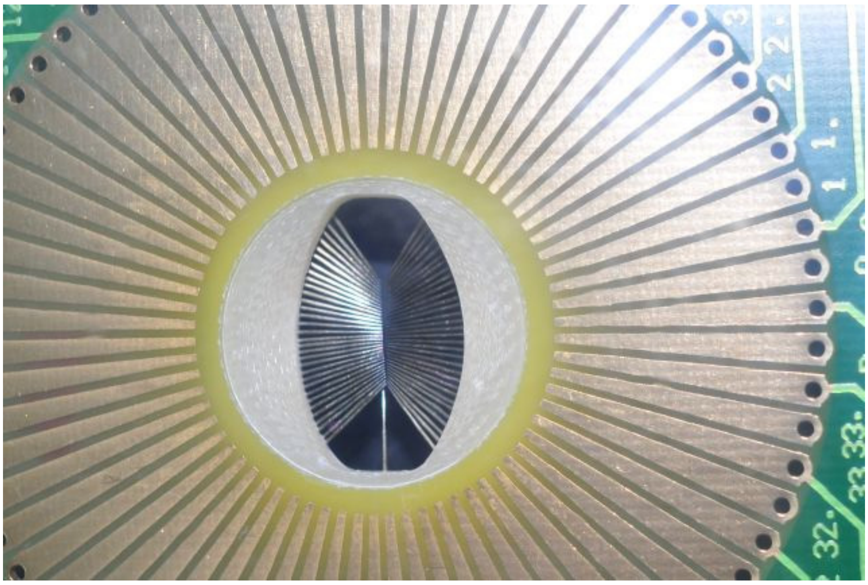


Figure 3.26. Probe card used for testing the leakage current of detectors. Contact to strips is made with pins on the left and the right and the bias contact is the single pin at bottom.

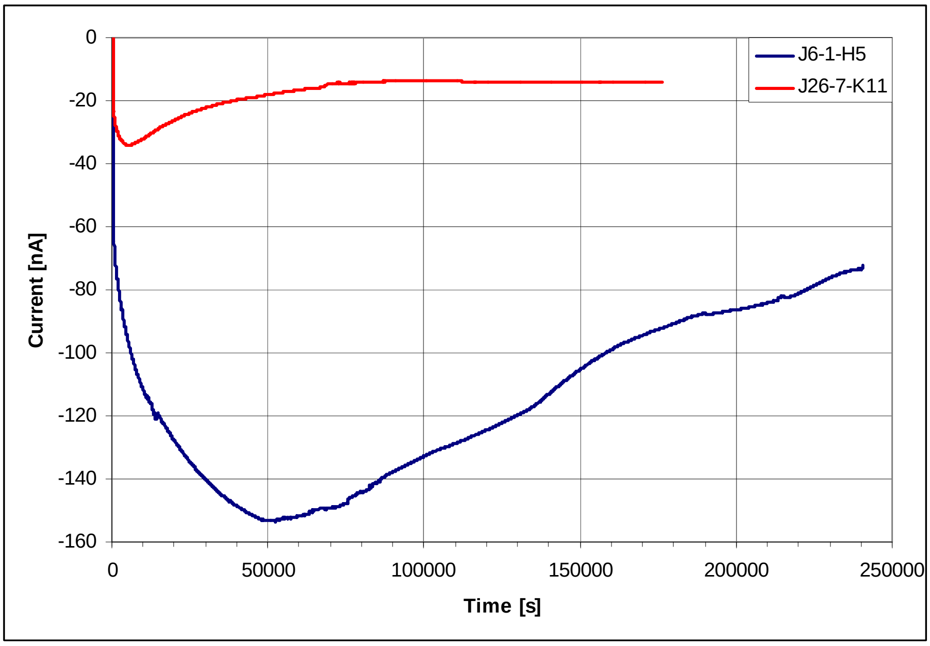


Figure 3.27. Leakage current in two detectors in a long term test. After initial increase the current reaches a maximum and then slowly decreases.

Towards the end of 2009, a conceptual design for upgrading the high energy NPA (KF1) was developed and presented at JET. The upgrade involves detector mounts, vacuum flange with feedthroughs, pre-amplifier electronics at torus hall, cabling to diagnostics hall and data acquisition hardware and software. It is planned to carry out the upgrade in collaboration with the JET operator and Ioffe institute. Upon approval of the final tests and conceptual design, Phase I of NPA project was closed.

3.6.2 Development of Micromechanical Magnetometer for ITER

EFDA Art. 5.1b Contract:	TW6-TPDS-DIASUP3
Research scientists:	E. Kuisma and J. Kyynäräinen, Tekes – VTT

Background: Magnetic diagnostics for ITER is to a large degree based on coils of different shapes at various locations, which respond to changes in the magnetic field. This is adequate for characterisation of short plasma pulses, but for longer pulses errors related to integration drift becomes excessive. To eliminate these errors introduction of DC-sensors based on the Lorentz force generated on current carrying coils have been proposed. Such sensors would not replace the coils, but strategically distributed they could provide a calibration reference for elimination of long term drift errors in coil outputs. The need for such sensors has been recognized in the central documents defining ITER diagnostics.

Micromechanical sensors fabricated on silicon wafers are on the other hand very small and can be cheaply reproduced in large quantities. Such sensors are typically based on the force balance of an elastic element formed from single crystal silicon. This technique is inherently suited for making force type magnetometers, into which the current coils readily be integrated by standard methods used in microelectronics. Prototypes of micromechanical low-field magnetometers have been developed at VTT for measuring e.g. the geomagnetic field. The magnetometers have two-axis magnetic flux density sensing with a chip size of $2\ \mathrm{mm} \times 3\ \mathrm{mm}$ (Figure 3.28). Even when packaged and with temperature compensation and calibration components they will fit in the 9 mm narrow space available.

ITER environment will pose a tremendous challenge not only to the sensor but also to the readout electronics owing to radiation, temperature, cable length, and the non-serviceability of the sensors.

Goals: Characterisation of the micromechanical steady state magnetometer in laboratory environment. Irradiation of the sensors with higher dose. Testing and development of the readout electronics for the magnetometer.

Progress in 2009: Vacuum-encapsulated second generation magnetometers were characterized to evaluate the fabrication process and magnetometers were tested in high magnetic flux densities in laboratory environment. Two new readout circuits were implemented and tested and their noise performances were analyzed.

Magnetic field measurements were performed in magnetic flux densities up to 1 T, half of the maximum field that will be present in ITER (Figure 3.29). Higher flux density was not feasible with the electromagnet employed in the tests but the magnetometers are expected to work even better at 2 T. The readout electronics included the excitation circuit and preamplifiers, but in the final performance analysis also the signal conditioning circuitry has to be taken account of. Direct dc readout was used in magnetic field measurements but other measurement techniques need to be studied further.

Test results show that the measured resolution of 0.60 mT/rtHz is enough to meet the minimum requirement of ±5 mT. With capacitive crosstalk compensation the resolution was still 21% better but the compensation could only be done in one field direction at a time. Long-term stability of the signal needs to be studied. The measured crosstalk between x- to y- field directions was 0.025% which meets the 1% specification. In reality the magnetic field crosstalk is even less than that since there were small alignment errors in the measurement.

Temperature dependence of the magnetometer was studied around room temperature. Signal amplitude showed a linear temperature dependence of 0.48%/K. In ITER the operational temperature range will be around 100 ºC but tests at this temperature range were not feasible with the present test facility.

Sensor chips were irradiated with neutrons in VTT’s Triga fission reactor (Figure 3.30). In the first irradiation the fast neutron (> 12 MeV) fluence was $2.2 \cdot 10^{16}$ n/cm^2. This level corresponds to the maximum expected fluence at half of the sensor locations in ITER. Resonance frequencies had changed only by 0.11% and the coil resistances by 4.4% after the irradiation. However, the Q-values decreased on the average by 49%. Most probably this is due to degradation of the vacuum level inside the chips. Another reason for the decreased Q values may be the reduction of the air gap between the moving plate and the capping wafer since neutron irradiation is known to cause compaction of glass which, in turn, can lead to bending of the chip. This decrease of the Q values, if not too large, can however be compensated by increasing the excitation current. The maximum expected fluence of fast neutrons among all sensor locations will be as high as $7.3 \cdot 10^{17}$ n/cm^2. A second irradiation corresponding to this value was performed but water had leaked in the test tube, the chips were detached from the substrates due to bending of the FR4 PCB and they could not be measured even after re-bonding. To conclude, the irradiation results suggest that the silicon sensor structure itself has good radiation hardness but the vacuum encapsulation technique should be improved, e.g., by using silicon direct bonding instead of silicon-glass anodic bonding. To confirm this assumption, more irradiation tests should be performed.

Although measurements in laboratory environment seem promising, the proof of operation in fusion reactor would still require in situ tests. For example, there will be a toroidal magnetic field of 10 T present together with multiple time dependent effects such as RIEMF and RITES. Long cables between the magnetometers and readout electronics will also require more work with the electronics design.

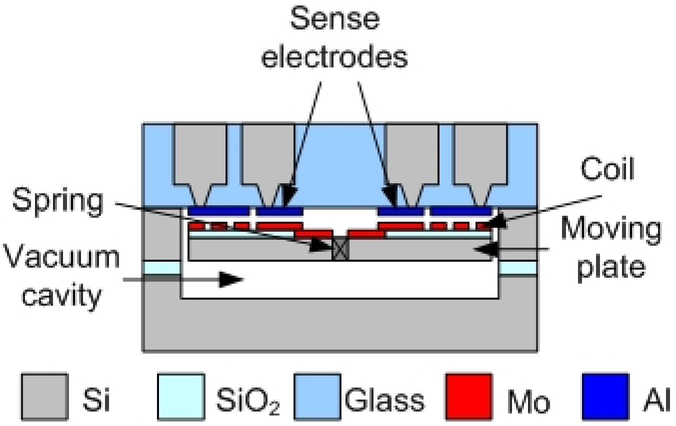


Figure 3.28. Cross-section of the magnetometer chip.

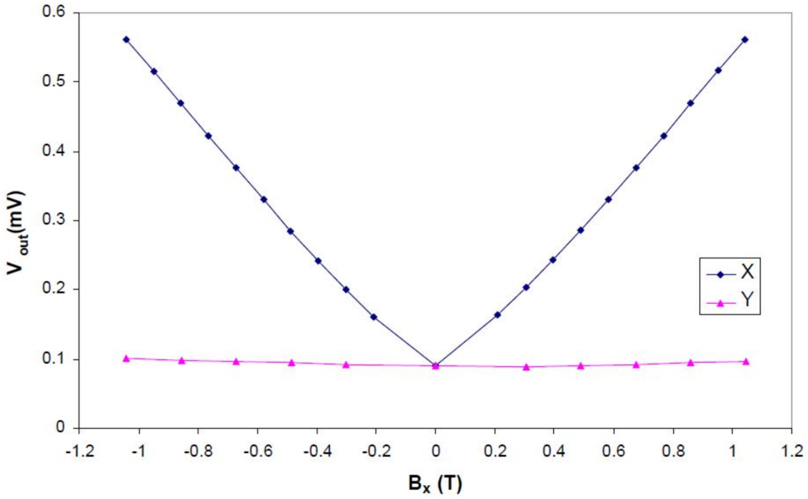


Figure 3.29. Magnetic field sensitivity of the magnetometer. The blue curve is the response in the x-direction and the pink in the y-direction, when the field was in the x-direction.

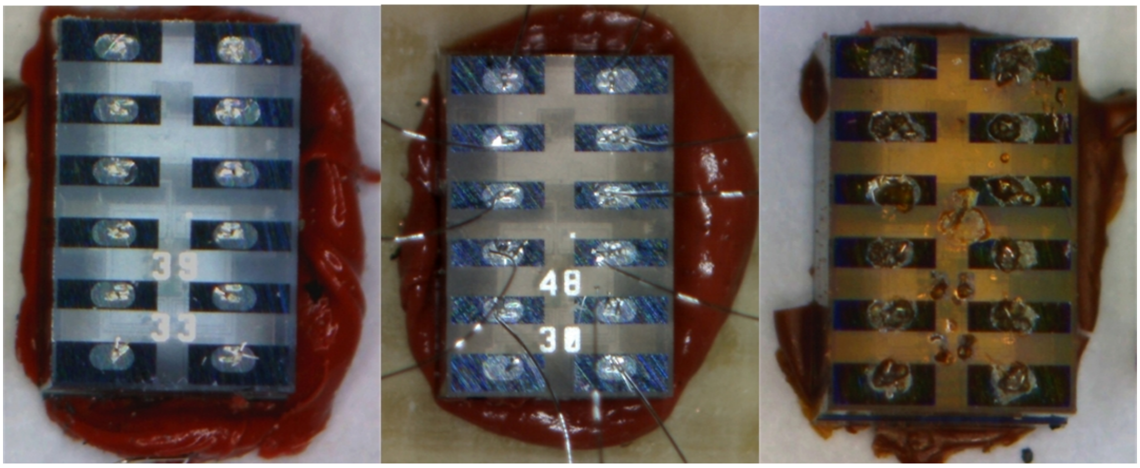


Figure 3.30. Microscope images of the magnetometer chips before and after neutron irradiation. Left: not irradiated; centre: fast neutron fluence of $2.2 \cdot 10^{16}$ n/cm^2; right: fast neutron fluence of $7.3 \cdot 10^{17}$ n/cm^2. A radiation induced color change in the glass capping wafer is apparent.

3.7 Material Research

3.7.1 He-Fe-Cr potential

EFDA PWI tasks:	WP08-09-MAT-REMEV 3
Principal investigators:	K. Nordlund, C. Björkas and N. Juslin, Tekes – University of Helsinki
Collaboration:	SCK-CEN

Ferritic/martensitic steels are considered candidate structural materials for fusion reactors, as they are known to be resistant to swelling and irradiation compared to other steels. These steels will contain small amounts of helium, due to neutron irradiation, as 14 MeV neutrons produce He through (n,a) transmutation reactions. He is known to degrade the mechanical properties of steels due to e.g. bubble formation, blistering and loss of fracture toughness. There is an ongoing international effort to understand and predict radiation damage in steels with a multi-scale approach, including density functional theory, Molecular dynamics (MD) and Monte Carlo simulations. Within Europe the activity is coordinated within the REMEV EFDA task.

Molecular dynamics (MD) computer simulations are well suited for the length and time scales of primary damage formation due to collision cascades. Modeling real steel with up to dozens of different elements is still out of reach for MD simulations, but good models exist for FeCr which can be used as an approximation for ferritic steels. Until recently no inter-atomic potential for Fe-Cr-He existed, but in 2008–2009 we developed one.

Using this potential we studied the effect of He defects in $Fe_{90}Cr_{10}$ on the damage formed due to collision cascades. For up to 5 keV cascades, less than about 0.5% He has little impact on the damage production, while a higher concentration significantly increases the total number of Frenkel pairs. This increase is about fourfold for 1% He in a 5 keV cascade. This is explained by formation of substitutional He reducing the recombination. In comparison with cascade damage in Fe with He defects, we see an even higher increase in FeCr. The methods used, however, are not identical and further studies will be needed to determine the exact nature of the difference between FeHe and FeCrHe. For substitutional He the damage production in a cascade decreases. During equilibration at room temperature, the He interstitials cluster together. The interstitials and defect clusters tend to migrate and form away from Cr atoms. Due to the cascade the He concentration in the cascade region increase by about 30% and the Cr concentration in the vicinity of He atoms increase, though remain at about half that of a random solution.

3.7.2 Strain rate effects in Fe and FeCr alloy

Emerging Technologies:	WP08-09-MAT-ODSFS
Principal investigator:	S. Tähtinen, Tekes – VTT

In this work Fe and Fe9%Cr steel samples have been tensile tested using strain rates from 10^{-4} down to 10^{-8} s^{-1} at test temperature of 55°C. Figure 3.31 indicates a market increase in work hardening rate of Fe when the strain rate is decreased from 10^{-5} to 10^{-6} s^{-1}. This unexpected negative strain rate dependency was not observed in Fe9%Cr alloy which showed only a minor decrease in flow stress with decreasing strain rate

TEM characterisation of the Fe samples showed that the microstructure changed from a typical band dominant structure to a dislocation cluster dominant structure with decreasing strain rate. Dislocation clusters formed already at early state of deformation and cluster density seemed to increase with increasing amount of strain. No dislocation cells or bands were observed in Fe samples after low strain rate tensile testing. On the other hand, the deformation structure of the Fe9%Cr alloy showed a typical band and cell dominated dislocation structure with no effects of strain rate.

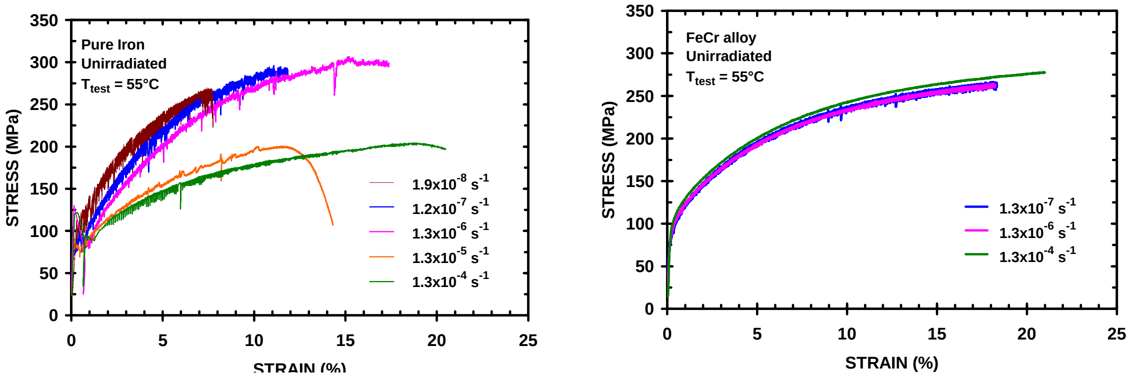


Figure 3.31. Tensile stress-strain curves of a) Fe and b) Fe9%Cr alloy with different strain rates between $1.3\text{x}10^{-4}$ and $1.9\text{x}10^{-8}$ s^{-1} at 55°C.

3.7.3 MD simulations of the erosion behaviour of WC due to noble gas and plasma irradiation

EFDA PWI tasks:	WP08-09-MAT-WWALLOY
Principal investigators:	K. Nordlund and K. Vörtler, Tekes – University of Helsinki

Deuterium trapping and re-emission: Studying the plasma surface interactions between deuterium and impurities originating from the plasma with WC has a direct application in the context of the next experimental fusion reactor ITER. In ITER, the plasma facing components of the divertor part of the reactor (where the highest heat loads are expected) will consist of carbon fiber composite (CFC) and tungsten. Due to material erosion and migration processes, WC will inevitably form in films in the divertor region during reactor operation. In the fusion reactor the hydrogen isotopes deuterium and tritium will be in the plasma state where also impurities will be present. The impurities originate from the wall materials, the fusion reaction product helium, and other noble gases that are, for example, used for cooling. Studying the interaction between deuterium and those impurities with WC is important for the following reasons: (i) Chemical changes in the wall material by hydrogen isotope and impurity bombardment determine, among other things, how fast the wall material degrades during reactor operation. (ii) Studying D re-emission from wall material to the plasma also affects the recycling of unburned fuel. (iii) The T retention in the wall material is, apart from degrading the material’s properties, an important factor for ITER; the retention of the hydrogen isotope tritium in the reactor components is a safety criterion for operation. The feasibility of future commercial fusion reactors depends on all three latter mentioned facts.

Generally, solid materials degrade due to hydrogen accumulation, where the trapped hydrogen can form voids, bubbles, and blisters. There exists a lack of comparison of experimental and simulation data, which also includes the chemical processes. The reasons are simulation difficulties arising due to the experimental value of the D flux, which restricts the system size and therefore the realization of realistic simulations. Therefore, a direct understanding of the trapping and re-emission mechanisms of D in WC has not yet been obtained. Another interesting feature of energetic D implantation into tungsten is the formation of blisters on its surface. This effect is also seen if carbon is present in the tungsten matrix. A “blister” is a void or bubble close to the sample surface. As blistering, we refer here a rupture in the sample leading to an expanding void. This process is also sometimes called flaking or exfoliation. The mechanism of blister formation in tungsten is not yet fully understood, although both experiments and FEM simulations have been performed to tackle this problem. Recent experiments indicate that diffusion processes of D in tungsten are responsible for forming blisters.

This work was the first MD study focusing on deuterium trapping and re-emission in WC. Moreover, chemical and structural changes in the material were studied in detail. MD simulations of deuterium co-bombardment with impurities on crystalline WC with ion energies from 100 to 300 eV were performed. D bombardment with and without impurities changes the structure from crystalline to amorphous. Moreover, D trapping can lead to a “blistering/flaking”-like effect. If a steady-state D concentration is reached, the force it exerts due to the D_2 gas pressure can lead to a rupture in the sample (Figure 3.31). This mechanism is the consequence of the high fluxes in the simulations. It is not responsible for blisters seen in experiments that are related to diffusion processes and where fluxes are orders of magnitude lower. D_2 re-emission after annealing to 600−1 000 K showed that D_2 is highly mobile in WC. Thus, the concentration of C in WC determines the amount of trapped D.

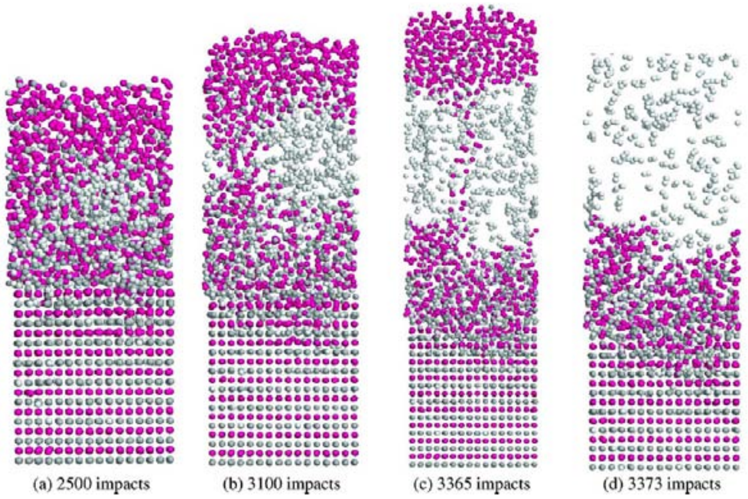

(a) 2500 impacts (b) 3100 impacts (c) 3365 impacts (d) 3373 impacts

Figure 3.32. Snapshots of D_2 bubble formation leading to blistering: (a) after 2 500, (b) 3 100, (c) 3 365, and (d) 3 373 ion impacts with 90% D and 10% W (100 eV) on W-terminated WC. The light grey spheres represent D, the dark grey C, and the magenta ones W atoms. The figures show the projection of a full 3D cell into a 2D plane.

Sputtering of WC due to noble gas and plasma irradiation: Sputtering is the process which describes the removal of surface atoms caused by particle bombardment. It is widely applied in e.g. surface analyzing techniques and surface processing. Generally two sputtering phenomena are distinguished: physical and chemical sputtering. Physical sputtering is caused by momentum transfer from the bombarded ions. Depending on the mass and energy of the impinging particles also dimers and clusters are found in the sputtered particles. In chemical sputtering chemical reactions between the impinging particles and the material take place causing molecule sputtering. The threshold energy for chemical sputtering is below the physical one. Bond-breaking by light ions in the "swift chemical sputtering" process also leads to molecule emission.

Sputtering is a crucial issue in fusion reactors. In a fusion reactor the hydrogen isotope rich plasma is not perfectly confined by magnetic fields. Ions from the plasma will therefore reach the reactor walls. Interactions between the ions from the plasma and the Plasma Facing Materials (PFMs) cause among other effects sputtering. Details of the sputtering of the PFMs are needed for the safety of the reactors, since the lifetime of the wall materials also depends on surface erosion. Moreover, the sputtering of PFMs increases the impurity level of the plasma; since those not fully ionized sputtered particles reduce the energy of the plasma by radiation.

There exist a few experimental studies of sputtering on WC by pure D bombardment. Mixed ion beam experiments with C and D ions bombardment have only been conducted on pure W, but at higher ion energies than considered here. Noble gas ion bombardment has only been studied by Binary Collision Approximation (BCA) simulations using He and Xe ions. Only one study of sputtering by D bombardment on WC surfaces has been previously conducted using Molecular Dynamics (MD) simulations. Träskelin *et al.* used a realistic interaction model allowing chemical effects to be described. This study is continued in this work by considering the plasma impurities C, W, He, Ne, or Ar in addition to D bombardment, and therefore performing mixed ion impacts. Moreover, we consider a higher fluence (a higher number of impacts) and a divertor relevant temperature of 600 K. This work focuses on ion energies from 100 to 300 eV, i.e. in the region of the highest sputtering yields for D on WC for low energies. The sputtered species (single atoms and small molecules) were analyzed in detail.

Generally, the C and W sputtering yields are higher when impurities are present compared to pure D bombardment. We observed a chemical effect on the W sputtering yield due to the C and Ar impurities. Adding C or Ar impurities to D bombardment changed the composition of the sample, and more W was sputtered, compared to what would be expected if no chemical effects are present. This chemical effect is particularly interesting for applications in fusion reactors, where lots of different impurities are present in the plasma.

Preferential C single atom sputtering was observed. W was dominantly sputtered as WC dimer or other small W_xC_y molecule (Figure 3.33). The WC dimer and cluster/molecule sputtering was almost only seen in impurity bombardment, meaning that the heavier C, W and noble gas ions were responsible for their sputtering. Analyzing the sputtering mechanism showed that it is of physical origin. We assume that dimers and small cluster sputtering would also occur in other compounds like e.g. BeC and BeW.

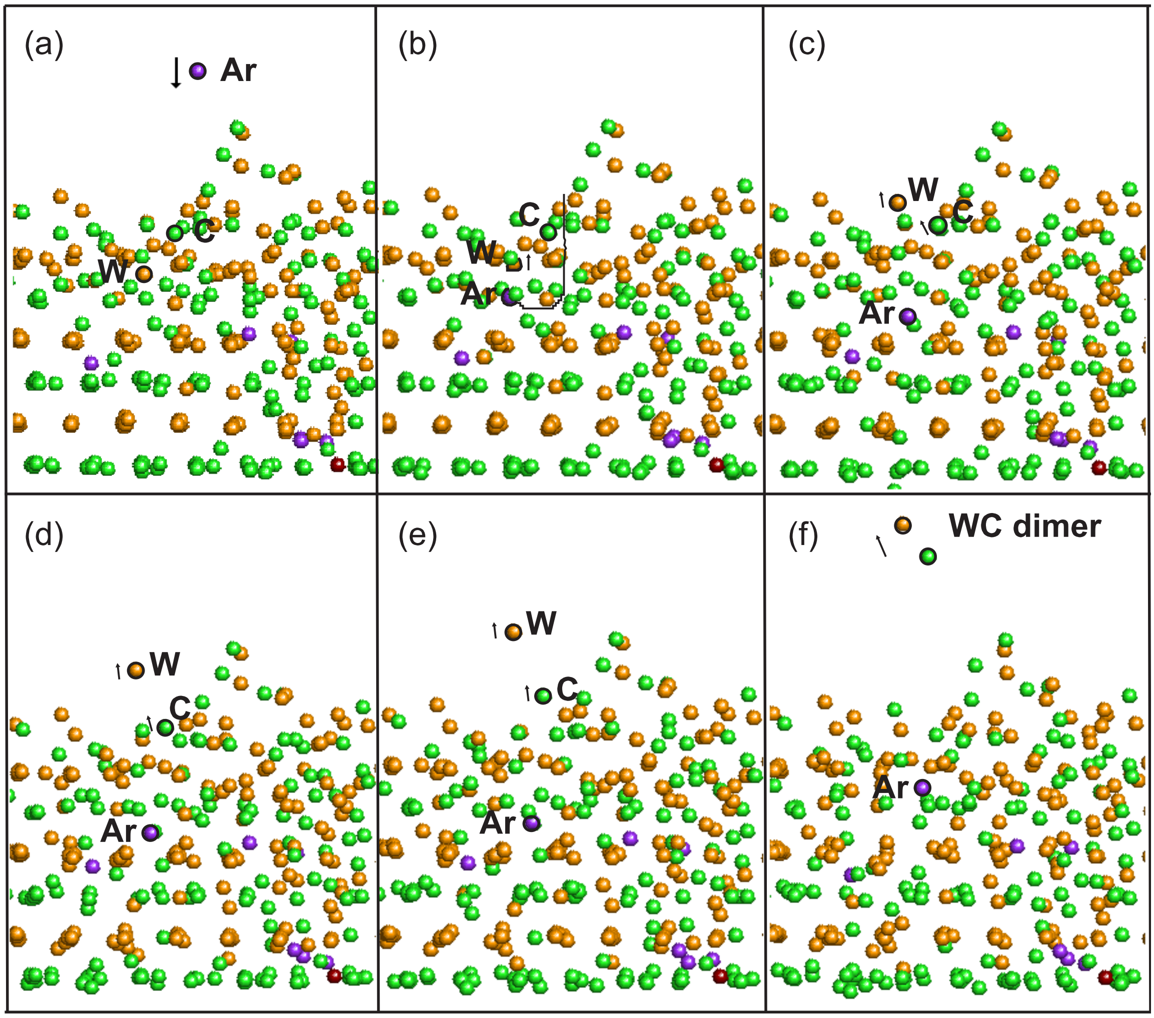


Figure 3.33. Snapshots of WC dimer sputtering. (a) 300 eV Ar is bombarded, first hitting a C atom near the surface and leading to multiple collisions in the sample ((b) shows its trajectory) and finally colliding with a W atom. In (c)-(e) this W pulls along the C atom from the surface, and (f) shows the sputtered WC dimer. The arrows indicate in which directions the atoms are moving. Color code: green is C, orange W, purple Ar, red D. The figures show the projection of a full 3D cell into a 2D plane.

3.8 Euratom and EFDA Fusion Training Scheme

3.8.1 EFDA goal oriented training in fusion theory and modelling – GOTiT

EFDA GOT:	WP08-GOT-GOTiT
Tekes trainees:	L. Aho-Mantila, O. Asunta, S. Janhunen, and S. Leerink
Tekes mentors:	J. Heikkinen, VTT and T. Kurki-Suonio, TKK

The year 2009 was very intensive for the EFDA Goal Oriented Traning in Theory, GOTiT for short. Within Tekes we have four GOTiT trainees: L. Aho-Mantila, O. Asunta, S. Janhunen, and S. Leerink. The monthly e-seminar series was coordinated by Tekes (T. Kurki-Suonio and S. Leerink) and it consisted of presentations given by both high-level experts and GOTiT trainees. GOTiT also offered three high-level intense courses during 2009 and extensive lecture material in this field was prepared and distributed by the organizing associations. A two-week course on Single Particle Physics and Monte-Carlo methods at KTH Stockholm, Sweden and VTT Espoo, Finland, 19–30 October 2009, jointly organized by Tekes – TKK and VTT and KTH Sweden, a two-week course on Magnetic Control of Tokamak Plasmas at the Università di Napoli Federico II, Napoli, Italy, 17–26 November 2009, and a one-week course on Optimization and Parallel Computing at CCFE, UK, 5–8 May 2009. These courses were attended by not only our trainees but also by other advanced graduate students from TKK.

3.8.2 EFDA Fellowship – M. Groth

EFDA Fellowship:	WP08-FRF-TEKES/Groth
Fellower:	M. Groth, Tekes – TKK

During the first year of the appointment as an EFDA Fellow in Fusion Research M. Groth accomplished the goals originally set in the application:

- supported the JET and ASDEX Upgrade related research activities at Helsinki University of Technology, Finland, and the Technical Research Centre of Finland,
- supervised several graduate and undergraduate students at Helsinki University of Technology, and
- continued performing detailed simulations of JET, ASDEX Upgrade, and DIII-D plasma using sophisticated edge fluid codes, including the two main European codes EDGE2D/EIRENE and SOLPS.

Several publications and the attendance of an ITPA Divertor and Scrape-off Layer working group meeting resulted from this work. M. Groth was selected for the position as the deputy task force leader the 2010–2011 JET ITER-like wall campaign in June 2009.

3.8.3 Euratom Fusion Training Scheme (EFTS): PREFIT programme

PREFIT Partners:	Tekes – TUT/VTT, CEA and OTL

Overview of the programme: PREFIT is implemented as an integrated training and research programme. Each researcher works towards the award of a PhD from TUT by a combination of training work and a research project. To attain a PhD from TUT a researcher must accumulate 70 credits from all of the activities and, in addition, deliver and defend a PhD thesis of high academic quality as judged by an independent expert in the field.

The overall programme is shown schematically below:

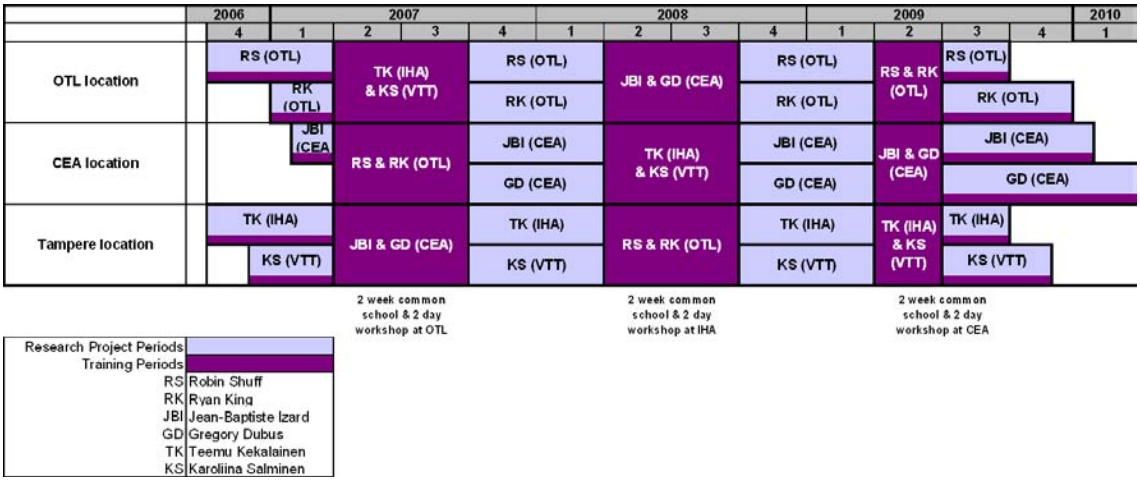


Figure 3.34. Schematic view of PREFIT programme.

The research project did continue throughout the entire 3-year period and had two primary deliverables: a State-of-the-Art report after 1 year and a final thesis at the end of 3 years. The training programme did comprise three 6-month periods at each partner site to undertake a mixture of on-the-job training, short project assignments, classroom lectures, workshops and conferences. Each researcher was required to deliver a written report at the end of each training period and a report summarising the knowledge gained during all three Common Schools.

Training during 2009: As stated in the PREFIT contract, all six researchers were assigned to partner sites for the second 6-month period of their formal training during the summers of 2007 and 2008. For the summer of 2009 the six researchers were assigned to home sites for the third 6 month period of their formal training.

The third PREFIT common school was hosted by the CEA from 2 June 2009 to 16 June 2009. For the last time, the six PREFIT researchers, were given the opportunity to meet at a single place and to receive common classroom training elements. This time the period was divided in two parts. During the first 5 days PREFIT students attended theoretical courses on robotics at the Paris VI – Pierre & Marie Curie University. Then for the rest of 5 days students were back to the CEA site in Fontenay-aux-Roses to be given lectures on different specific robotic applications developed at the CEA. The annual PREFIT workshop was held at the end of this common school. In this occasion students presented the results they've obtained in our respective research projects for the past 12 months.

The main objective of common school was to strengthen knowledge on robotics with formal classroom style training. The courses provided by the ISIR focused on fundamentals of robotics through lectures and practical works on Matlab using the platform habitually used by the students of the Paris VI University. CEA provided students with training in various aspects of robotic technologies, not only for ITER. Students were offered the benefit of the CEA experts' extensive experience in the development of robotic and manipulation devices mainly for nuclear applications.

Addressed topics covered during this common school:

- Kinematic, velocity and dynamic models of robotic structures
- Parameters identification
- Position and velocity control of robotic structures
- Long-reach inspection arm for ITER
- Control of the AIA
- Manipulation of objects in the micro world
- Modelling of transmission chains
- Elements on the effect of radiations on materials and equipments
- Introduction to the problem solving TRIZ method
- Introduction to supervising systems and supervisory control
- Force reflective master slave systems, bilateral coupling
- Feedback on electronic rad-hardening.

Moreover, the students were given the opportunity to visit of the new ISIR facilities at the Paris VI University. Demonstrations on two remote handling systems were also organised at CEA: force-feedback manipulation on the Staübli RX90, and collision avoidance and assistance to the operator on the Maestro telerobotic system.

The year 2009 was the year when PREFIT researchers concluded their studies. All of the researchers did complete their all three training periods and have successfully submitted corresponding training reports including their research topic state-of-the-art reports. Three Dr-Thesis drafts are currently under Academic pre-evaluation phase.

4. ACTIVITIES OF THE ESTONIAN RESEARCH UNIT

4.1 Assessment of LIPS Diagnostics for In-Situ Characterisation of In-Vessel Components

Institute:	Institute of Physics, University of Tartu
Research Scientists:	Matti Laan, Mart Aints, Ants Haljaste, Peeter Paris and Jüri Raud

In 2009 we have tested the coating materials, which are representative for ITER and are thus important candidates for plasma –surface interaction studies inside the reactor. The main attention has been paid to the developing of marker coatings. In the main part of laser induced plasma spectroscopy (LIPS) studies, the radiation of KrF laser (λ = 248 nm) has been used, but some preliminary measurements were carried out using the first (λ = 1 064 nm) and the third (λ = 355 nm) harmonics of Nd/YAG laser.

Two different sets of samples were studied. The first set of samples was prepared by DIARC-Technology Inc. (Finland). The set had diamond like carbon (DLC) layer of 1.5 μm thickness and Re interlayer of 50 nm thickness on stainless steel (SS) substrate. The second set was prepared at the National Institute for Laser, Plasma and Radiation Physics (Romania). In this case Ti as a substrate material was coated by W layer of 11 μm thickness and the thickness of Mo interlayer was 2 μm.

Spectra in 350–850 nm wavelength region were recorded by ME5000 spectrometer (Andor Technology), changing both the width of the recording time-gate Δt and the delay time t_d of the gate opening from the laser pulse. For finding of optimum value of delay time t_d, LIBS spectra of a graphite sample were recorded. The broadening of spectral lines was caused by Stark effect. When the delay time was increased, the line width and continuum intensity decreased considerably (Figure 4.1). Besides, the growth of t_d led to a considerable fall of spectral line intensity and when $t_d \geq 200$ ns, the line was not detectable.

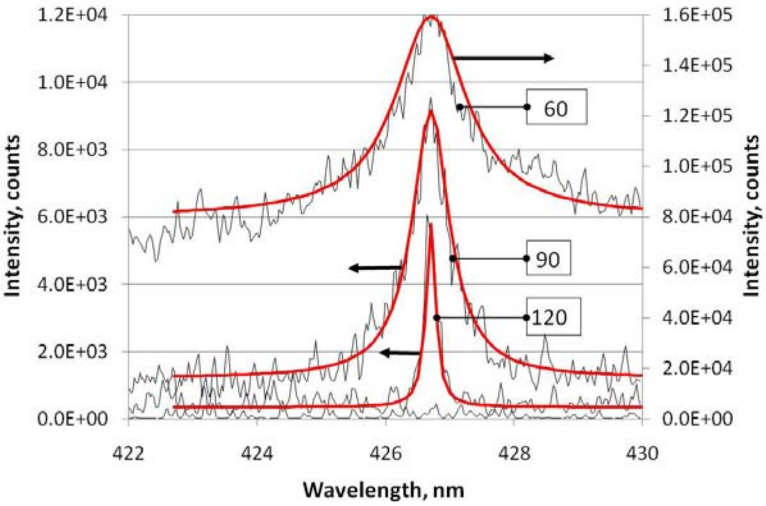


Figure 4.1. Graphite sample; Δt = 100 ns; Φ = 14 J cm^{-2}; parameter – delay time t_d, ns; spectra are averaged over 5 recordings and fitted with Lorentzian shape.

Because of high density of spectral lines, in the case of metals the overlapping limited the number lines suitable for characterisation of elements. Besides, the need to analyse single-shot spectra makes it impossible to take ensemble averages of the recorded data. A detailed analyse allowed to clarify the main source of fluctuations – variation of the background signal.

Figure 4.2 gives for W-Mo-Ti sample the intensities of W lines as a function of laser shot number. Intensity of a single spectral line is fluctuating in a large limit and fluctuations belonging to different spectral lines of are not correlated. The averaging of normalised intensities over the spectral lines of an element diminished considerably shot to shot fluctuations.

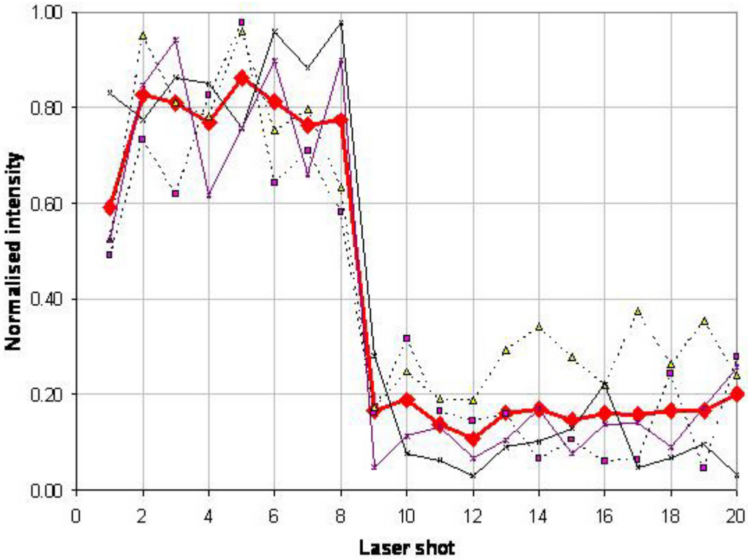


Figure 4.2. W-Mo-Ti sample. Thinner lines belong to single spectral lines of W; thicker line presents the average of normalized average of four Mo spectral lines.

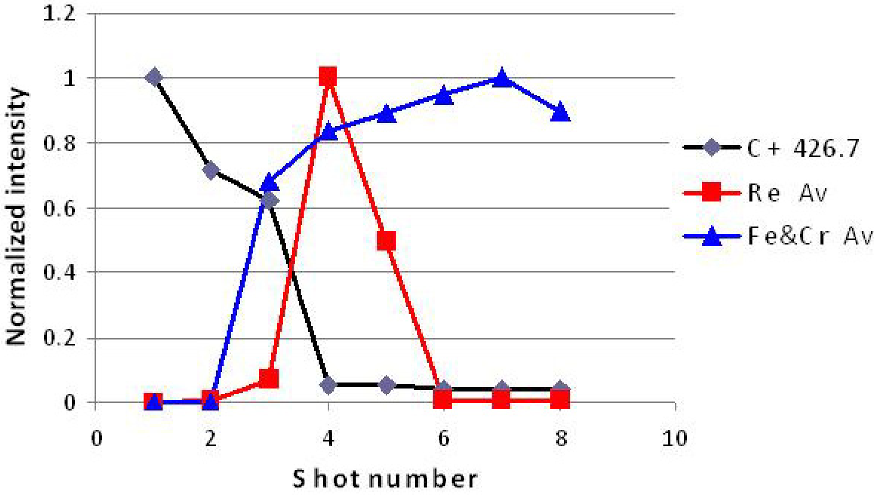


Figure 4.3. DLC-Re-SS sample. Average of normalized intensities as function of laser shot number.

4.2 Attenuation of Radiation Damage in Dielectric and Composite Materials of Interest for a Fusion Reactor

Institute:	Laboratory of Physics of Ionic Crystal (LPIC), Institute of Physics, University of Tartu
Research Scientists:	Aleksandr Lushchik, Sergei Dolgov, Irina Kudryavtseva, Tiit Kärner, Fjodor Savikhin, Evgeni Vasil'chenko
PhD Students:	Evgeni Shablonin, Anna Shugai

Backrgound: Many specialists in the field of radiation material science find that one of the significant obstacles impeding the development of nuclear and especially thermonuclear energetics is insufficient radiation resistance of various construction materials: primarily metals and alloys, and also semiconductors, wide-gap dielectrics and superconducting materials. In particular, the radiation resistance of wide-gap materials (WGMs, E_g = 7-15 eV - Al_2O_3, MgO, $MgAl_2O_4$, Y_2O_3, $Y_3Al_5O_{12}$, SiO_2, Li-containing materials, etc) promising for future industrial high-temperature heat (≥ 1 000°C) fusion stations should be substantially enhanced. It is obvious that this complicated task can be solved only on the basis of subsequent basic research. In 2007–2008 our main attention was paid to the separation of novel non-impact mechanisms of radiation damage in α-Al_2O_3, MgO and Lu_2O_3 crystals. It was found that, besides the universal for solids impact (knock-out) mechanism, stable Frenkel defects (FDs, F centres and oxygen interstitials) in these materials are also created due to the recombination of hot (non-relaxed) electrons and holes. The energy released at such hot recombination exceeds the threshold for the creation of FDs (E_{FD}). According to our suggestion, the efficiency of FD creation via hot recombination could be significantly reduced by doping the materials with some impurity ions, thus the energy excess of hot carriers is partly spent on the direct excitation of these impurity centres resulting in impurity luminescence emission or heat release (the solid-state analogue of Frank-Hertz effect in gases).

Main Results in 2009: The experimental investigations of novel non-impact creation mechanisms of FDs and their associations were continued mainly for MgO single crystals grown at our laboratory: highly pure crystals, Cr- or Be-doped samples and, for the first time, crystals previously plastically deformed by ~5% along long [001] crystal axis. Radiation defects, formed by 2-GeV heavy gold or uranium ions, were carefully investigated using methods of luminescent/optical spectroscopy, a probing 2–15 keV electron beam or 300 keV electron pulses. It is shown, that a joint action of impact and non-impact processes of radiation damage should be taken into account. Impact mechanisms induce formation of deformations and the behavior of hot electron-hole recombination (i.e. non-impact mechanism) occurs under complicated conditions (similar to that under uniaxial plastic deformation). Simple and doped $Lu_3Al_5O_{12}$ and Gd_2SiO_5 crystals were studied by several experimental methods as well.

Figure 4.4.a presents the emission spectrum measured for a MgO crystal preliminarily plastically deformed at 300 K under the excitation by 15 keV electrons at 5 K. The spectrum contains an intense narrow band at 7.65 eV, i.e. at the edge of fundamental absorption, a step at 7.2–6.8 eV and two bands peaked at 5.2 and 2.9 eV. Two latter emissions undergo significant enhancement just after inelastic stress. Deformation related emission bands as well as the emissions connected with the presence of F and F^+ centres (2.4 and 3.15 eV, respectively) have been also detected at 5 K in MgO preliminary irradiated with 2-GeV gold ions. The emission of free excitons (~7.77 eV) is suppressed both in plastically deformed or ion-irradiated samples. The excitation spectra for 2.9 and 5.2 eV emissions measured for the plastically deformed MgO crystal using synchrotron radiation are shown in Figure 4.4.b. The emission at 2.9 eV is efficiently excited in a wide region of 6.8–7.4 eV (excitation of oxygen near bivacancies). The excitation band for the emission at 5.2 eV is relatively narrow (7.5–7.6 eV) and is connected with the excitation of oxygen nearby cation vacancies. The arrows indicate the region where exciting photons form free excitons.

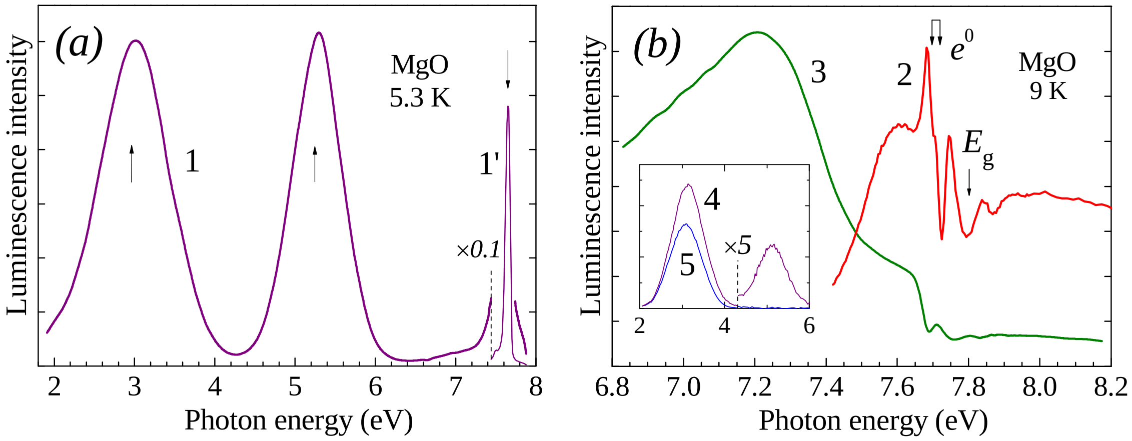


Figure 4.4. The emission spectra at the excitation by 15-keV electrons (1 and 1') or 7.6 (4) and 7.2 eV (5) photons and the excitation spectra for 5.2 (2) and 2.9 eV (3) emission measured for MgO at 5–9 K. All spectra are measured for the samples preliminarily plastically deformed (~5%) at 300 K.

Figure 4.5.b shows the curves of thermally stimulated luminescence (TSL) measured for two MgO:Cr samples irradiated by 15-keV electrons at 5 K. The TSL peak at 335 K is significantly more intensive in a MgO:Cr sample, which previously underwent uniaxial plastic deformation, than in a non-deformed crystal. The deformation leads to a sharp increase of the number of holes localized nearby cation vacancies (so-called V^0 centres) as well as to the appearance of a low-temperature TSL peak at ~53 K.

The impact mechanisms of radiation damage causes strong deformation of irradiated samples, thus facilitating the creation of FDs via the non-impact mechanisms connected with electronic excitations. In MgO with $E_{FD} > E_g$, the recombination of relaxed electrons and holes does not lead to the creation of FDs in the regions of perfect lattice. However, the probability of hot recombination (between non-relaxed carriers) with the creation of FDs is considerably high in the tracks of swift heavy ions (~2 GeV, Au or U) with extremely high density of electron-hole pairs. The efficiency of such hot recombination could be decreased if before recombination hot electrons/holes directly excite impurity centres thus transforming into the relaxed ones. The transition of an impurity centre from an excited state into a ground state occurs via an impurity luminescence emission or a heat release (package of phonons).

The latter processes have been studied in MgO:Be (6.1 eV emission arises at the excitation of oxygen ions nearby Be^{2+}) and MgO:Cr (100 ppm) crystals. As an example, Figure 4.5.a. presents the dependence of the cathodoluminescence (CL) intensity on the temperature measured at the cooling down (400 → 6 K) of MgO:Cr^{3+}. The 1.7 eV impurity emission occurs at the excitation of oxygen ions near a Cr^{3+} impurity ion. To avoid a high irradiation dose, short-run (30 s) pulses of an electron beam (5 keV, 50 nA mm^{-2}) and a subsequent 60 s pause were used at the cooling of MgO:Cr^{3+} with $\beta = 10$ K min^{-1}. In 1–2 s after a pulse of electron irradiation was stopped, the intensity of CL drastically decreased (by 4–5 orders of magnitude). The results presented in Figure 4.5 testify that a solid-state analogue of FHE provides in MgO:Cr^{3+} a considerable contribution to a fast (10^{-3}-10^{-6} s) component of CL associated with radiative transitions in Cr^{3+} centres. This conclusion is especially apparent for the temperature region of 400–180 K, while the competition between the solid state Franck-Hertz effect and some other phenomena can explain the behaviour of CL temperature dependence at $T < 80$ K.

A joint action of impact and non-impact processes of radiation damage should be taken into account. Impact mechanisms induce the formation of deformations and the behavior of hot electron-hole recombination (i.e. non-impact mechanism) occurs under complicated conditions (similar to that under uniaxial plastic deformation). The latter circumstance stimulated the direct experiments on the simulation of hot recombination in pure and plastically deformed NaCl single crystals under irradiation by synchrotron radiation (incl. 12.84 eV photons) or ArF excimer laser (12.84 eV emission in the regime of two-photon absorption). It is shown, that FDs in radiation-resistant systems (formation energy of FD pair exceeds the energy gap) can be formed even at 5 K via hot electron-hole recombination. The high-temperature stabilization of these defects is facilitated in plastically-deformed crystals.

It was shown also that a joint action of impact and non-impact processes causes the efficient creation of FDs, their associations and even macro-size defects in ioniccovalent wide-gap metal oxides (e.g., $Lu_3Al_5O_{12}$) under irradiation with GeV-heavy ions at fluences of ~10^{12} ions cm^{-2}. On the other hand, such irradiation does not induce macro-size radiation damage in MgO and Al_2O_3 single crystals. A further investigation of the influence of the presence of luminescent impurity ions or preliminarily formed F centres, interstitials and their associations on the heavy-irradiation-induced damage of a crystal lattice in wide-gap materials lies ahead.

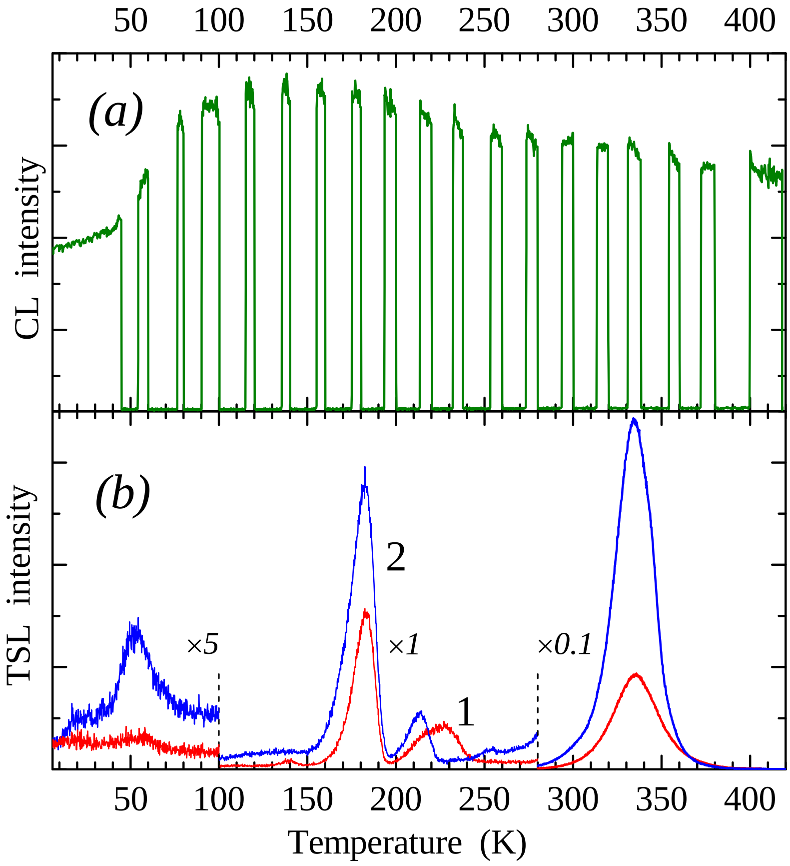


Figure 4.5.a. The dependence of the CL intensity on the cooling temperature (400 K → 6 K) for a MgO:Cr^{3+} crystal under excitation by 5 keV electrons. (b) The TSL curves measured for 3.4 eV (curve 1) and 3.2 eV emission (curve 2) in MgO crystals irradiated by 15 keV electrons at 6 K. The samples were previously annealed at 1 575 K (1) or plastically deformed (5%) at 295 K (2).

4.3 Tritium Depth Profile Measurements of JET Divertor Tiles by AMS

Institute:	Institute of Physics, University of Tartu; VTT; NIPNE (MEdC)
Research Scientist:	M. Kiisk, C. Stan-Sion (MEdC), J. Likonen, M. Enachescu (MEdC) and M. Dogaru (MEdC)

Specific objectives: First test results with the newly installed experimental set-up for tritium analysis at NIPNE, preparation of samples for AMS analysis. AMS analysis of tritium depth profiles in selected JET divertor tiles.

In 2008, principal agreement for joint collaboration with Horia Hulubei National Institute of Physics and Nuclear Engineering, Laboratory of Accelerator Mass Spectrometry to carry out experiments on tritium depth profile measurements was founded.

Accelerator mass spectrometry (AMS) is a highly sensitive analyzing method that provides complementary information to other conventional methods used to analyze or diagnose fusion experiments, but is the only method capable to determine low concentrations of Tritium in different substrates.

Tritium standard samples were prepared, with different Tritium concentrations in carbon, adequate to calibrate the concentrations that will be measured in the divertor tiles from JET. The T/C standards were produced with concentrations of 10^{-9} and $10^{-8.}$ The substrate matrix is close to a CFC structure. Produced T standards were used in our experimental set-up to test and calibrate the newly installed AMS experimental facility for Tritium Dept Profiling in Bucharest (NIPNE) Figure 4.6. shows the new experimental set up and the new tritium detector system.

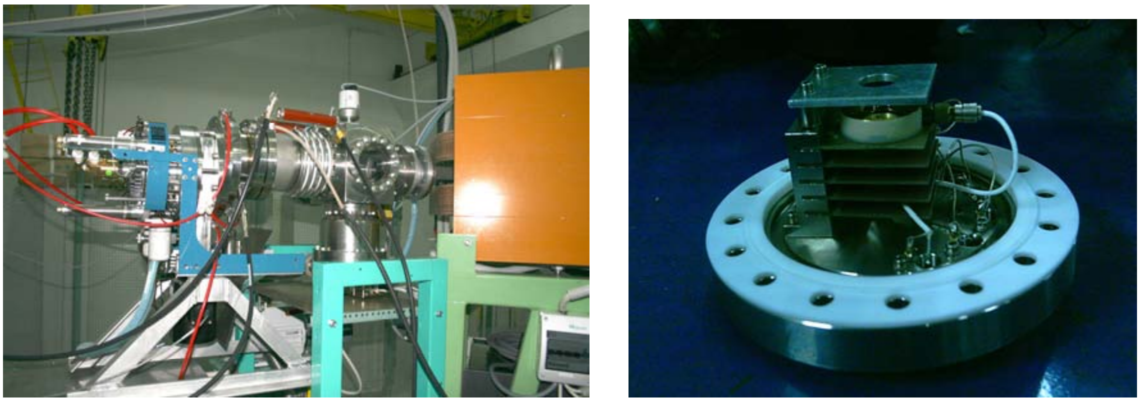


Figure 4.6. mage of the new sputter ion source used for dept profiling of elemental concentrations and the multi array of 3 Si-pin detectors, used for light particle detection and discrimination.

In the present research task AMS performs a depth profile (DP) measurements. The depth scanning is done by sputtering of accelerated ions – ^{133}Cs on the sample surface. By measuring continuously the produced rare ions (Tritium) one will register in the detector different count rates according to the concentration at depth of sputtering. Experimentally, the DP requires the sputter erosion rate to be uniform on the analyzed target area. Ions sputtered from the crater sides should not be included in the analyses because they do not reveal the true concentration. In order to correct the rim effects we developed a mathematical unfolding procedure.

For an efficient and confident depth profiling of concentrations by AMS the parameters of the devices of the facility have to be optimized experimentally. Optimal values have been carefully chosen for the beam currents and for the acceleration conditions. The new prepared standard samples were mounted on the target wheel and were introduced into the vacuum chamber of the ion source (Supplementary, two blank samples of pure Carbon were introduced to determine the background level and the cross talk effect in the ion source. Moreover, 2 samples of low T/C concentration, with T implanted in pyrolitic carbon, were also introduced in the sputter ion source to allow a complete simulation of a depth profiling.

The ^{12}C ions were chosen to form the pilot beam. However, the stripping probability of negative ions in the terminal is not the same for all possible charge stages to be attained at a certain terminal potential. The main role has however the possibility to obtain the magnetic rigidity for ^{12}C (M $(1+q)/q^2 =$ const) very close to the magnetic rigidity of Tritium. The differences should not exceed 0.5 MeV for the Terminal voltages of the tandem accelerator. For a larger value of the difference the tuning with the pilot beam is not anymore precise. The state charge 3^+ of the ^{12}C ions satisfies well this constraint. Thus, the pilot beam was chosen to be formed by $^{12}C^3$+ ions.

The events in the detector are registered continuously. Assuming a continuous sputtering rate the elapsed time will be converted to depth. The calibration of the scanned depth is done off line, by optical profilometry. Spectra of the Tritium particles were recorded and Depth profile spectra were calibrated using the standard samples. For the AMS analysis samples with lower T activity concentration from divertor tiles and JET campaigns 1998–2004 have been selected: 3 samples from G1B and 1 sample form tiles G7A and G8B. All samples were cut were like a disk, having 10mm diameter and 3mm thickness. Figure 4.7 shows the locations of the cuts in tile G1B.

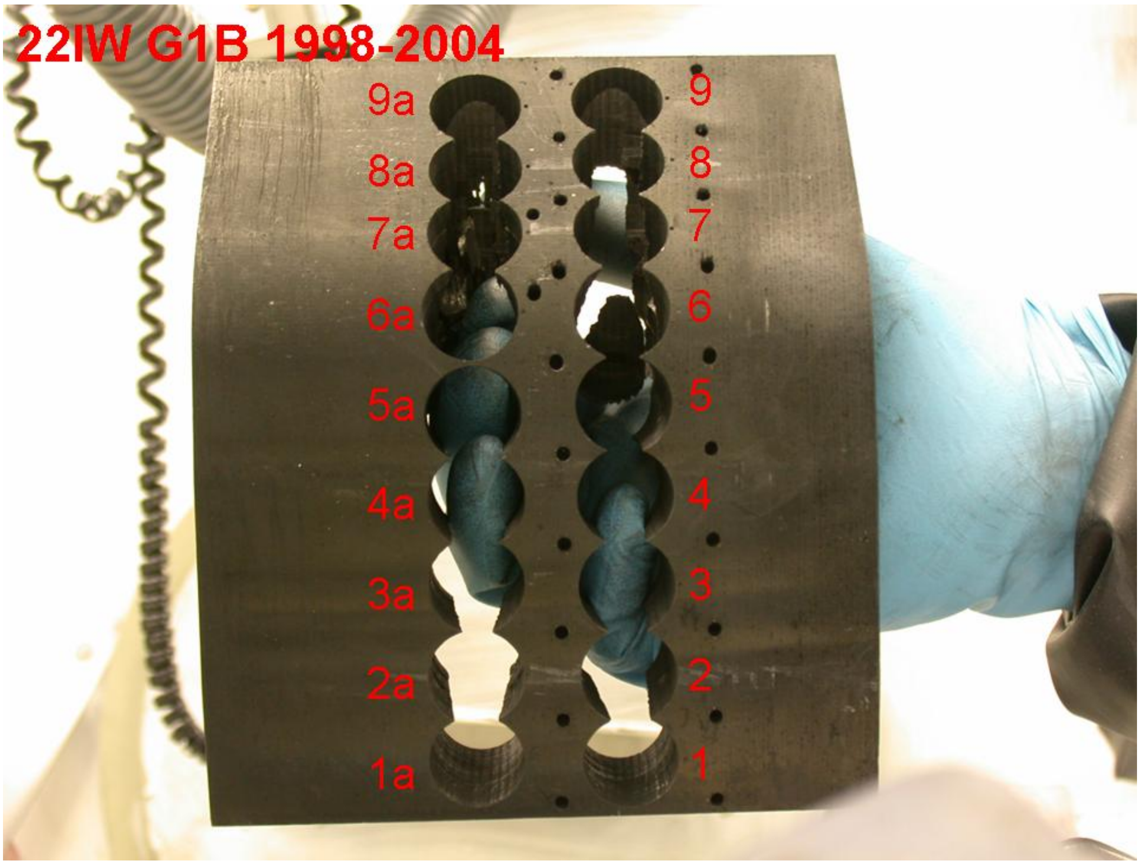


Figure 4.7. Locations of samples from tile G1B. In the AMS DP experiment samples form locations 2, 5 and 8 were used.

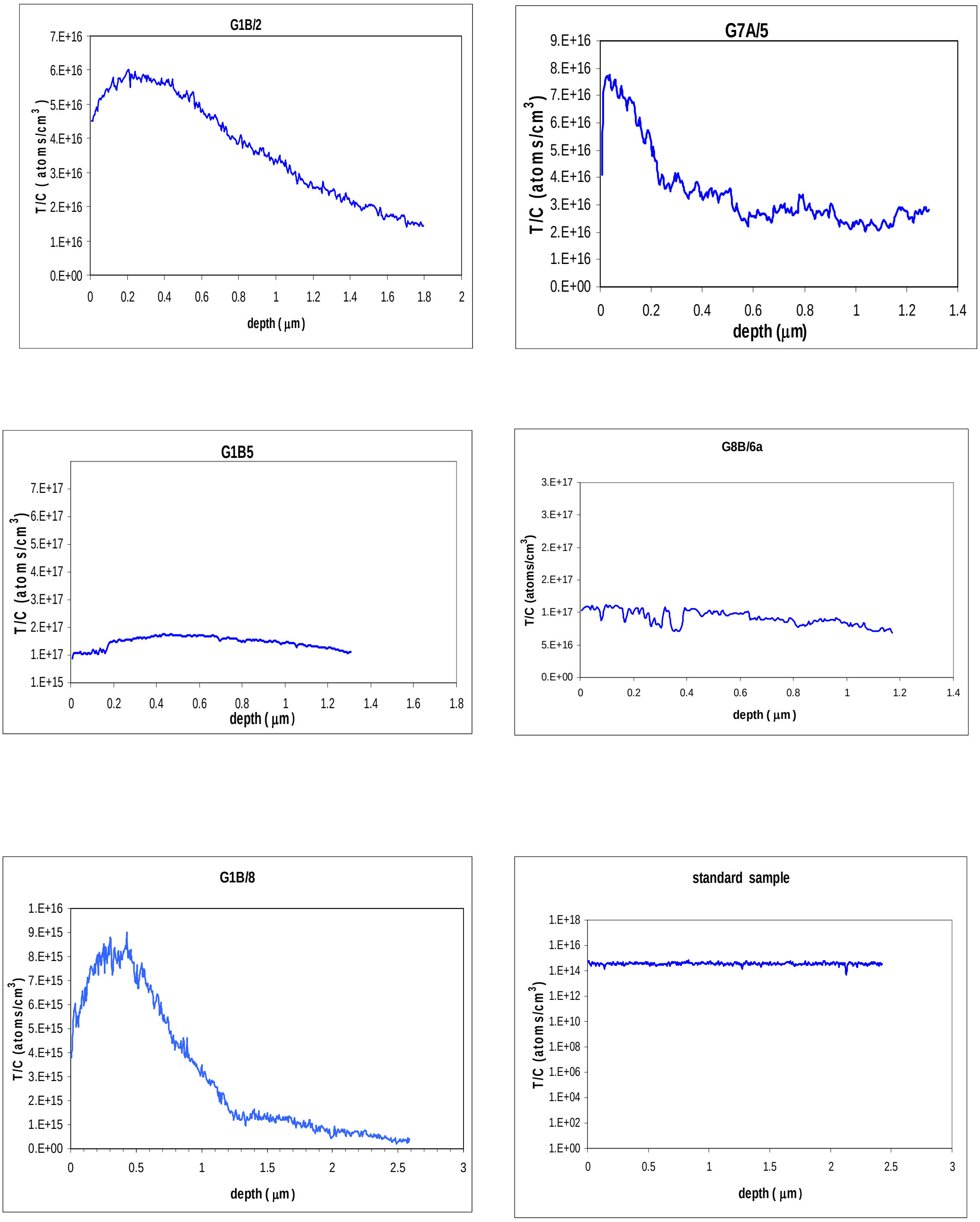


Figure 4.8. Tritium depth profiles measured by AMS.

The measured concentrations of DP are shown in Figure 4.8. All data were corrected for the background value of T during the measurements. For the entire experiment the background level was 10^3 lower than the smallest measured concentration. The averaged concentration of T does not exceed 10^{17} atoms/cm^3. Taking into account the possible wide incidence angles of the colliding particles and the fast diffusion T in CFC, wide peaks are expected for the maximum values of the power ranges. The decisive contribution to the widening of the peak distribution is due to the CFC structure of the divertor tiles at JET. In addition, samples from tile 1 and 8 suffer continuous deposition during the campaign, which “grows” constantly the surface layer and hence, widens the concentration peak.

Therefore, the peaking of the DP at a depth of about 0.25 μm corresponds to the implant of Tritium at temperatures close to the plasma temperature. The divertor samples are cut from a toroidal distribution. Integrating the DP down to the measured dept one obtains the amount of T trapped per unit area (atoms/cm2).

In Figure 4.9 the integrated values of T deposition up to about 3 μm depth are indicated, according to their locations on the divertor from JET.

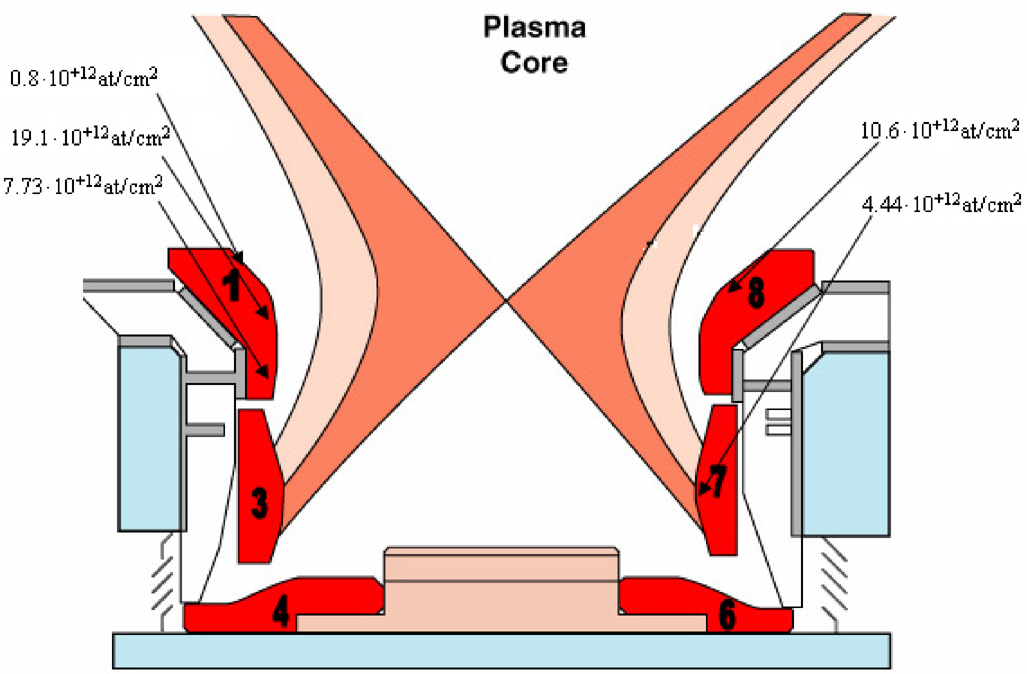


Figure 4.9. AMS integrated concentration values of T in CFC tiles at different locations on the JET divertor.

5. JOC SECONDMENTS AND STAFF MOBILITY

Several staff mobility visits of total 678 days took place in 2009. The visits were hosted by the Associations IPP Garching (233 days, MA Art. 1.2.b collaboration), CCFE Culham (58 days), SCK-CEN Mol (29 days), University of Tartu (28 days) and FOM Rijnhuizen (16 days). Other staff mobility actions were EFDA meetings (PWI, ITM, FT, TGs) meetings (43 days), ITPA meetings (22 days), Goal Oriented Training GOTiT (86 days) and US (160 days) for IEA Large Tokamak experiments and EU-US visits. Tekes (University of Helsinki hosted a visit of 28 days from the Slovakian Association.

Two physicists and one engineer were seconded to the CCFE JET Operating Team, Johnny Lönnroth and Antti Salmi (code development and modelling) and Ville Takalo (remote handling). One engineer from VTT was seconded to the ITER IO at Cadarache in 2009, Tommi Jokinen (Assembly).

5.1 CCFE JOC Secondments

5.1.1 JET remote handling for ILW experiment

JOC secondee: V. Takalo, Tekes – TUT/IHA

Ville Takalo is a remote handling expert from IHA/TUT seconded in CCFE Engineering Department Remote Handling Group at JET. The EP2 2010-2011 shutdown converts the wall to be more ITER like with new design, new materials, new diagnostic and enhanced power. Majority in-vessel work is carried out remotely and work comprises over 8000 components to be handled remotely. During the EP2 shutdown Ville Takalo acts as Remote Handling Operations Responsible Officer.

5.1.2 JET code development and modelling

JOC secondees: Johnny Lönnroth and A. Salmi

The main activity was the JET code integration and ITM work. Modelling covered JETTO transport simulations and MISHKA-1 MHD analysis related to the pedestal stability. The following issues are described in more detail in Section 3.

- Dependence of plasma performance on the characteristics of the H-mode pedestal
- Implications of pedestal MHD stability limits on the performance of ITER Scenario 2
- ELM module to JETTO
- ASCOT-JETTO integration.

5.2 Staff Mobility Visits and Reports

5.2.1 LIBS measurements of marker samples at University of Tartu – 1st visit

Name of seconded person:	Antti Hakola
Sending Institution:	TKK / Association Euratom-Tekes
Host Institution:	University of Tartu, Estonia
Dates of secondment / Mission:	1–14 February 2009

Work Plan / milestones:

1) Participating in the LIBS measurements at University of Tartu, integrating a new spectrometer in the LIBS setup, and optimizing its operation.
2) Measuring a series of test samples with well-defined marker layers on them and comparing the results with earlier data.

Report: This visit was part of active collaboration between the Finnish and Estonian research units in the field of laser-induced breakdown spectroscopy (LIBS). The experimental LIBS work is done at the Gas Discharge Laboratory of the University of Tartu, and the role of TKK and VTT is to provide samples for experiments and participate in the actual measurements.

In LIBS, short and intense laser pulses are focused on the studied sample, and a small amount of material is removed, ablated, from its surface during each pulse. The emitted species will end up in an excited state and, as a result, emit sharp resonance radiation at specific wavelengths, which are characteristic to the elements of the sample. The emitted light is collected with an optical spectrometer and analysed. Being a non-invasive technique to determine the elemental composition of the studied sample – and in real time – LIBS will be a powerful tool for erosion and deposition studies in fusion reactors, as well as to tackle important research questions, e.g., the retention of tritium in wall structures

To obtain quantitative information for controlling the fusion reactor, the LIBS technique has to be developed such that it will be possible to accurately monitor changes in the composition and thickness of different coatings and marker layers when they are exposed to laser irradiation. In particular, this requires sensitive measurements of the emission spectra with a time resolution better than 1 µs. This way, it is guaranteed that only light originating from the ablated particle cloud is recorded and that the intensities of the different spectral lines can be compared with each other after each laser pulse.

<u>Milestones #1 and #2:</u> The Gas Discharge Laboratory of University of Tartu purchased in late 2008 a new Andor Mechelle spectrometer which covers a wide wavelength area from 200 nm to 1 000 nm and which has a good spectral resolution of $\lambda/\Delta\lambda = 5\ 000$. In addition, the spectrometer is equipped with a fast CCD camera which can be gated to record data at sub-nanosecond timescales. During the mobility visit, this spectrometer was taken into use and integrated into the experimental LIBS setup. This setup consists of a UV ecimer laser ($\lambda = 248$ nm) producing 35-ns long pulses typically with energies

around 100 mJ, the necessary focusing and imaging optics, fibre coupling for the spectrometer, and the experimental vacuum chamber with a base pressure of 10^{-2} mbar.

After carefully aligning the whole setup and calibrating the spectrometer, a series of measurements were made with different reference samples (brass, tungsten, and graphite). Finally, a few marker samples – 1 and 2 µm thick W films on graphite and a sandwich of 0.1 µm Re + 2 µm W + 4 µm diamond-like carbon layers on stainless steel – were studied. The delay and the length of the gate during which the spectrometer is receiving data were varied, as well as the repetition rate and intensity of the laser pulses. The optimum recording window was observed to be some 200 ns after the laser pulse and with duration of 200 ns – 1 µs.

The analysis was complicated by the multitude of lines in the visible spectral region, whose intensities also tended to fluctuate from pulse to pulse. In addition, the sensitivity calibration was for some unknown reason poor in the regime from 300 nm to 390 nm, and thus peaks in this interval could hardly be distinguished from background noise. However, all the prominent lines of the simple brass test sample could be identified proving that the wavelength calibration was correct. Moreover, the shapes of the spectra taken from the W reference sample were similar to those measured with the old spectrometer (which was not as sensitive as the new one and which didn’t have the option for gated measurements). In the case of marker samples, the emission spectrum was taken after each laser shot, and changes in the structure of the lines were observed whenever one of the layers was completely removed; for example, two or three pulses were needed to drill through the 2 µm thick W layer on one of the samples.

Unfortunately, due to problems with the laser, the fluence on the target was not always high enough to evaporate carbon, and thus definite conclusions of the functionality of the spectrometer could not be drawn, yet. Nevertheless, these results form a basis for further work to enhance the sensitivity calibration of the spectrometer around the critical regions and to make it possible to see spectral lines of all the elements in question without so much fluctuation in their strengths. In addition, time-resolved measurements help in identifying the different phases of the ejected particle plume: radiation from hot plasma, excitation of somewhat cooled atoms, and finally formation of molecules and heavier clusters. The atomic region is the most interesting since there the lines are sufficiently narrow so that they will not overlap with each other. Despite the shortcomings mentioned above, the milestones were reached.

5.2.2 LIBS measurements of deuterium-doped marker samples – 2nd visit

Name of seconded person:	Antti Hakola
Sending Institution:	TKK / Association Euratom-Tekes
Host Institution:	University of Tartu, Estonia
Dates of secondment / Mission:	8–21 September 2009

Work Plan / milestones: Participating in LIBS measurements at University of Tartu, measuring a set of new test samples with well-defined marker layers and doping levels of deuterium on them and comparing the results with earlier data.

Report: This visit is connected to the active collaboration between the Finnish and Estonian research units in the field of laser-induced breakdown spectroscopy (LIBS). It was a direct continuation to my earlier mobility trip to University of Tartu in February (1–14 February, 2009). The experimental LIBS work is done at the Gas Discharge Laboratory of the University, and the role of TKK and VTT is to provide samples for experiments and participate in the actual measurements.

In LIBS, short and intense laser pulses are focused on the studied sample, and a small amount of material is removed, ablated, from its surface during each pulse. The emitted species will end up in an excited state and, as a result, emit sharp resonance radiation at specific wavelengths, which are characteristic to the elements of the sample. The emitted light is collected with an optical spectrometer and analysed. Being a non-invasive technique to determine the elemental composition of the studied sample – and in real time – LIBS will be a powerful tool for erosion and deposition studies in fusion reactors, as well as to tackle important research questions such as the retention of tritium in wall structures

To obtain quantitative information for controlling the operation of fusion reactors, the LIBS technique has to be developed to accurately monitor changes in the composition and thickness of different coatings when they are exposed to laser irradiation. In particular, this requires sensitive measurements of the emission spectra with a time resolution better than 1 µs. This way, it is guaranteed that only light originating from the ablated particle cloud is recorded and that the intensities of the different spectral lines can be compared after each laser pulse.

Milestones #1 and #2: During my earlier visit in February, a new Andor Mechelle spectrometer was taken into use and integrated into the experimental LIBS setup. The setup now consists of a UV excimer laser ($\lambda = 248$ nm) producing 35 ns long pulses typically with energies around 100 mJ, the necessary focusing and imaging optics, fibre coupling for the spectrometer, and a vacuum chamber with a base pressure of 10^{-2} mbar. During the past spring and summer, the whole system has been modified to be wholly controlled by a computer and a new stepper-motor driven rotating mirror has been installed between the last focusing lens and the vacuum chamber. The rotating mirror enables realizing pre-determined patterns on the studied samples such that one could study the repeatability of the LIBS method.

After carefully aligning the whole setup, a series of measurements were made with different marker samples. The samples, produced by DIARC-Technology Inc, had a 4–5 µm thick diamond-like carbon (DLC) film on stainless steel and a 50-nm thick Re interlayer between the film and the substrate. Both undoped and deuterium-doped DLC films had been prepared, and some of the samples had been softened by nitrogen during their deposition. The focused laser pulses draw an oval or a row of spots on the selected sample, each spot separated by a pre-determined distance from the next. The pattern was re-drawn some 20–30 times, and the emission spectra were recorded after every laser shot. Due to problems with the spectrometer software, often the spectra from 2–8 neighbouring spots had to be summed up to be able to save the resulting data file. But this was not too serious a problem, on the contrary, this way it was easier to get rid of some of the fluctuations in the intensities of the spectral lines.

The DLC film and the substrate could easily be distinguished from each other when sufficiently high laser fluence (J/cm^2) was used. Typically, some 15 shots were needed for the laser pulses to drill their way through the coating; this could be seen as a clear change in the shape and strength of the spectra. Unfortunately, the deuterium level was so low in all the samples that the 656 nm spectral line, the line mainly used for the detection of hydrogen isotopes, was barely above the noise level. Only for the samples most heavily doped with deuterium, the line could be recognized without doubt but it still showed large fluctuations from shot to shot. This made determining the deuterium depth profile impossible. Solving this problem seems to require new samples with higher deuterium concentrations. Both the milestones were reached.

5.2.3 Energetic ions in AUG – 1st visit

Name of seconded person:	Taina Kurki-Suonio
Sending Institution:	TKK / Association Euratom-Tekes
Host Institution:	IPP-MPG
Dates of secondment / Mission:	8–21 February 2009

Work Plan / milestones:

1) With Dr. W. Suttrop discuss and prepare the continuation of QHM experiments in AUG with co-injected neutral beams to try and verify the claims of such operation at DIII-D.
2) With Dr. Krieger and Mr. Toni Makkonen (to arrive a week later) plan and prepare the continuation of the DIVIMP simulations of C-13 puffing experiments started during 2008.

Report:

1st task: We decided that I browse through AUG shots with significant ELM-free phases – be they classical or QHM phases – to try and pin down characteristics that, in addition to rotation, might control the edge stability, including suppression of ELMs and generation of EHO.

2nd task: It was decided that Toni Makkonen now focuses on the simulation of L-mode discharges where the behaviour of the SOL plasma is somewhat better understood. The SOL flows are an important unknown and DIVIMP’s major weakness is the assumption of having a stagnation point at the top of the machine while experimentally it is observed on the LFS of the machine. This together with appropriate diffusion coefficient is the major tasks in the DIVIMP simulations.

Additional, unforeseen tasks:

1) With Drs. Jenko and Hauff we discussed their latest results on the anomalous diffusion of fast ions due to ES and EM turbulence. Their most recent expressions (to appear in PRL) apply only to strongly passing and strongly trapped ions. It was agreed that they generalize their result into a form that is suitable for arbitrary pitch values at which point the model can be included in ASCOT and ASCOT can be used to simulate the redistribution of current drive beam ions in AUG.

2) With Profs. Günter and Lackner and Dr. Strumberger we discussed the effect of island structures, induced by ferritic material in wall structures, on fast ion confinement. Such structures now appear inevitable when non-periodic ferritic structures are introduced into the wall.
3) With Drs. Garcia-Munoz and Meo we planned the characteristics of the alpha particle simulation experiments that are part of an EFDA task.
4) AUG-PC meeting.
5) GOTiT Program Board Meeting.

5.2.4 Energetic ions in AUG – 2nd visit

Name of seconded person:	Taina Kurki-Suonio
Sending Institution:	TKK / Association Euratom-Tekes
Host Institution:	IPP-MPG
Dates of secondment / Mission:	13 July – 3 August 2009

Work Plan / milestones:

1) Continue with Dr. W. Suttrop the discussions and preparations of the continuation of QHM experiments in AUG with co-injected neutral beams to try and verify the claims of such operation at DIII-D.
2) With Dr. Krieger discuss the recent results of the DIVIMP simulations of C-13 puffing experiments and decide on how to proceed to obtain even better agreement with experiments.
3) Together with Dr. Garcia-Munoz prepare for the alpha simulation experiments (EFDA task WP08-TGS-01-01).
4) Obtain the relevant turbulence data to be used in ASCOT simulations of anomalous redistribution of NBI ions (Prof. Günter and Dr. Jenko).

Report:

1st task: This task was postponed to later times since it is unlikely that AUG will have reversed-I_p operation during 2009.

2nd task: It was decided that Toni Makkonen’s most recent DIVIMP simulation results already reflect so many experimentally measured C-13 characteristics that they warrant being included in the experimental paper that is currently under preparation by A. Hakola. It was further decided that, as the first attempt to more realistically include the SOL flows in the C-13 simulation, Makkonen will use the measured plasma background flows even though this violates the consistency of the background.

3rd task: the different alpha diagnostics for the alpha simulation experiments were discussed with Drs. Garcia-Munoz and Meo. It seems likely that CTS is not available for these experiments this year, so including FIDA in its preliminary stage is considered. The plasma scenario is now set and the experiments are foreseen to take place in November.

<u>4th task:</u> The diffusion coefficients extended to all orbit topologies were obtained from Dr. Hauff and the first set of turbulence parameters, including correlation lengths and ExB velocities, were decided on in discussions with Drs. Jenko and Hauff.

Additional, unforeseen tasks:

1) With Prof. Kallenbach we came up with new ideas to incorporate in ASCOT simulations in order to see if the ELM-time reversal of divertor target asymmetry could be explained by pedestal ions.
2) With Prof. Günter and Dr. Strumberger we discussed the possibility of ASCOT simulations in the presence of resonance magnetic perturbation (RMP). Here the primary interest would be the run-away electrons.
3) Benchmarking effort between the new NBI model in ASCOT and NUBEAM were launched with the help of Dr. Tardini.
4) With Drs. Ryter and Garcia-Munoz we planned the future development of NPA in AUG: should the focus be on MHD or in the NBI-CD ion redistribution?

5.2.5 Energetic ions in AUG – 3rd visit

Name of seconded person:	Taina Kurki-Suonio
Sending Institution:	TKK / Association Euratom-Tekes
Host Institution:	IPP-MPG
Dates of secondment / Mission:	18–31 October 2009

Work Plan / milestones:

1) Together with Dr. Garcia-Munoz do the final preparations for the alpha simulation experiments (EFDA task WP08-TGS-01-01) to take place in AUG in November. Also continue the planning of NPA upgrades and the FIDA diagnostic.
2) Tune the turbulence data used in ASCOT simulations of anomalous redistribution of fast ions (Dr. Jenko). This is needed both for the forthcoming Nuclear Fusion article and next year’s studies of current drive NBI ions in AUG.
3) Discuss with Dr. W. Suttrop and the AUG experimental group the feasibility of the QHM experiments in AUG with co-injected neutral beams in 2010.

Report:

<u>1st task:</u> In the alpha simulation experiments (about ten shots) the capabilities of different diagnostics on measuring confined fast ions are to be studied. The candidate diagnostics are: CTS, FIDA, NPA, and high resolution neutron spectroscopy. We decided to propose two sub-experiments: 1) Issues related to the high energy of the confined alphas, and 2) issues related to the fact that the diagnostics will be probing a minority population deep in the core plasma. The shots are to take place in November.

<u>2nd task:</u> the first set of turbulence parameters, including correlation lengths and ***ExB*** velocities, was improved in discussions with Dr. Jenko. (In ITPA EP meeting in Kiev the diffusion coefficients used in ASCOT were found to be in line with other works in

the case of magnetic turbulence but an order of magnitude larger in the case of electrostatic turbulence).

3rd task: Based on collected wisdom on QHM operation both on DIII-D and AUG, Dr. Suttrop and I made detailed experimental plans on another try on QHM with co-injected neutral beams. These experiments are to take place in November/December.

Additional, unforeseen tasks:

> With Drs. Ryter and Pütterich we continued planning the future development of an active NPA in AUG: we shall use ASCOT to calculate the NPA signal resulting from neutralization of beam ions in the neutral cloud generated by another beam.

5.2.6 Simulating carbon-13 puffing experiments

Name of seconded person:	Toni Makkonen
Sending Institution:	TKK / Association Euratom-Tekes
Host Institution:	IPP-MPG
Dates of secondment / Mission:	15–28 February 2009

Work Plan / milestones: The co-deposition of hydrogen isotopes with carbon is a major challenge facing ITER. Carbon is planned to be used as a plasma-facing wall material due to its excellent thermal and mechanical properties. Carbon atoms are eroded from the walls and later re-deposited trapping hydrogen isotopes, such as radioactive tritium, with them. This poses a safety and licensing problem which makes understanding the physics behind carbon migration very important.

Carbon puffing experiments are one way to study carbon migration. In these experiments, carbon-13 marker is puffed into the tokamak where it is broken up, ionized, and finally transported to the wall. This is done in conditions where all the plasma parameters are well known to ease interpreting the results. Secondary Ion Mass Spectrometry (SIMS) can be used to determine the deposition profile on the wall.

Carbon puffing experiment are excellent for benchmarking simulation codes such as DIVIMP. Codes can then in turn be used to make predictions for ITER and to identify the key physics.

During my mobility visit in February 2009 I wish, with the help of Dr. Krieger, to improve previous DIVIMP simulation results and try to identify key physics behind carbon transport

Report: Besides being able to work with the computers and resources at the IPP, I met several times with Dr. Karl Krieger, Dr. Hans Werner Müller, and Dr. Marco Wischmeier. These meetings were vital as the DIVIMP program is not so well documented and I'm the only one running the program at my university.

Dr. Krieger provided help with running the DIVIMP program. We also discussed future goals and decided on a preliminary work plan. Currently, I'm in the middle of simulating the 2005 and 2007 global gas puffing experiments. Dr. Müller assisted with necessary Langmuir probe data from ASDEX Upgrade and Dr. Wischmeier helped with the magnetic background. All in all, the visit to IPP was very useful.

5.2.7 The implementation of a scrape of layer and pedestal region into the full f gyrokinetic code ELMFIRE

Name of seconded person:	Susan Leerink
Sending Institution:	TKK / Association Euratom-Tekes
Host Institution:	Center for Plasma Edge Simulation, Courant Institute of Mathematical sciences, New York, US
Dates of secondment / Mission:	1 April – 31 July 2009
Contact person at CIMS:	Professor C.S. Chang

Work Plan / milestones: Development of gyrokinetic transport codes for magnetized fusion devices has become one of the cornerstones of the present work under the EURATOM DoE(USA) bilateral agreement. USA universities and institutes have been forerunners in the world since 1983 in developing gyrokinetic codes, in particular with so called delta f method. Late 1990 and early 2000, EU has rapidly caught up with USA on gyrokinetic code development, not only with delta f scheme, but recently also taking lead with the full f scheme. The most advanced gyrokinetic full f particle-in-cell codes in the world are the ELMFIRE code (EuratomTekes) and the XGC-1 code (New York Courant Institute). It is the purpose of this mobility visit to transfer the most recent US advancements in knowledge of gyrokinetic theory and coding techniques in handling the Xpoint to ELMFIRE and to other full *f* gyrokinetic European codes (like GYSELA).

Cooperation with Professor C.S. Chang at the SciDAC Center for Plasma Edge Simulation: The SciDAC Center for Plasma Edge Simulation has been established by US DOE in 2005 and since then they have successfully developed the XGC code framework, including the XGC-1 code which includes a realistic scrapeoff, pedestal and wall region. Part of the visit to the SciDAC center will be spend to further investigate the quasineutrality and vorticity model (24 weeks). Since the XGC-1 code is also a full f gyrokinetic global code, calculating the axisymmetric radial electric field accurately is also for this code of major importance. Furthermore by the beginning of this visit a pedestal and SOL region has been incorporated into the ELMFIRE code. Depending on whether programming problems will still exist (numerical instabilities, resolution problems near the X-point, etc.) some time of the visit will be reserved for solving these problems with the help of the XGC group (24 weeks). The main goal of the visit however will be to benchmark the newly developed Elmfire code to XGC-1 simulations of the DIIID tokamak (2 months).

The milestones and deliverables of the visits are:

1) To provide a clear understanding of the limitations of gyrokinetic full f global codes while using quasi neutrality for solving the potential (To be reported in the intermediate report on 3rd April 2009).
2) To develop a numerical model for the Elmfire code which replaces the quasineutrality condition by the vorticity condition.

3) To finish the development phase of the SOL and Pedestal region in the Elmfire code.
4) To benchmark the newly developed Elmfire code to XGC-1 simulations of the DIII-D tokamak.

Report: During this visit the main goal was to extent the full *f* gyrokinetic codes ELMFIRE, developed by the Advanced Energy Systems Laboratory of the Helsinki University of Technology and the VTT Technical Research Center of Finland, to the pedestal and scrape of layer region.

To check whether the accuracy of the ELMFIRE code, as programmed in the core version, is good enough for the pedestal analytical benchmark cases were done first. A flux surface averaged simulation with constant ion and electron temperature profiles and a hyperbolic tangent pedestal profile for electron and ion density was performed. For these specific parameters there is an exact solution for the radial electric field where the pressure gradient should exactly cancel the potential gradient. When initializing the particles in their orbits with an radial electric field close to the analytical solution it was found that the radial electric field was indeed settling at the exact known analytical solution, indicating that the accuracy of the ELMFIRE code is good enough for the pedestal region. However when the value of the initialized electric field value was taken far from the analytical solutions the boundaries were getting unstable, leading to huge instabilities. For pedestal simulations, therefore, the radial electric field will always have to be initialized reasonably close to its neoclassical value.

A major change that was needed to implement the pedestal and SOL region in the ELMFIRE code was a more complex magnetic field background. The XGC-1 code already had this implemented by using the EFIT magnetic field solver. The elmfire code has started to do similar efforts while using the Helena magnetic field solver. However, after learning the CPU costs of the use of the magnetic solver in the XGC-1 code the ELMFIRE code is also simultaneously studying the implementation of an analytical solution for the magnetic field including the pedestal and SOL (Boozer, Phys. Fluids 27, 2441 (1984)). The implementation of both models is ongoing and as soon as the implementation has been finished benchmarking of the two models as well as benchmarking to the XGC-1 codes are planned.

Furthermore it has been found that the XGC code framework and the ELMFIRE code are based on two different gyro kinetic approaches and benchmarking of the two approaches would be an important check. To study the two approaches as good as possible it was chosen to use the most simple benchmark case. To do this however the analytical magnetic field model and the implicit kinetic electron model used in Elmfire still had to be implemented into the XGC code. The implementation of the electron scheme in the XGC code, however, has not been as strait forward. Reasons for this are the fact that the XGC code uses a different Runge scheme then the ELMFIRE code and a 2D potential solver instead of a 3D solver (so bad convergence was found). These differences are found and implementing the corrections is ongoing.

5.2.8 Radiation-induced microstructure evolution models for Fe alloys

Name of seconded person:	M.Sc. Ville Jansson
Sending Institution:	University of Helsinki / Association Euratom-Tekes
Host Institution:	SCK-CEN / Mol, Belgium
Dates of secondment / Mission:	1–29 May 2009

Work Plan / milestones: In the existing OKMC coarse-grained models describing the microstructure evolution undergone by body-centred-cubic Fe alloys under irradiation, many of the atomic-level mechanisms of defect mobility and reaction in α–Fe identified in the last few years are not taken into account. The effect of impurities, such as C and Cu, is allowed for only in a very tentative way. The effects of other elements, such as Ni and Mn, or P, are totally disregarded.

The objective of the project is hence to participate in the effort of refining existing OKMC models and extend them to binary and ternary model alloys for RPV steels. The work would proceed progressively, addressing first Fe, then FeC and FeCu, then FeCuC, and finally making an attempt to consider also the effect of elements such as Ni and Mn, or P. Altogether, these are the alloying elements that chiefly influence and determine the mechanical property degradation process affecting RPV steels in operation. The work will focus on the extensive use of molecular dynamics techniques (on the use of which longstanding expertise exists within the SMA group) for the study and quantification of atomic level processes and mechanisms determining the microstructural evolution. During the visit to SCK-CEN, M.Sc. Ville Jansson will get introduced to the project and start using the software applied at SCK-CEN in this field.

Report: During his visit to SCK-CEN in Mol, Belgium, Ville Jansson got introduced to the molecular dynamics code DYMOKA and begun to use it for simulations of interactions between defects in RPV steels. In particular, the interaction between a loop of seven interstitial Fe atoms and a vacancy in a BCC Fe lattice and also the interaction between a identical loop and a C atom was studied using DYMOKA. Furthermore, simulations with two larger loops of 19–25 Fe atoms were started. One simulation where the loops interacted perpendicularly to each other and one where the loops interacted parallel to each other are long term simulations and are not finished yet.

Added to this, Ville Jansson participated in the “Topical day of contributions to understanding materials degradation mechanisms for improved safety of nuclear reactors” held at SCK-CEN 12th May, as well as a group meeting the day before, where the discussions were about the roadmap to produce a reasonable parametrisation for object KMC and rate theory models for pure Fe, Fe-C and Fe-Cu alloys, and the mechanisms to be introduced in the two models, in such a way that the two can be compared directly when applied to the same problem. Another smaller meeting inside the group was held 14th May, where Dr. L. Malerba, Dr. D. Terentyev (SCK-CEN), Dr. A. Serra, Dr. N. Anento (UPC, Barcelona) and M.Sc. Ville Jansson participated. At this meeting, the different research tasks were divided and distributed inside the research team.

In summary, the cooperation between Ville Jansson, from the computational material group, led by prof. Kai Nordlund at University of Helsinki, and the modelling team at SCK-CEN, led by Dr. L. Malerba, has got a good start, which indeed was one of the objectives of the visit. Ville Jansson has now got a good introduction to the programs used at SCK-CEN and in particular the MD simulation code DYMOKA. The project will now proceed and a telephone conference is planned in July to compare results.

5.2.9 Erosion probe studies at ASDEX Upgrade

Name of seconded person:	Antti Hakola
Sending Institution:	TKK / Association Euratom-Tekes
Host Institution:	IPP-MPG
Dates of secondment / Mission:	7 June – 4 July 2009

Work Plan / milestones: Exposing time-resolved marker probes to ASDEX Upgrade plasma, two successful discharges for each probe (2–3) is needed. Analyzing the probes after their exposure using NRA and/or RBS and determining the erosion of the marker stripes and re-deposition of material between the stripes. Participating in meetings in June 18 and July 2, both connected to plasma-surface interaction studies.

Report: This visit was part of active collaboration between the Finnish research units TKK and VTT of the Tekes Association and Max-Planck-Institut für Plasmaphysik (IPP Assiciation) in the field of plasma-wall interaction. Our joint projects are closely connected to the research done in ASDEX Upgrade, and the focus areas are studying erosion of first-wall tiles, deposition of material on them, retention of plasma fuel, and migration of material in the torus. Since 2002, erosion and deposition in ASDEX Upgrade have been studied with the help of special marker coatings on selected divertor and limiter tiles produced by the Finnish coating company DIARC-Technology Inc. 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 determined. The analyses are done using secondary ion mass spectrometry (SIMS) at VTT and Rutherford backscattering (RBS) and nuclear reaction analysis (NRA) at the accelerator laboratory of IPP.

So far, the research has mainly been based on data obtained from *post mortem* surface analyses, i.e., the tiles have been measured after an experimental campaign when they have been subjected to hundreds or thousands of different plasma discharges. Information on the erosion processes during single or only a few discharges is largely missing. To fill this gap, five so-called time-resolved probes were produced by DIARC in 2006. The graphite probes have four 5-mm wide and 50-nm thick marker stripes (C, Al, Ni, and W) on them, separated by a distance of 5 mm from each other, and they can be easily mounted on a manipulator to be in contact with plasma during a limited number of discharges.

Milestone #1: During the present visit, one of the time-resolved probes was exposed to five plasma discharges in ASDEX Upgrade. The main goal was to investigate erosion of the different stripe materials. It turned out that three of the probes had already been exposed in 2007 and the remaining fifth probe had been stored so carelessly (glue marks from Scotch tape and signs of oxidization on one of the stripes) that it could not be used in the experiments.

To make modelling of the results possible with the ERO code, we selected the experiment to be done under L-mode conditions in deuterium. The relevant ASDEX Upgrade discharges were #24664-24669, and the most important plasma parameters were I_p = 800 kA, B_t = -2.3 T, n_e = 5.7-6.0 × 10^{19} m^{-3}, and P_{aux} = 1.3 MW (of NBI power). In addition, an extra discharge (#24675) without the probe was performed with strike-point scans and with the same plasma parameters as those in the actual experiment. In addition to the standard diagnostics, the Li beam was used during the shots to get information about the T_i profiles in the probe plane and a fast IR camera was looking at the probe to record the temperature distribution at its surface.

The probe was attached to the midplane manipulator of ASDEX Upgrade such that its surface with the marker stripes was orthogonal to the magnetic field lines. This surface was tilted by 45° with respect to the vertical tangent plane of the torus, and during the discharges the front tip of this 50-mm long surface was moved to a distance of approximately 50 mm from the separatrix; this corresponded to the tip being some 10 mm outside the limiter tiles. The experiment was done successfully and this milestone was thus reached.

Milestone #2: The probe was analyzed at the accelerator lab of IPP both before and after the experiment using RBS. The measurements were made in the Bombardino analysis chamber with 3-MeV protons and at 5-mm steps along every marker stripe and each of the three uncoated carbon stripes between the markers. The spectra of the backscattered protons were simulated with the SIMNRA program, which gives the compositions and thicknesses of the marker layers and can thus be used to determine their erosion.

The results from W, Ni, and Al markers were analyzed and the pre- and post-exposure data were compared with each other. The results indicated that the W and Ni stripes had been eroded to some degree close to the front edge of the probe (the part closest to plasma during the experiment). The net erosion was < 5 nm for W and < 10 nm for Ni. For Al, the simulations indicated similar results but these have to be taken with some caution due to several complications in interpreting the data. The results from the carbon stripe could not be analyzed due to the lack of a well-defined metal marker between the carbon stripe and the graphite substrate. No signs of deposition were observed on the uncoated areas between the marker stripes. The measurements were made, the results were analyzed and this milestone was therefore reached.

Milestone #3: While staying at IPP, I took part in two important meetings. The first of these (in June 18) was about the evaluation of the European facilities dedicated to plasma-surface interaction studies. The second one (in July 2) was a kick-off meeting for the tasks on laser cleaning of first-wall components. This milestone was reached.

5.2.10 Modelling of scrape-off layer and plasma-surface interaction

Name of seconded person:	Leena Aho-Mantila
Sending Institution:	TKK / Association Euratom-Tekes
Host Institution:	IPP-MPG
Dates of secondment / Mission:	21 June – 31 July 2009

Work Plan / milestones: Local ^{13}C methane injection experiments have been conducted in the divertor region of ASDEX Upgrade tokamak. By analysing the obtained deposition pattern important information about carbon migration can be obtained. The relevant numerical modelling has been ongoing since June 2008. The numerical tools are the SOLPS fluid plasma / Monte Carlo neutrals code package and the Monte Carlo impurity following code ERO. The modelling is a PhD thesis project and part of an EFDA PWI task. It is done in close collaboration with the IPP edge plasma modelling group and supervised by Dr. Marco Wischmeier (IPP).

The modelling focuses on L-mode experiments carried out in LSN normal magnetic field configuration in 2007–2008. A new injection experiment at AUG is planned for the end of the 2009 campaign. The purpose of this experiment is to investigate the effect of ExB drift on carbon transport in the divertor plasma by reversing the toroidal magnetic field.

Goals

1. Improving the SOLPS solution for the L-mode plasma background, in particular concentrating on the effect of drifts. Collaboration with the IPP edge plasma modelling group.
2. Modelling methane transport with the ERO code, discussion of results with local experts. Preparing a manuscript of the work for the PET workshop in September.
3. Planning of the ^{13}C methane injection experiment in 2009.
4. Analysis of the AUG experimental data obtained during the last ^{13}C experiments.
5. Analysis of the AUG experimental data obtained during an erosion probe experiment in June 2009.

Report: Modelling the L-mode plasma background for 2007 AUG ^{13}C injection experiment with SOLPS was continued (collaboration with M. Wischmeier, D. Coster). Recent modifications to the SOLPS5.0 source code turned out to have a significant influence on the plasma solution at the outer target. A new solution both with and without activated drift terms was therefore sought for.

The plasma conditions in the 2007 L-mode discharge configuration were further investigated by carrying out two test discharges at AUG in July. These included midplane probe measurements of plasma temperature, density and flow velocity, and spectroscopic measurements of the outer divertor plasma. Analysis of probe data was discussed with H.W. Müller, who also explained how to use the required analysis routines.

Results from NRA analysis of ^{13}C deposition in 2008 L-mode experiment were discussed with K. Krieger.

First ERO results of ^{13}C transport under the influence of ExB drifts calculated with SOLPS were discussed with M. Wischmeier. The proposal for the 2009 ^{13}C injection experiment was revised according to the most recent results from simulations and analysis of experimental data.

Plasma data obtained during an erosion probe experiment in June 2009 was analysed. In addition, two test discharges were carried out to obtain midplane probe measurements of n_e, T_e and flow velocity. The milestones of this visit were completed.

5.2.11 Comparison LIBS spectra produced by IR and UV lasers

Name of seconded person:	Peeter Paris
Sending Institution:	Institute of Physics, University of Tartu, Estonia
Host Institution:	FOM Institute for Plasma Physics, Rijnhuizen, NL
Dates of secondment / Mission:	15–30 October 2010

Work Plan / milestones: Preparation of joint experiments on Laser Induced Breakdown Spectroscopy (LIBS). A comparative study of time resolved shot-to shot LIBS produced by UV and IR laser radiation. Aim is optimization of the LIBS laser wavelength in tokamak wall erosion/deposition diagnostics, coordinate the actual parameters and details of needed apparatus for further joint experiments.

Report: LIBS expected to enable in-situ diagnostics of tokamak wall erosion/ deposition. For measurements the erosion or deposition rate on tokamak walls, LIBS signals will be calibrated specially manufactured reactor wall-like samples with known parameters. Intense plasma fluxes could seriously influence the properties of the cover layers of samples, consequently they could influence LIBS signals. The joint experiment foresees recording LIBS signal from samples before and after exposing them to intense plasma fluxes generated by linear plasma devises for plasma-surface-interaction (Pilot, Magnum).

As the first step, the comparative study of LIBS produced by UV and IR laser radiation was carried out in collaboration with FOM Rijnhuizen Institute (Netherlands) in the laboratory of the FOM Institute. The details and parameters needed for further joint experiments were discussed and if possible then tested and optimized. Nd-YAG laser from FOM institute was utilized. Most of recording and measuring apparatus and devices including Mechelle ME5000 spectrometer, variable attenuators and test chamber were transported to FOM from Tartu University. LIBS signals were compared for two wavelength of the Nd–YAG laser – for the fundamental harmonic 1 064 nm and for the third harmonic 355 nm. The delay time between laser pulse and spectrometer recording was optimized. Samples under the test were produced and delivered by the National Institute for Laser, Plasma and Radiation Physics of Romania and DIARC (Finland) Samples were covered with thin layers of tokamak relevant materials (tungsten with Mo interlayer, carbon-tungsten composite and also deuterium doped diamond-like-carbon) on different substrates.

Main results

1) At the same value of fluence of laser radiation the ablation rate of 1 064 nm wavelength pulses for tested composite layers is considerably lower
2) The ratio of element lines follows the concentration for both laser wavelength
3) The depth profiles of layers are reliably detectable for both wavelengths
4) No significant differences in spectral line widths and signal to background ratio for both laser wavelengths was discovered.

It could be concluded that if the higher ablation rates are important, the UV laser is preferable. For achieving analytical spectra there is no decisive difference, which wavelength is used. The main or second harmonic of Nd-YAG can be used.
For determination of layers depth profile the laser beam should have instead of the Gaussian profile a top-hat profile.

The visit fulfils the expected aims in preparation of joint experiment; performed measurements enable to optimize LIBS device parameters, LIBS laser wavelength.
The milestones for this visit were achieved.

5.2.12 Modelling of scrape-off layer and plasma-surface interaction

Name of seconded person:	Leena Aho-Mantila
Sending Institution:	Helsinki University of Technology TKK
Host Institution:	IPP-MPG
Dates of secondment / Mission:	27 November – 19 December 2009

Work Plan / milestones: Local ^{13}C methane injection experiments have been conducted in the divertor region of ASDEX Upgrade tokamak. By analysing the obtained deposition pattern important information about carbon migration can be obtained. The relevant numerical modelling has been ongoing since June 2008. The numerical tools are the SOLPS fluid plasma / Monte Carlo neutrals code package and the Monte Carlo impurity following code ERO. The modelling is a PhD thesis project and supported by EFDA PWI and ITPA. It is done in close collaboration with the IPP edge plasma modelling group and supervised by Dr. Marco Wischmeier (IPP).

The modelling focuses on L-mode experiments carried out in LSN normal magnetic field configuration in 2007–2008. Revised experiments with reversed field and current for model validation will be carried out in December 2009.

Goals

1) Improving the SOLPS solution for the L-mode plasma background, in particular concentrating on the effect of drifts and power balance. Collaboration with the IPP edge plasma modelling group.
2) Modelling methane transport with the ERO code, discussion of results presented at the PFMC12 and PET12 workshops with local experts. Preparing a manuscript of the work.

3) Oral presentation at the ASDEX Upgrade seminar on December 2.
4) Planning and coordination of the ^{13}C methane injection experiment on December 18.
5) Continue analysis of the AUG experimental data obtained during the last ^{13}C experiments.

Report: Modelling the L-mode plasma background for 2007 AUG injection experiment with SOLPS was continued (collaboration with M. Wischmeier, A. Chankin), with variation of input power to the scrape-off layer. Simulations with reversed Bt/Ip were initialized and variations in the calculation grid were discussed. Spectroscopic data from ^{13}C experiments in 2007–2008 was analysed and discussed (R. Dux, S. Potzel, M. Wischmeier). Langmuir probe data analysis was discussed (H. W. Müller).

A presentation on “Carbon Transport in the Outer Divertor of ASDEX Upgrade” was held on the AUG seminar on December 2. Discussion of results presented at the PFMC12 and PET12 workshops with a large audience (over 30 participants).

A ^{13}C methane injection experiment was planned and carried out successfully on December 18th, at the end of the campaign (collaboration with the ASDEX Upgrade Team). Discussion of future experiments and tile analyses with R. Neu and V. Rohde. The milestones of this visit were completed.

5.2.13 Fast Scrape-off layer modelling using SOLPS

Name of seconded person:	Mathias Groth
Sending Institution:	TKK / Association Euratom-Tekes
Host Institution:	IPP-Garching
Dates of secondment / Mission:	8 November – 5 December 2009

Work Plan / milestones:

- Verify bolometry and IRTV data analyses for AUG discharges 21303-21327.
- Continue UEDGE modelling of AUG discharges, post-process solutions.
- Present results to IPP Garching edge modelling group.
- Receive training in SOLPS, set up first cases, e.g., for 2007 AUG C13 experiment (22573–22585).
- Assist L. Aho-Mantila in preparing 2009 ^{13}C injection.

Report:

1. The quality of the bolometry and IRTV data was re-assessed and extended, and a significantly better power balance was achieved following re-analysis of the total heating power (A. Kallenbach, A. Tardini, C. Fuchs, T. Eich).
2. The density with UEDGE was completed, and repeated with different chemical sputtering yields and recycling boundary conditions to better match the re-analyzed bolometry data.

3. We had several small-group discussions on data analysis and fluid edge modelling between A. Kallenbach and M. Wischmeier.
4. D. Coster set me up with a SOLPS benchmark case. About one week was spent to set up SOLPS and the post-processing routines in my user area. A density scan for the benchmark case was carried out and the simulations post-processed for heat flux fall-off length. B2.5 standalone (without EIRENE) and coupled SOLPS cases were run.
5. The scientific team held a few control room-type meetings to prepare the 2009 ^{13}C experiment in reversed toroidal magnetic field/plasma current configurations.

5.2.14 Momentum and Particle transport, Joint ITPA Experiment TC-15 between JET, DIII-D and NSTX

Name of seconded person:	Tuomas Tala
Sending Institution:	VTT / Association Euratom-Tekes
Host Institution:	General Atomics, San Diego, US
Dates of secondment / Mission:	9–22 May 2009

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, both on DIII-D and JET.

Report: An experiment to study the dependence of momentum and particle pinch on several plasma parameters, such as collisionality, density scale length, q-profile and Te/Ti ratio, was successfully carried out on DIII-D. A good 3-point collisionality scan with NBI modulation for momentum pinch and a 2-point collisionality scan with gas puff modulation for particle pinch were achieved. Pellets were used to scan the density gradient length successfully. The reflectometry shows very clean density modulation which enables us for the first time to analyse the particle pinch and diffusivity on a large tokamak. The JET part of this ITPA experiment is scheduled in autumn 2009.

5.2.15 Implementation of the model for the magnetic islands to the guiding centre orbit tracing code ASCOT

Name of seconded person:	Antti Snicker
Sending Institution:	TKK / Association Euratom-Tekes
Host Institution:	MPG-IPP Garching
Dates of secondment / Mission:	1–14 November 2009

Work Plan / milestones: The purpose of the visit is to implement and test a magnetic island model to our local guiding centre orbit following code ASCOT. The model has already been used to estimate the fast ion losses during the NTM's in ASDEX upgrade by, e.g., Dr. E. Poli and E. Strumberger.

However, ASCOT can enhance earlier studies by several means. Thing that have already been implemented to ASCOT:

- We have a realistic 3D structure for the plasma facing components (PFC)
- Energy and pitch angle scattering processes are taken into account.

Moreover, recently we have developed tools to take into account the finite gyro radius, i.e. to use full orbit integration instead of guiding centre integration.

In future, ASCOT will be used both to estimate the fast ion losses during NTM activity and redistribution of fast ions during inside the plasma during the whole slowing down process, latter being something that nobody has really studied in full detail so far.

Moreover, the visit also enables an invaluable networking opportunity and also provides a close view into the fusion experiments, which is not doable in Finland.

Report: During the stay, the magnetic island model was implemented to ASCOT. Moreover, the model was tested with the real ASDEX Upgrade magnetic background. The tests showed that the model works as it should work and some of the earlier results in ASDEX Upgrade discharge (mainly island width and radial location) were reproduced with ASCOT. In addition, I acquainted to magnetic coordinates and relativistic Lagrangian formalism. As a by-product, the relativistic equations of motion in magnetic coordinates with the most general perturbation in the magnetic vector potential were derived. This is new foundation in literature.

During the mission, we noticed an interesting ASDEX Upgrade discharge (#25523) with a lot of NTM activity. It was also heavily measured by the fast ion loss detector (FILD). Hence, we started to build up a simulation to reproduce the experimental results. This work is in progress at the moment and we expect to see an agreement between the simulation and experiment. Moreover, the same model can be used to predict NTM effects in ITER.

The networking with the community was also successful. The weekly social events (sports and dinners) provided a wonderful way to get to know people, whereas the almost daily visits to the control room provided a small view to the experiment itself. Also the discussions concerning experimental data, for the discharge of our interest, proved to be very fruitful.

5.2.16 TBM Experiment on DIII-D

Name of seconded persons:	Tuomas Tala
Sending Institution:	VTT / Association Euratom-Tekes
Host Institution:	DII-D General Atomics, San Diego, USA
Dates of secondment / Mission:	9–21 November 2009

Work Plan / milestones: The main goal of the experiment from my point of view was to quantify the effect of TBM mock-up on H98, β, density and rotation. The second goal more physics oriented goal was to compare the effect of TBM on rotation on DIII-D with the effect of magnetic field ripple on rotation on JET. In addition, the influence of TBM on heat and particle transport as well as fast ion losses is studied. (The scope of the whole set of TBM experiment was even wider, but under this mobility agreement, the aforementioned goals are the main ones.) The TBM experiment was a joint experiment among all the ITER parties.

Report: A series of experiments was performed on DIII-D to mock-up the field that will be induced in a pair of ferromagnetic Test Blanket Modules (TBMs) in ITER. A set of coils producing both poloidal and toroidal field was placed inside a re-entrant horizontal port close to the plasma. The localized ripple defined by $\delta B_{TBM}/B_T$ on the last closed flux surface at the outboard midplane was varied from 2% to 8%, exceeding the value of ~1.6% expected from a pair of representative 1.3 ton TBMs in ITER. The direct effects of TBM error fields increased with localized ripple. The largest effects were on plasma rotation, which dropped by 10% at 2% ripple and by 40 to 50% above 4% ripple. The interaction with existing MHD modes also caused mode locking and disruptions at high ripple values. The TBM effects depended on the global plasma normalized β_N, with very little effect for $\beta_N < 1.5$ (e.g., plasma initiation, L-mode, H-mode threshold). The effects increased with β_N, leading to drops of up to 15–18% in $H_{98}(y,2)$, β_N, and ne for β_N up to 2.6 and local TBM ripple > 5%.

5.2.17 ITPA TBM experiment for ITER at DIII-D

Name of seconded persons:	Antti Salmi
Sending Institution:	TKK / Association Euratom-Tekes
Host Institution:	DII-D General Atomics, San Diego, USA
Dates of secondment / Mission:	9–21 November 2009

Work Plan / milestones: The goal of the experiment is to compare the effect of TBM on rotation on DIII-D with the effect of magnetic field ripple on rotation on JET. In addition, the influence of TBM on heat and particle transport as well as fast ion losses is studied. (The scope of the whole set of TBM experiment is wider, but under this mobility agreement, the aforementioned goals are the main ones.) The TBM experiment will be a joint experiment among all the ITER parties.

Background: The effect of ripple on JET rotation has been analysed in great detail and it has a major impact on rotation, both on the magnitude and the profile. To be able to make reliable predictions for rotation in ITER, on top of the effect of ripple, the effect of TBM should be quantified. It is also important to understand how the TBM affects rotation, i.e. does it add “extra torque” in the plasma or rather brake rotation by adding “extra viscosity” in NTV-like way. In the case of ripple on JET, the main effect on rotation is clearly to add extra torque (rather than increased viscosity) in the counter-current direction due to enhanced amount of lost ions caused by ripple (mainly fast ions). With TBM, it is not so clear that the same mechanism will be the dominant one.

Experimental Approach/Analysis plan: At least the following scans should be performed in the experiments: B_t scan, n_e or collisionality scan and NBI alignment (co, counter, normal, tangential) scans. Ripple is known to affect the magnitude of the chances in rotation during these scans on JET. Therefore, it is probable that these parameters will be important in understanding the role of TBM on rotation on DIII-D as well. In the analysis of the experiments, the main tool is the Monte-Carlo Orbit-following ASCOT code. ASCOT has been used to model ripple loss ions on JET (NBI and ICRH fast ions and to some extent also thermal ions). With TBM on DIII-D, ASCOT can be used in a similar way, i.e. calculating the torque due to TBM.

Report: ITER will have perturbations in the magnetic field that will brake the axi-symmetry and thus allow enhanced radial transport of energetic and thermal particles. The so called Test Blanket Modules (TBMs) designed for tritium breeding testing are one such perturbation. In earlier ITER modelling tasks it has become more clear that TBMs can make the field stochastic and possibly cause significant extra losses at least for MeV ions.

Since the potential extra losses of the fast ions could be harmful for ITER first wall or on the toroidal rotation it is important to gain confidence in the numerical simulations. DIII-D TMB mock-up experiment is the best chance to achieve experimental validation for the results. Comparisons against some of the dedicated fast ion diagnostics data as well as the toroidal rotation changes (this would need transport analysis also for quantitative results) should be able to verify whether code predictions are correct.

The main motivation for authors participation in the experiment was to collect all necessary information for modelling the experiment with a guiding centre orbit following Monte Carlo code ASCOT. The required data includes not only the plasma profiles and NBI powers but also the underlying geometries and magnetic equilibrium reconstructions and TBM perturbation field.

The Scientific Coordinator for the experiment, Michael Schaffer, provided his vacuum field calculation of the TBM perturbation. It is given on an equidistant R/Z/phi grid [$129 \times 129 \times 360$] separately for both the race track coils (toroidal field) and solenoid coil (poloidal field). Experimental point names TBMC and TBMS provide the correct normalisation factors for summing up the data. Fields were initially calculated on 1kA and 426.7A currents, respectively. Also in the calculations TBM position was 1cm closer to the plasma than was realised in the experiment.

Toroidal field ripple data was not accessible directly but instead the toroidal field coil coordinates were provided which were then used to calculate the ripple. Comparisons against old hard-copy printouts showed good agreement and validate the method used.

The axi-symmetric equilibrium field in the form of g-eqdisk can be produced for the time and discharge of interest using the “EFITviewer” (available at least on delphi.gat.com). The final magnetic field (under vacuum field paradigm) is then the sum of all the above.

NBI geometry was discussed with Dr Solomon and confirmed that the 1998 paper by H. Chiu “*Measurement of neutral beam profiles at DIII-D*” still applies (google hit no: 1). DIII-D intranet gives further details of the NBI toroidal alignment.

Idl data export procedure can be used for exporting spline fitted profile data from reviewplus. *gadat* (IDL) reads experimental point names and *restore* (IDL) reads exported idl structures. During the visit an introduction to the relevant tools for obtaining the data concerning a specific discharge was given to all international participants. A short summary of remote access to DIII-D is listed here for reference:

- Ssh – Y to the GA login node hydra.gat.com (ssh – Y is needed for X)
- Ssh – Y further to the node of your choice (delphi / eos / …)
- Start 4d (or directly efitviewer / reviewplus / …)
- Please note that the graphical connection may be slow.

The status of the modelling efforts as of January 2010 is the following: DIII-D NBI system has been implemented in ASCOT and is now in testing phase. The vacuum 3D magnetic field data for the toroidal field ripple and the TBM field have been converted into ASCOT format and are also being tested. First trial simulations with the whole system could be expected to start in a few weeks time.

Planned simulations include in the first stage 140150 which shows the maximum effect on rotation. TBM amplitude and distance scans should follow.

6. OTHER ACTIVITIES

6.1 Conferences, Workshops and Meetings

Association staff members participated in the following conferences, workshops and meetings excluding the EU Fusion Programme and Fusion for Energy committee meetings.

- Timo Kiviniemi participated in the kick-of meeting of TGS-01 task, Jülich Germany, 22 January 2009.
- Antti Hakola, Kalle Heinola participated in the EFDA monitoring meeting on MAT-WWALLOY Task in Garching, Germany 26–27 January 2009.
- Tuomas Tala participated in the JET General Planning Meeting in JET, Culham, UK, 26–28 January 2009.
- More than 100 guests participated in the DTP2 inauguration at VTT, Tampere, 29 January 2009.
- Markus Airila, Leena Aho-Mantila, Carolina Björkas, Antti Hakola, Niklas Juslin, Taina Kurki-Suonio, Jari Likonen, Toni Makkonen, Kai Nordlund and Katharina Vörtler participated in the Finnish–German Workshop on Materials Migration in Tervaniemi, Finland, 29–30 January 2009. Local organisers M. Airila and T. Kurki-Suonio.
- Antti Hakola visited UT GDL for common experiments, 2–13 February 2009.
- Matti Laan participated in the JET Task Fusion Technology JWP9 kick-off teleconference, 13 February 2009.
- Tuomas Tala, Johnny Lönnroth and Antti Salmi participated in the biannual Task Force T Workshop in JET, Culham, UK, 16–18 February 2009.
- Seppo Karttunen participated in the Joint Meeting of the International Fusion Research Council (IFRC) and IEA Fusion Power Coordinating Committee at IAEA Headquarters, Vienna Austria, 24–25 February 2009.
- Antti Hakola gave an invited talk titled “Nuclear fusion – where the extreme states of matter meet” (in Finnish) for mathematics, physics, and chemistry teachers at the 5th Anniversary Symposium of the LUMA Centre, Helsinki, 27 February 2009.
- Madis Kiisk visited NIPNE, Tandem Accelerator Facility, MEdC, Romania, 1–5 March 2009.

- Antti Hakola, Eero Hirvijoki, Salomon Janhunen, Simppa Jämsä, Tuomas Koskela, Taina Kurki-Suonio, Toni Makkonen, Rainer Salomaa and Antti Snicker participated in the XLIII Annual Conference of the Finnish Physical Society, Espoo, 12–14 March 2009.
- Matti Laan participated in the 39th Estonian Physics Days, 18 March 2009.
- Matti Laan participated in the kick-off meeting of the EFDA Topical Groups (TGS) WP08-TGS-01-04 Task, Frascati, Italy, 20 March 2009.
- J. Lönnroth participated in a Task Force Integrated Tokamak Modelling ITER Scenario Modelling Group working session in Lisbon, Portugal on 23–28 March 2009.
- Seppo Karttunen visited IPP-CR, Prague, Czech Republic, 24 March 2009.
- Tuomas Tala participated in the ITPA Transport and Confinement meeting in Naka, Japan, 31 March – 2 April 2009.
- Peeter Paris participated in the Annual Meeting of the EFDA Diagnostics Topical Group on the 2010–2011 Work programme, Garching, Germany, 1–2 April 2009.
- L. Zhai and A. Muhammad attended 7th International Conference on Fluid Power Transmission and Control, Hangzhou, China, 7–10 April, 2009.
- Kai Nordlund, Spring MRS meeting, symposium Ion Beams and Nano-Engineering, 13–17 April 2009, San Francisco, USA, invited talk.
- T. Kurki-Suonio participated in the 2nd Meeting of the ITPA topical group on energetic particle physics, Seoul, 21–24 April.
- Susan Leerink participated in the Sherwood Meeting on Fusion Theory, Denver, USA from 1–4 May 2009.
- O. Asunta participated in Course on Optimization and Parallel Computing at CCFE, UK 5–8 May 2009. Lead lecturer: Adrian Jackson.
- Markus Airila, Leena Aho-Mantila, Antti Hakola, Seppo Koivuranta, Jari Likonen and Katharina Vörtler participated in the 12th International Workshop on Plasma-Facing Materials and Components for Fusion Applications, Jülich, Germany, 11–14 May 2009.
- Kai Nordlund visited SCK-CEN Mol, Belgium, 25–27 May 2009, Presentation of supervisor statement for M. Sc. Ville Jansson.
- L. Zhai and A. Muhammad attended 11th Scandinavian International Conference on Fluid Power SICFP’09, 2–4 June 2009, Linköping, Sweden.
- 52 participants from the Finnish and Estonian Research Units participated in the Euratom-Tekes Annual Fusion Seminar, Pärnu, Estonia, 3–4 June 2009. Invited talk by A. Donne from FOM.
- Madis Kiisk and Matti Laan participated in JET TF Fusion Technology – 1st Semi-Annual Monitoring Meeting, 5 June 2009, teleconference.

- Seppo Karttunen participated in the EFDA Technical Meeting on the EU PSI Facilities at EFDA CSU Garching 17–18 June 2009.
- Seppo Karttunen participated in the EPS Plasma Physics Division Board Meeting in Sofia, Bulgaria, on 28 June 2009.
- S. Karttunen, S. Janhunen, T. Koskela and S. Jämsä participated in the 36th European Physical Society Conference on Plasma Physics, Sofia, Bulgaria, 29 June – July 3, 2009.
- Kalle Heinola participated in the EFDA monitoring meeting on WP08-09-MAT-WWALLOY task in Stockholm, Sweden, 1–2 July 2009.
- Carolina Björkas participated in the Joint TFE-SEWG Material Migration and Material Mixing Meeting, Culham, UK, 7–8 July 2009.
- Seppo Karttunen visited Fusion for Energy (F4E), Barcelona, Spain, 7–9 July 2009.
- Antti Snicker participated in the Nordita Master Class in Physics 2009, Hillerød, Denmark, 26 July – 1 August 2009.
- Kai Nordlund participated in the 19th International Conference on Ion-Surface Interactions, Zvenigorod, Russia, 23–27 August 2009, invited talk.
- Matti Laan participated in the III Central European Symposium on Plasma Chemistry, Kyiv, Ukraine, 23–27 August 2009.
- Sanna Tervakangas and Jukka Kolehmainen visited UT GDL on 31 August 2009.
- Tuomas Koskela and Simppa Jämsä participated in the 9th Carolus Magnus Summer School on Plasma and Fusion Energy Physics, Herbeumont-sur-Semois, Belgium, 31 August – 11 September, 2009.
- Leena Aho-Mantila, Jukka Heikkinen and Susan Leerink participated in the 12th International Workshop on Plasma Edge Theory in Fusion Devices, Rostov Veliky, Russia, 2–4 September 2009.
- Carolina Björkas, Seppo Tähtinen and Katharina Vörtler participated in the 14th International Conference on Fusion Reactor Materials, Sapporo, Japan, 6–11 September, 2009.
- Markus Airila and Susan Leerink participated in the ITM General Meeting at IPP, Jülich, Germany, 8–11 September 2009.
- Antti Hakola visited UT GDL for common experiments, 8–18 September 2009.
- Rainer Salomaa participated in the International Conference on Nuclear Energy for New Europe 2009 (NENE09), Bled, Slovenia, 14–17 September 2009 (invited plenary lecture).
- Kai Nordlund, Psi-k Summer School “Computational Nanoscience for Renewable Energy Solutions”, 14–18 September 2009, Helsinki, Finland, invited talk.
- Kai Nordlund, OECD Nuclear Energy Agency Meeting. Paris, France, 18–19 September 2009.

- Antti Snicker participated in the IPP Summer University on Plasma Physics and Fusion Research, Greifswald, Germany, 21–25 September 2009.
- T. Kurki-Suonio participated in the 3rd Meeting of the ITPA Topical Group on Energetic Particle Physics, Kiev, Ukraine, 24–25 September.
- Peeter Paris and Matti Laan participated in the 5th Euro Mediterranean Symposium on Laser Induced Breakdown Spectroscopy, 27 September – 3 October 2009.
- Seppo Karttunen participated in the EFDA Technical Meeting on DEMO Status at EFDA CSU Garching, 28–30 September 2009.
- J. Lönnroth and T. Tala participated in the 12th International Workshop on H-Mode Physics and Transport Barriers in Princeton, New Jersey, USA, 30 September – 2 October 2009.
- Tuomas Tala participated in the ITPA Transport and Confinement Meeting in Princeton, New Jersey, USA, 5–7 October 2009.
- J. Lönnroth participated in an ITPA Pedestal and Edge Topical Group Meeting in Princeton, New Jersey, USA, 5–7 October 2009.
- S. Sipilä and O. Asunta participated in the 13th European Fusion Theory Conference, Riga, Latvia, 12–15 October 2009.
- Peeter Paris visited FOM Plasma Institute, Netherlands, 14–30 October 2009.
- Katharina Vörtler and Ville Jansson participated in the MATRE-1 School in Rochehaut-sur-Semois, Belgium, 18–23 October 2009.
- L. Aho-Mantila, O. Asunta, S. Janhunen, S. Jämsä, T. Koskela and M. Nora participated in the GOTiT Course on Single Particle Physics and Monte Carlo Methods in the Royal Institute of Technology, Stockholm, Sweden and Espoo, Finland, 18–30 October 2009.
- M. Airila, J. Heikkinen, T. Kiviniemi, A. Salmi and S. Sipilä gave lectures on the GOTiT Course on Single Particle Physics and Monte Carlo Methods, Stockholm, Sweden and Espoo, Finland, 19–30 October 2009.
- Antti Hakola and Taina Kurki-Suonio participated in the Annual ASDEX Upgrade Program Seminar, Ringberg, Germany, 25–30 October 2009.
- Madis Kiisk visited NIPNE, Tandem Accelerator Facility, MEdC, Romania, 1–4 November 2009.
- T. Koskela participated in the DEISA Training Course, Amsterdam, Holland, 3–4 November 2009.
- Antti Hakola and Jari Likonen participated in the 8th Annual Meeting of the EFDA-PWI Task Force, Warsaw, Poland, 4–6 November 2009.
- Antti Hakola participated remotely in a Review Meeting on Emerging Technologies – Dust and Tritium Management, held in Garching, Germany, 16 November 2009.

- Leena Aho-Mantila participated in the GOTiT Course on Magnetic Control of Tokamak Plasmas at the Università di Napoli Federico II, Napoli, Italy, 16–26 November 2009.
- Flyura Djurabekova, Fall MRS meeting, symposium Materials Research Needs to Advance Nuclear Energy, 29 November – 2 December 2009, Boston, USA, invited talk.
- Kai Nordlund, Fall MRS Symposium Materials Research Needs to Advance Nuclear Energy, 29 November – 2 December 2009, Boston, USA, invited talk.
- Madis Kiisk and Matti Laan participated in Task Force Fusion Technology, second Semi-Annual Monitoring Meeting of the FT tasks and Kick-off meeting for the task JW10-FT-3.60, Culham, UK, 1–4 December 2009.
- Carolina Björkas and Rainer Salomaa participated in the 17th European Fusion Physics Workshop in Budapest, Hungary, 7–9 December 2009.
- J. Heikkinen, S. Janhunen, S. Karttunen, T. Kiviniemi, S. Leerink, R. Salomaa, S. Sipilä, T. Tala participated in the Finnish–Russian Seminar on High Temperature Plasma Physics, Espoo, Finland, 9–11 December 2009.
- Kai Nordlund, EFDA MAT-REMEV Meeting, Alicante, Spain, 18–20 December 2009.

6.2 Visits

The following visits to European and US laboratories took place in 2009. The Staff Mobility actions are given in Section 5.

- J. Lönnroth was seconded to EFDA-JET, Culham, UK under the auspices of the JET Operating Contract on 1 January – 31 December 2009.
- Salmi was seconded to EFDA-JET, Culham, UK under the auspices of the JET Operating Contract on 1 January – 1 May 2009.
- V. Takalo was seconded to EFDA-JET, Culham, United Kingdom under the auspices of the JET Operating Contract on 1 January – 31 December.
- Tuomas Tala was seconded to JET on 1 January – 23 October (TF-T leader).
- Marko Santala was on S/T Secondment to JET 5 January – 8 April and 5–30 October 2009.
- Susan Leerink visited Massachusetts Institute of Technology (MIT), Boston, USA, 2 January – 31 March 2009.
- O. Asunta visited EFDA-JET, Culham, UK, 19 January – 6 March, 2–13 November and 7–18 December.
- Mikko Siuko, Jorma Järvenpää, Harri Mäkinen, S.-P. Leino, H. Saarinen, Jouni Mattila, Liisa Aha, Salvador Esque visited ITER, Cadarache, France, 11–12 March 2009.

- Carolina Björkas and Kai Nordlund visited the Technical University of Darmstadt, Germany, 1–4 April 2009.
- Karoliina Salminen and T. Kekäläinen visited Université Pierre et Marie Curie, Paris and CEA Fontenay-aux-Roses, 2–12 June 2009.
- Karoliina Salminen, Mikko Siuko, Jouni Mattila and T. Kekäläinen attended PREFIT Workshop in CEA Fontenay-aux-Roses on 15–16 June 2009.
- Jari Likonen was seconded to JET on 22 June – 10 July 2009.
- Markus Airila was seconded to JET on 22 June – 31 July 2009.
- Kai Nordlund and Flyura Djurabekova, IPP Greifswald, Germany, 9–12 August 2009, research collaboration with Prof. Ralf Schneider.
- Antti Salmi was seconded to EFDA-JET Culham Science Centre, Oxfordshire, 14 October – 9 September 2009.
- Mikko Siuko, Jorma Järvenpää, Harri Mäkinen, Jouni Mattila, Peetu Valkama visited ITER, Cadarache, France, 22–23 October 2009.
- Antti Salmi was seconded to EFDA-JET Culham Science Centre, Oxfordshire, 7–18 December 2009.

6.3 Visitors

- Dr. S. Booth from EC Commission visited VTT (DTP2) on 14–15 January 2009.
- Dr. L. Semeraro, from F4E, Spain visited VTT (DTP2) on 22 January 2009.
- Prof. F. Wagner, from Max-Planck-Institut für Plasmaphysik, visited TKK 11 March 2009.
- Prof. A. Kallenbach, from Max-Planck-Institut für Plasmaphysik, visited TKK, 21–22 December 2009.
- Dr. K. Krieger from Max-Planck-Institut für Plasmaphysik, visited TKK for 6 days.
- Dr. L. Semeraro, from F4E, Spain visited VTT (DTP2) on 15–16 April 2009.
- IEA Executive Committee visited VTT (DTP2) on 19 May 2009.
- Dr. T. Jokinen from ITER IO, Cadarache, France visited VTT (DTP2) on 10 June 2009.
- Dr. Vicente Manuel Queral from CIEMAT and Dr. Manuel Ferre from Univ. Politécnica de Madrid, Spain visited VTT (DTP2) on 26 June 2009.
- Drs. L. Semeraro, and C. Damiani from F4E, Barcelona, Spain, visited VTT (DTP2) on 10 August 2009.
- Dr. C. Lungu from National Institute for Laser, Plasma and Radiation Physics, Bucharest, Romania visited VTT, 24–28 August 2010.

- Dr. Malerba, Lorenzo, SCK-CEN Mol, Belgium, visited the Department of Physics at the University of Helsinki, 1–5 September 2009.
- Prof. T. Maslova from Department for Policies and Innovation Development, Committee for Science and Higher Education, City of St Petersburg, Russia, Prof. I. Maksimtsev from St Petersburg State University of Economics and Finance, Russia, E. Tarasenko Head, Department for External Relations, SPb FinEc, Russia, I. Vostrikova Head, Unit for Congress exhibition activities, SPb FinEc, Russia and I. Sarno, The Baltic Institute of Finland visited VTT (DTP2) on 9 September 2009.
- The Network of Excellence for Innovative Production Machines and Systems (I*PROMS) EC, EB and GC meeting participants visited VTT (DTP2) on 24 September 2009.
- Dr. F. Parra from the Massachusetts Institute of Technology (MIT) visited VTT on 7–10 October 2009.
- Ambassador Shapardanov, Canadian Embassy, S. Chase, Senior Trade Commissioner, Canadian Embassy, J. Nyman, Trade Commissioner, Canadian Embassy, S. Vihersaari, Trade Commissioner, Canadian Embassy visited VTT (DTP2) on 8 October 2009.
- The Commission members of the Association Euratom-Tekes Steering Committee Dr. Doug Bartlett, Dr. Steven Booth and Mr. Marc Pipeleers visited VTT (DTP2) on 21 October 2009.
- Prof. Antonis Goulas, Aristotle University of Thessaloniki, Greece visited VTT (DTP2) on 5 November 2009.
- Drs. J. Palmer, D. Hamilton and A. Martin from ITER, France visited VTT (DTP2) on 17 November 2009.
- Prof. Inessa Loukmanova and Prof. Pjotr Grabovyj from Moscow State University of Civil Engineering (MGSU) visited VTT (DTP2) on 2 December 2009.
- Dr. V. Naulin from Risø-DTU National Laboratory and JET TF-T leader visited VTT on 1–2 December 2009.
- Dr. Daniela Cancila from CEA LIST visited VTT (DTP2) on 4 December 2009.
- Dr. A. Gurchenko from the Ioffe Institute, St. Petersburg visited TKK from 9–19 December 2009.
- Prof. E. Gusakov from the Ioffe Institute, St. Petersburg visited TKK from 9–19 December 2009.
- Dr. V. Bulanin from the Technical University of St. Petersburg visited TKK from 9–19 December 2009.
- Drs. L. Semeraro and S. Esque from F4E, France visited VTT (DTP2) on 15 December 2009.

7. FUSION FOR ENERGY AND ITER ACTIVITIES

7.1 2008–2009 Host Activities Related to DTP2 Test Facility Operation and Upgrade Preparation

F4E Grant Contract:	F4E-2008-GRT-MS-RH-01
Principal Investigators:	Mikko Siuko and Jorma Järvenpää, VTT Jouni Mattila, TUT/IHA

7.1.1 Objectives

The main purpose of the Divertor Test Platform 2 (DTP2) facility, located in VTT Tampere, Finland, is to allow for operational testing of prototypes of the Remote Handling (RH) movers, manipulators and tooling required for removal/replacement of divertor cassettes from ITER.

The objectives of the present grant are:

1. Test, verify and develop further the ITER divertor maintenance scheme and devices,
2. The exploitation of the existing DTP2 hardware/software, with a series of handling tests on the cassette mock-up,
3. Provision and exploitation of new DTP2 hardware/software related to operations with a manipulator arm (WHMAN),
4. Preparation of hardware procurement related to operation with a Cassette Toroidal Mover (CTM) and additional cassette end-effectors.

The present specification defines the tasks related to operation and preparation of the upgrade of DTP2 until the end of May 2010. The areas of the identified action are:

- Operational testing of the prototype Cassette Multifunctional Mover (CMM) with Second Cassette End-Effector (SCEE) and CMM WHMAN required for replacement of the second divertor cassettes in ITER,
- Support in preparation for the delivery of Standard and Central Cassette End-Effectors prototypes (StCEE and CCEE, respectively) in order to allow operation on central, third and subsequent cassettes,
- Support in preparation for a DTP2 upgrade to extend the existing Divertor Region Mock-up (DRM) up to 80 degrees toroidally,

- Support in preparation for delivery of a CTM prototype (optionally, the possibility to procure another WHMAN for the CTM will be explored).

The term operation is understood to mean the preparation of the DTP2 components to be handled, the set up of the ancillary services, the preparation of the data acquisition system and control system, the actuation of lifting devices for transporting components, etc.

Among the operations, in particular, a test is meant to cover a specific series of elementary instructions on DTP2 cassette mover and manipulator and tooling resulting in a divertor remote handling sequence which, in given conditions, produces experimental results suitable to be analysed and judged.

7.1.2 Main results in 2009

Task-1: Stand-alone CMM tests: Task 1 aims to verify the basic principle of the planned divertor Cassette replacement scheme. It includes testing the operations of the developed Cassette Multifunctional Mover (CMM) and its Second Cassette designated end-effector SCEE. Work includes control system tuning and programming, device calibration and mechanical adjustments.

During 2009, CMM tests on test stand were finished and tests from factory floor in DRM were started (Figure 7.1). One of the main achievements has been successful installation and removal of the Second Cassette (Figure 7.2). Video of this operation was sent to the ITER organization and it was published on the first page of the ITER Newsline #110.

The work in Task 1 has included calibration, measuring and checking the accuracy of the CMM-SCEE operations, as well as calibrating the virtual models with the DRM environment. Compensation of load effects has been implemented to the control software not only to increase positioning accuracy but also to be able to visualize true position and deflections of the Cassette in 3D environment. Work is going on to improve the representation of the real components' physical behaviour.

Characteristics of the CMM have been measured by applying the EN ISO 9283 standard. Some of the results of the measurements are presented in Table 7.1.

Table 7.1. CMM accuracy.

Position repetition accuracy	**Worst case**	**Average**	**Unit**
CMM without load	0,8	0,4	**mm**
CMM with 9 000 kg load	0,5	0,5	**mm**
Position accuracy	**Worst case**	**Average**	**Unit**
CMM without load	1,5	1,3	**mm**

Figure 7.1. Factory floor control station.

Figure 7.2. Divertor cassette entering the second cassette position.

Task-2: WHMAN tests: Task 2 is related to the development of hardware and software to achieve the desired functionality of WHMAN. The WHMAN is required to assist CMM during the divertor maintenance operation.

For this purpose WHMAN is required to be installed on CMM. The Sliding Table (ST) forms the mechanical interface between WHMAN and CMM and also provides an additional degree of freedom to WHMAN. The detailed design of ST was finished along with the manufacturing drawings. The parts of the ST were manufactured and components were procured. The parts and components were installed on CMM. The CMM body was also machined to achieve the desired alignments for the installation of ST. The ST installed on CMM is shown in Figure 7.3.

Along with the design and installation of ST on CMM the desired modifications in the DRM (Divertor Region Mockup) were studied. These modifications are required to provide the electrical and hydraulic interfaces to WHMAN for its operation on top of CMM. These include the additions of intermediate wiring cabinet and new umbilical on DRM and connectors and cabling on CMM. The design for these modifications was finalized and components were procured. Currently the implementation of these changes on DRM and CMM is underway. The design of these changes is demonstrated in Figure 7.4.

The WHMAN-HLC 2.0 was designed to control and operate the WHMAN on the test stand. With this version of WHMAN-HLC it was possible to achieve and test the basic functionality of the WHMAN. The WHMAN-HLC 3.0 includes the additional functionalities such as force feedback, haptic interfaces to master manipulator, data visualization and accusation and fault reporting (Figure 7.5). More modular approach was adopted for the development of WHMAN-HLC 3.0 so that different parts of software such as data accusation and fault reporting can be run separately (Figure 7.6). The WHMAN can be operated employing all the eight joints. The next version of WHMAN will provide the operation of WHMAN on top of CMM. This lays down the foundation for the future development of WHMAN functionality. The future development will involve the operation of WHMAN from the DTP2 control room, on top of CMM inside the divertor region to perform and verify the divertor maintenance operations.

Additionally position, force and impedance control performance of WHMAN are under investigation. Since the environment inside the ITER reactor is noncompliant and the remote handling tasks can only be defined approximately a strictly position controlled manipulator can result in damaging the reactor and the manipulator itself. Hence, force control along with the position control needs to be implemented for the manipulator. The widely investigated approach to meet this requirement is to employ the impedance control. Since, WHMAN is an intrinsically redundant manipulator, different strategies to exploit the redundant degrees of mobility are been studied. The implementation and investigation of impedance control along with the utilization of redundant degrees of freedom for improved dynamic performance can provide some useful results and insight for the control of WHMAN. Dynamic manipulability index of WHMAN as a function of manipulator's configuration is shown in Figure 7.7.

Figure 7.3. Photograph of ST on CMM.

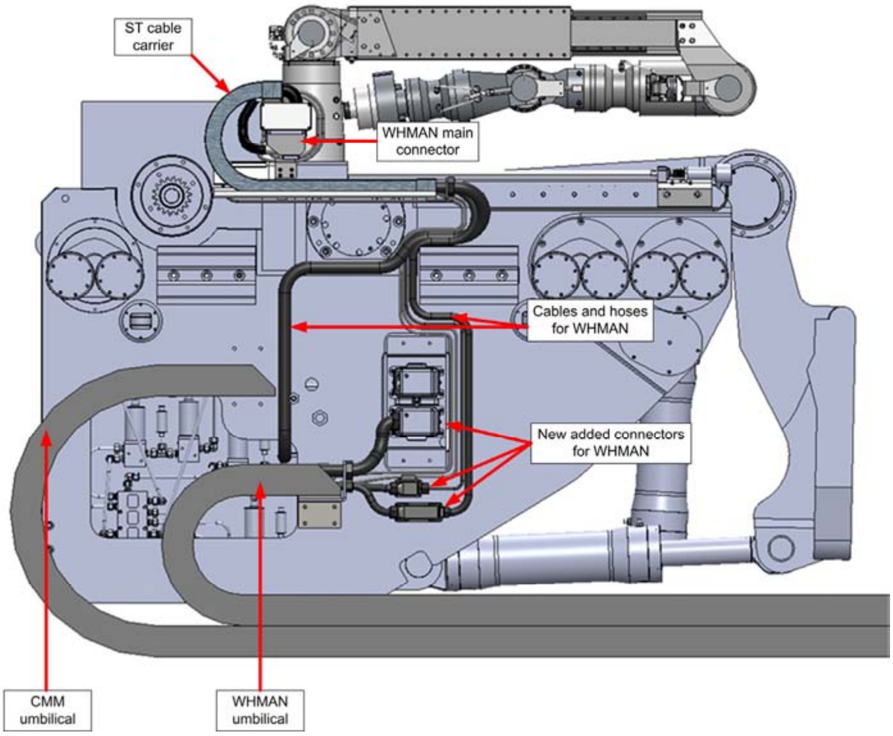


Figure 7.4. Planned changes in DRM and CMM.

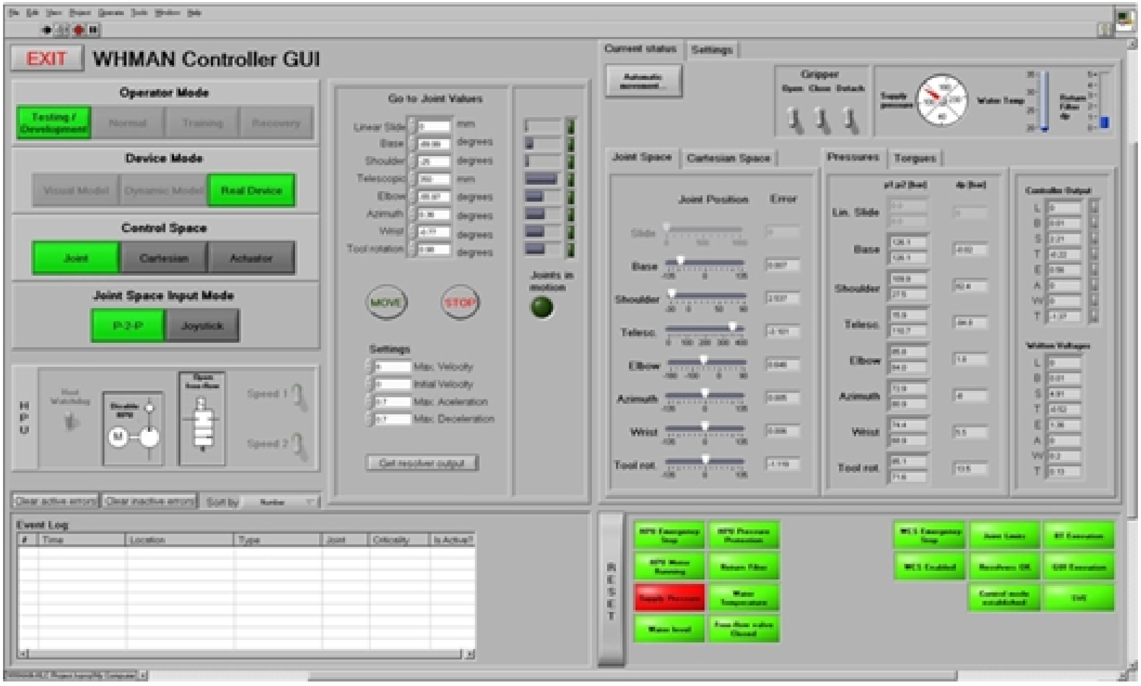


Figure 7.5. A look at WHMAN-HLC 3.0 main GUI.

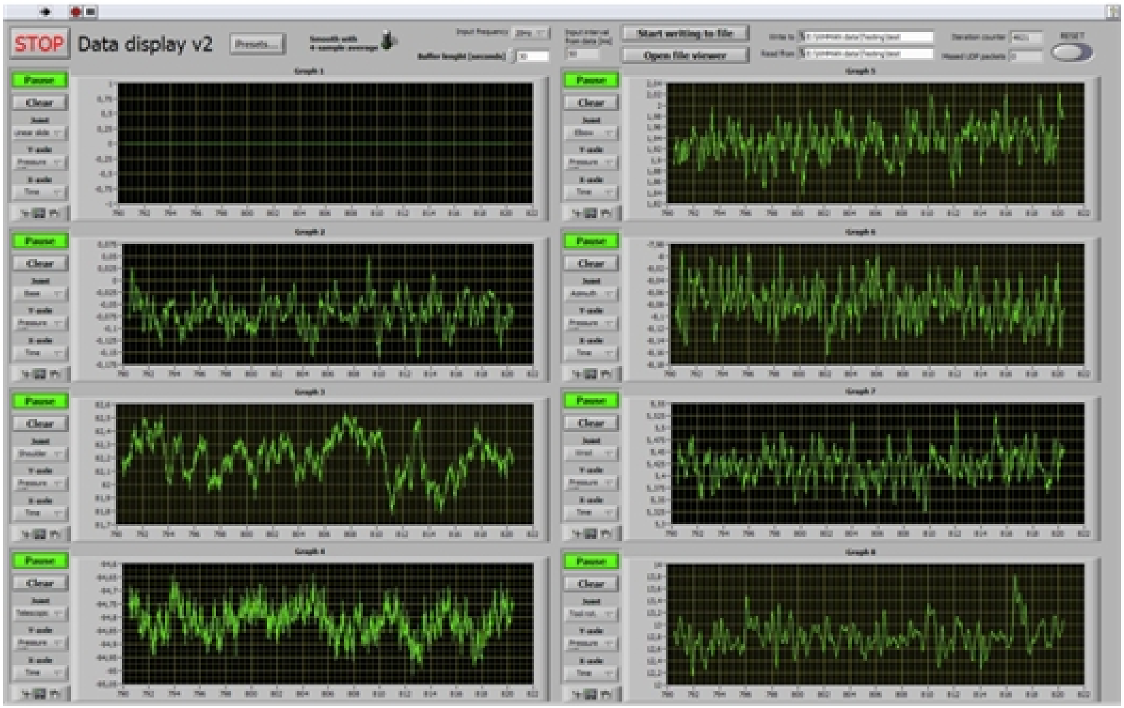


Figure 7.6. Data accusation and plotting GUI.

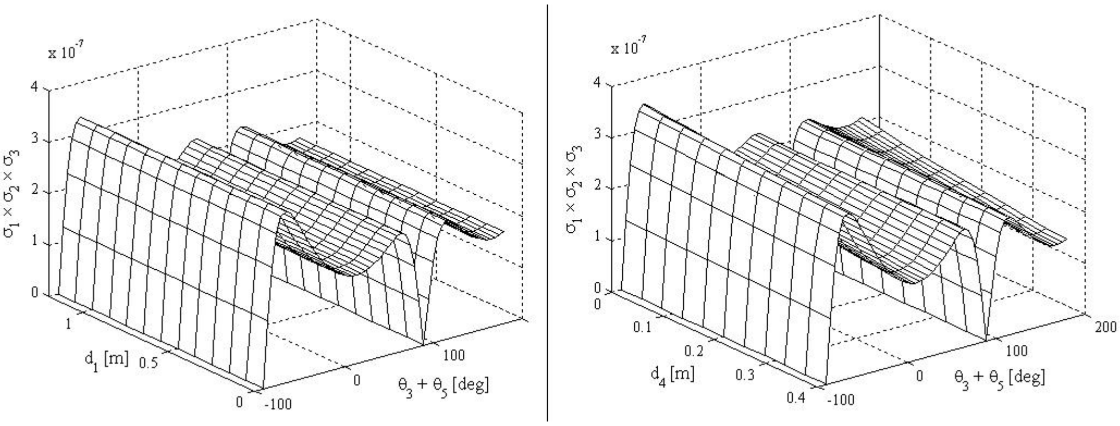


Figure 7.7. Dynamic manipulability index as a function of d_1, d_4 and $\theta_3+\theta_5$.

Task-3: Design and procurement of CMM additional end-effectors: This task entails designing concepts for CMM end-effector(s) for handling the central cassette, standard cassettes and the CTM.

The Second Cassette End-Effector (SCEE) has been functional and been tested since 2008. Now, additional end-effectors are needed to test the transportation and installation of the other cassettes into the Vacuum Vessel. The optimum situation would be where all the cassettes could be transported by only one multi-purpose end-effector, but as the cassettes are equipped with different auxiliary equipment and have different requirements, this cannot be the case. Therefore, two different end-effectors were developed to transport different types of cassettes. As the SCEE is already manufactured and being tested, and its trajectories have been designed for bringing in and installing the Second Cassette, it was decided that the other two end-effectors should be physically as much alike the SCEE as possible, thus reducing the further workload on generating the cassette trajectories.

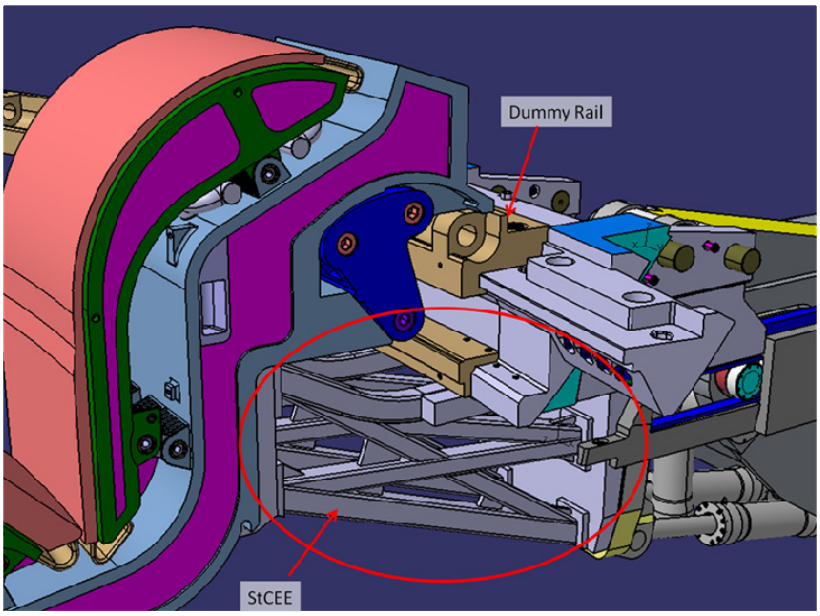


Figure 7.8. SCEE.

For this task, the concept designs for the two end-effectors were produced (Figures 7.8 and 7.9). System Requirements Documents (SRDs) for the end-effectors, created prior to beginning the concept design, were used as a basis for the designs. While the SRDs contain exact low-level requirements and information, the concept designs were designed according to the more general, high-level requirements set in the SRDs. These requirements were mapped and traced during the design and documentation process. In addition to the concept designs, 3D CAD models, SRDs and Design Description Documents are provided as a part of this task.

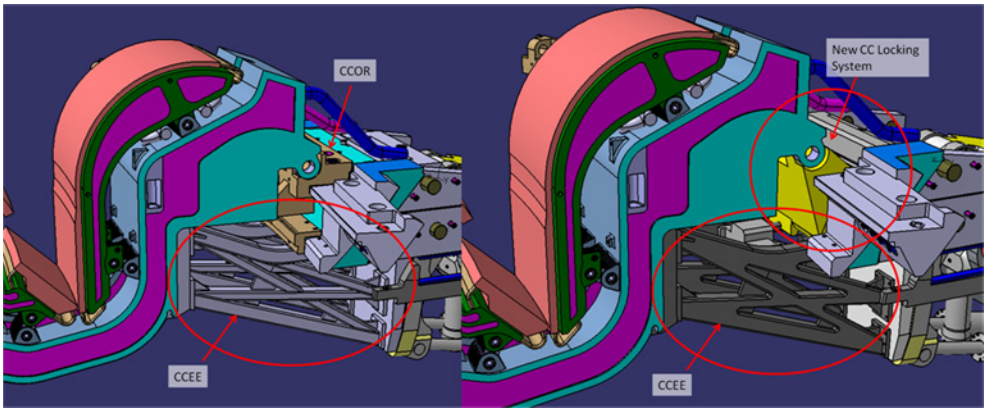


Figure 7.9. CCEE with CCOR (left) and New CC Locking System (right).

Additionally, a new concept proposal for the Central Cassette Locking System is presented in the deliverables 7.9. This new design takes into account the requirements set by the remote handling equipment and process. CATIA-model of this new concept design is provided as well as the detailed description and documentation.

Task-4: Design of DRM toroidal extension and upgrade: In the DTP2 hall, there is 27° sector of the lower part of the ITER Vacuum Vessel and maintenance tunnel (DRM). This construction allows testing of the Second Cassette replacement with the CMM Mover. For the future tests DRM has to be enlarged up to 80°. The divertor cassette locking system and the inner and outer toroidal rails in DRM have to be upgraded to meet the latest ITER design. Also, interfaces for the Central cassette and further CMM end-effectors are not considered in the DRM current design, so they will be upgraded to meet the latest ITER-design.

In 2009, 3D CATIA model of the up-to-date model has been finished (Figure 7.10). The new model includes all new features in the current ITER design. Based on this model, manufacturing drawings of the new parts will be produced in the next phase.

Occupational safety of the DRM environment has been developed. Working methods, walking platforms, ladders, very heavy component (CMM) lifting methods and equipment have also been developed during the last year (Figure 7.11).

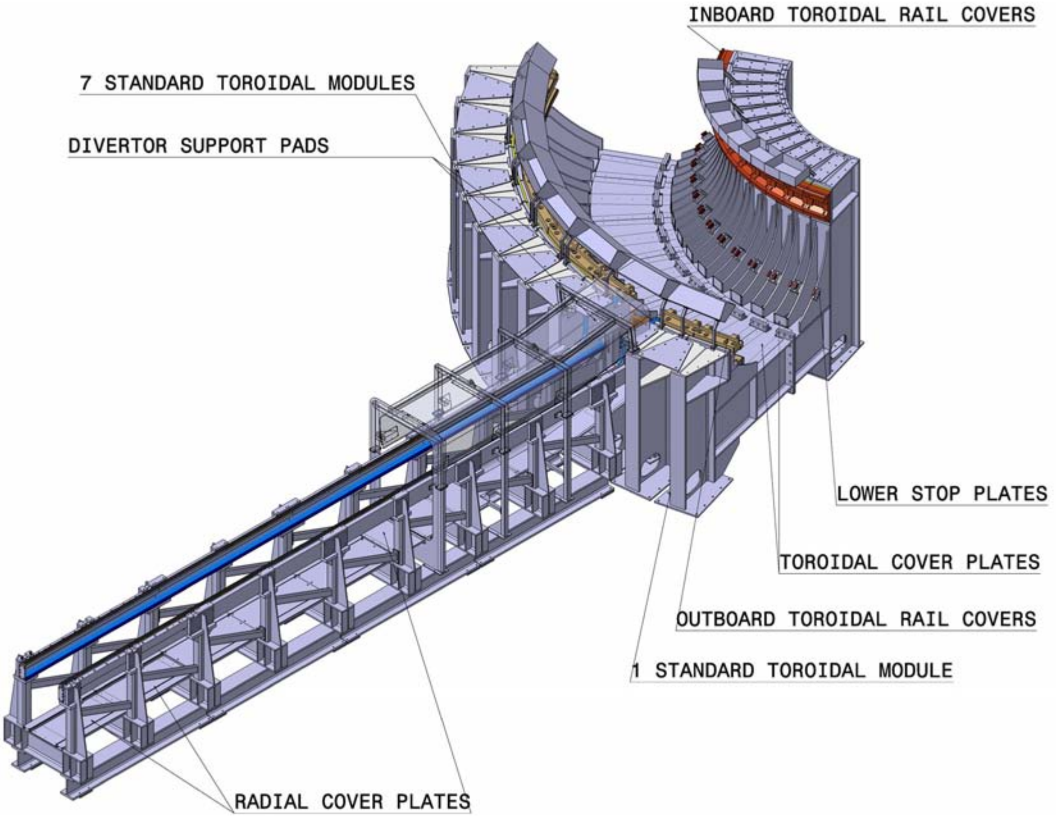


Figure 7.10. 3D model of the upgraded DRM.

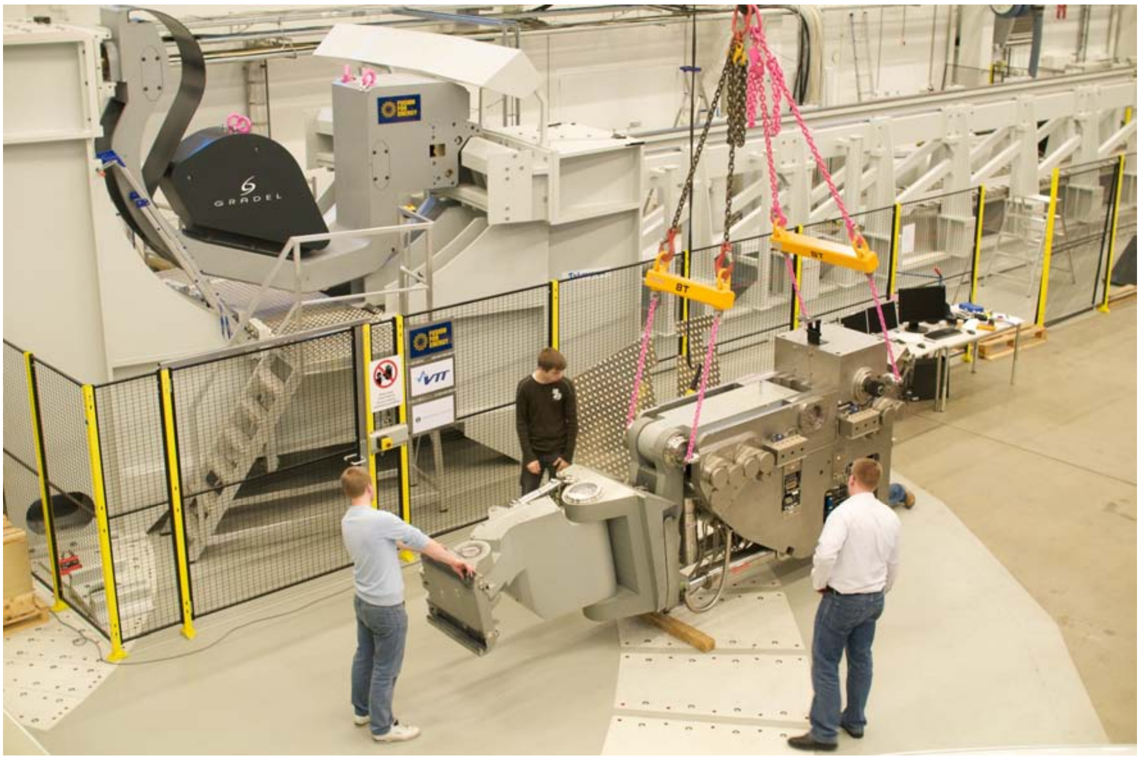


Figure 7.11. CMM lifting.

Task-5: Design of Cassette Toroidal Mover (CTM): In-vessel transportation of the Divertor Cassettes is carried out by CTM (Cassette Toroidal Mover). CTM carries cassettes to the radial port, where CMM transports cassettes to the Transfer Cask. CTM is moving on wheels along the toroidal rails, driven by rack-and-pinion -system. CTM is equipped with a lifting system supporting the Cassette during transportation. On CTM, there is a manipulator arm which is used to carry out assisting operations, like handling tools for opening the Cassette locking system and cutting the Cassette cooling pipes.

CTM design is in progress and 3D model concepts have been done (Figure 7.12). One of the most important tasks of the CTM is to carry divertor Cassette, and transport it using the CTM inner and outer rail drives. The space on CTM is very limited and design has to be optimized. Therefore three different concepts have been introduced for final construction.

For the CTM energy supply and control- and data cables there is an umbilical system. In this task different solutions for the umbilical system have been developed. CTM is transported to the Vacuum Vessel by CMM, and it needs several specific operational sequences. Design of these remote handling operational concepts has also been part of this task.

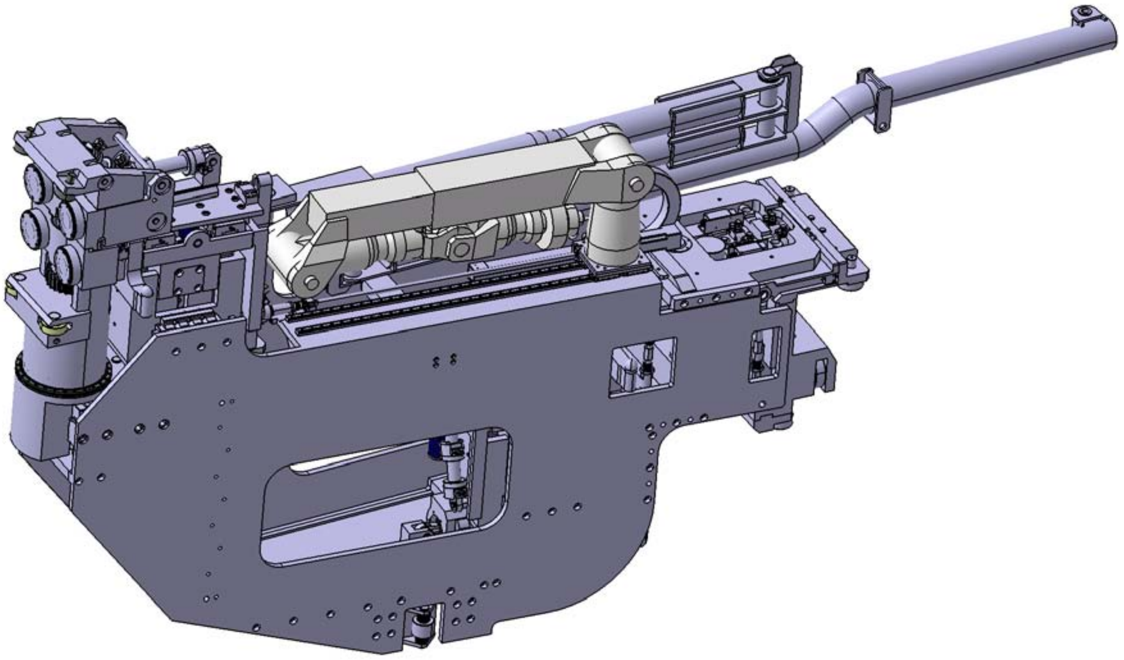


Figure 7.12. CTM 3D design concept.

Task-6: Design and tests of DTP2 supervisory system upgrade: In Task 6 supervisory system is developed and this means developing the sub-systems of the DTP2 control room and communication interfaces between them. This work consists of defining, designing and implementing features that assist operators to execute CMM and WHMAN tests (Task-1 and Task-2). It also includes usability studies and collection of user input to find out most significant features to be developed in the next version.

In 2009, version 2 of the supervisory system was finalized meaning that remote control of the real CMM-SCEE is possible. Previously only virtual model of the CMM could be controlled from the DTP2 control room. Control room layout (Figure 7.13) was upgraded in order to locate there 4 persons; 1 supervisor and 3 operators. The old layout was designed for only 3 persons and therefore new user roles and responsibilities were defined. Control room upgrades also include updating virtual models of the Divertor Region Mockup (DRM) and Cassette Multifunctional Mover (CMM).

Virtual Reality software IHA3D was further developed to allow mixed reality applications. For example, previously only virtual camera displays were possible. Now IHA3D can display video image from real cameras that can also include augmented reality (AR). AR system is being demonstrated for the remote handling operator assistance. AR system finds WHMAN Tool (Water-Hydraulic Jack) on the video image based on the Jack CAD-model recognition and furthermore calculates its pose in respect of desired coordinate frames. Projection of the CAD-model is then used to highlight the Jack in the video image in order to help the operator identify its Cartesian 6 DOF pose (Figure 7.14).

New sub-system IHAPlanner (Figure 7.15) was introduced. This software can be used for planning and execution of test sequences. Having detailed sequences and making sure that they are executed the same way every time is essential for example in CMM operational trials from the Control room done in Task-1.

Figure 7.13. Upgraded DTP2 Control room.

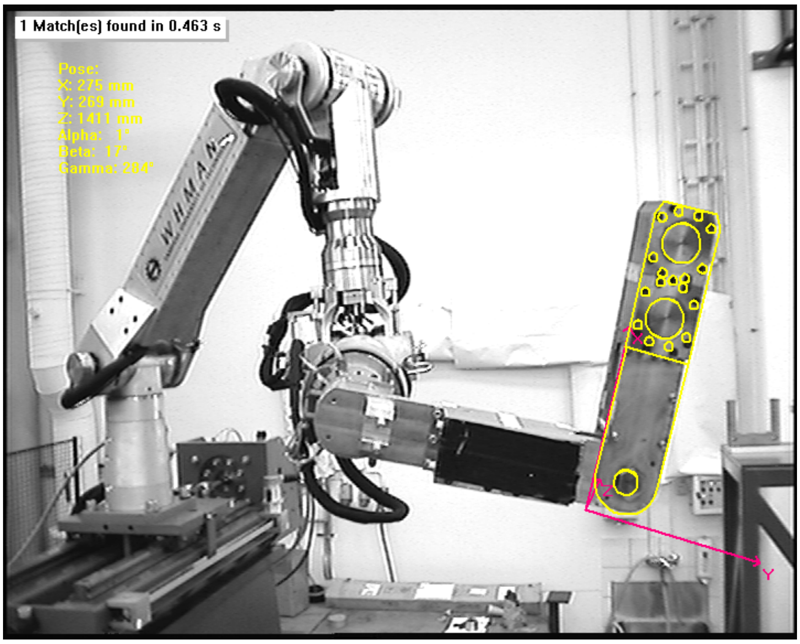
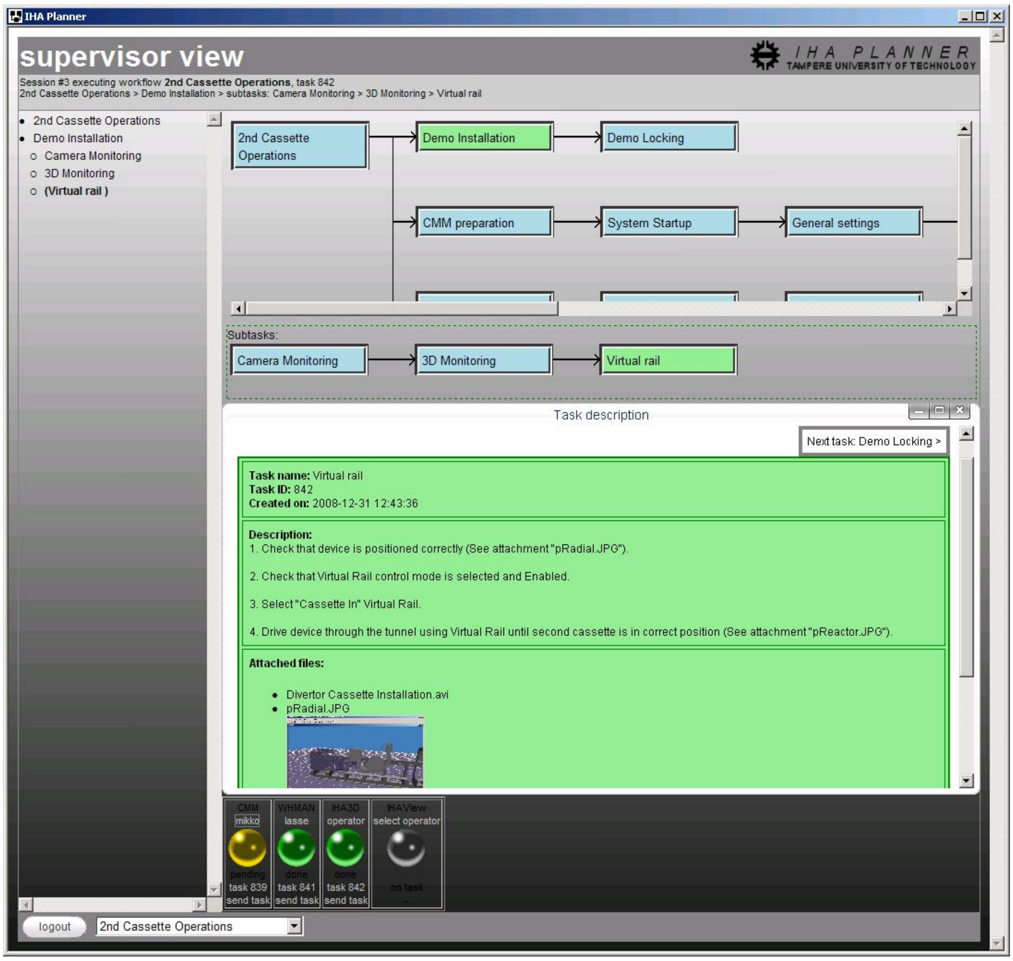


Figure 7.14. Projection of WH Jack model added on top of video image.



Session #3 executing workflow **2nd Cassette Operations**, task 842
2nd Cassette Operations > Demo Installation > subtasks: Camera Monitoring > 3D Monitoring > Virtual rail

Task name: Virtual rail
Task ID: 842
Created on: 2008-12-31 12:43:36

Description:
1. Check that device is positioned correctly (See attachment "pRadial.JPG").

2. Check that Virtual Rail control mode is selected and Enabled.

3. Select "Cassette In" Virtual Rail.

4. Drive device through the tunnel using Virtual Rail until second cassette is in correct position (See attachment "pReactor.JPG").

Attached files:

- Divertor Cassette Installation.avi
- pRadial.JPG

Figure 7.15. IHAPlanner software for planning and execution of test sequences.

7.2 Advanced Fabrication of ITER Vacuum Vessel (ADFAB)

Institute:	VTT Industrial Systems
Principal Investigator:	Veli Kujanpää
Research Scientists:	Kalervo Leino and Miikka Karhu

7.2.1 Objective

The objective of the project is to introduce Finnish manufacturing technologies to ITER, F4E and AFCEN and to gain acceptance to their use in ITER Vacuum Vessel. The technologies include components made by Powder Metal Hot Isostatic Presing (PM-HIP) process and Laser Arc (Laser Hybrid) Welding.

7.2.2 Results

Sample components made by the PM-HIP process have been made and introduced to the fusion energy community in SOFT conferences. Information of the process and its major features and advantages has been submitted to ITER Organization, Fusion For Energy, AFCEN as well as to the most potential manufacturers of the vacuum vessel components in Europe and in Korea.

PH-HIP material is also subjected to welding research, to determine its weldability and the properties of the welds. In welding, both narrow gap TIG and Laser Arc (Laser + MIG/MAG) processes are used. The weldability research will be completed in early 2010.

7.3 Assembly Welding of ITER Vacuum Vessel – Pre-study

Institutes:	VTT Industrial Systems and Lappeenranta University of Technology
Principal Investigator:	Timo Määttä
Research Scientists:	Veli Kujanpää, Kalervo Leino, Miikka Karhu, Mika Sirén, Jukka Väinölä, Heikki Handroos and Huapeng Wu

7.3.1 Objective

The objective of the project was to study the assembly welding task of the Vacuum Vessel Sectors to the complete Vacuum Vessel, to determine issues that need particular attention in order to make the assembly welding task successful. The data gained in the project is aimed at being at disposal to a party that is considering making contract of the Vacuum Vessel assembly welding task.

7.3.2 Results

The work resulted in conclusions that three issues within the assembly welding work are of particular importance and require considerable research and development inputs to be finished successfully. These issues are handling of the parts, welding work itself and quality control and assurance of welding.

Different approaches to solve the problems were determined and particular research tasks were defined. It seems inevitable that both development of methodologies and tuning of the vessel design are still required.

8. PUBLICATIONS 2009

8.1 Fusion Physics and Plasma Engineering

8.1.1 Publications in scientific journals

1. T. Tala, K.-D. Zastrow, J. Ferreira, P. Mantica, V. Naulin, A.G. Peeters, G. Tardini, M. Brix, G. Corrigan, C. Giroud and D. Strintzi. Evidence of Inward Toroidal Momentum Convection in the JET Tokamak. Physical Review Letters 102 (2009) 075001.

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8.1.2 Conference articles – physics and plasma engineering

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80. P. Mantica, F. Ryter, D. Strintzi, T. Tala, C. Giroud, T. Johnson, E. Lerche, T. Loarer, A.G. Peeters, S. Sharapov, D. Van Eester, P.C. de Vries, L. Zabeo, K.-D. Zastrow and JET-EFDA Contributors. Experimental Study of the Ion Critical Gradient Length and Stiffness Level and the Impact of Rotational Shear in JET. 22nd IAEA Fusion Energy Conference, Geneva, Switzerland, October 13–18, 2008. Paper EX/2-4.

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101. P. Mantica, F. Ryter, D. Strintzi, T. Tala, C. Giroud, T. Johnson, E. Lerche, T. Loarer, A.G. Peeters, S. Sharapov, D. Van Eester, P.C. de Vries, L. Zabeo, K.-D. Zastrow and JET-EFDA contributors. Experimental Study of the Ion Critical Gradient Length and Stiffness Level and the Impact of Rotational Shear in JET. 13th EU-US Transport Task Force Workshop on Transport in Fusion Plasmas, Copenhagen, Denmark, 1–4 September 2008. Paper O-2.

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108. A. Snicker and S. Sipilä. SOFI – Single Orbit Following Implement. XLIII Annual Conference of the Finnish Physical Society, Espoo 2009. P. 291.

109. S. Jämsä, T. Kurki-Suonio and H.-U. Fahrbach. ASDEX Upgrade team. The effect of radial electric field on fast ions in a tokamak as viewed with a neutral particle analyser. XLIII Annual Conference of the Finnish Physical Society, Espoo 2009. P. 257.

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8.2 Fusion Technology

8.2.1 Publications in scientific journals

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128. S. Tähtinen, P. Moilanen and B.N. Singh. Results of in-reactor deformation experiments and their implications. Presented at 14th International Conference on Fusion Reactor Materials, Sapporo, Japan 6–11th September 2009.

129. R. Salomaa. Nuclear Pre-Renaissance – the Case Finland, plenary paper #1. Proceedings of the International Conference on Nuclear Energy for New Europe 2009 (NENE09), Bled, Slovenia, 14–17 September 2009. (in print)

130. R. Salomaa, R. Kyrki-Rajamäki and T. Vanttola. GEN4FIN – A R&D Platform for Educating Finnish Nuclear Engineers, poster paper #1106. Proceedings of the International Conference on Nuclear Energy for New Europe 2009 (NENE09), Bled, Slovenia, 14–17 September 2009. Abstract in print.

8.2.3 Research reports

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8.3 General Articles

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133. Suomi osallistuu fuusioreaktorin rakentamiseen Ranskassa. Hämeen sanomat 15.3.2009, p. 5 (in Finnish)

134. R. Kuivanen. Harnessing fusion power spawns new expertise. VTT Impulse 2 (2009) 26–31.

8.4 Doctoral and Graduate Theses

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136. N. Juslin. Computer simulation of H and He effects in fusion reactor materials. PhD thesis, University of Helsinki 2009.

137. J.-S. Lönnroth. Predictive modelling of edge transport phenomena in ELMy H-mode tokamak fusion plasmas. PhD Thesis, TKK Dissertations 195, Helsinki University of Technology, Espoo 2009.

138. T. Kivelä. Kinematic calibration of fusion power plant maintenance robot" MSc Thesis, Tampere University of Technology 2009.

139. J. Tiitinen. Applying UML in a LabVIEW Based Control System" MSc Thesis, Tampere University of Technology 2009.

140. P. Valkama. Design of a six degree of freedom water hydraulic arm for remote handling" MSc Thesis, Tampere University of Technology 2009.

141. F. Amjad. Requirements Management System – Implementation on ITER End-Effector Design, Master of Science Thesis, Tampere University of Technology, Tampere, 2009.

142. J. Väyrynen. Improving the Safety and Reliability of a Water Hydraulic Manipulator, Master of Science Thesis, Tampere University of Technology, Tampere, 2009.

143. M. Tolonen. A 3D Visualization System with Collision Detection Support, Master of Science Thesis, Tampere University of Technology, Tampere, 2009.

8.5 Publications of Estonian Research Unit

8.5.1 Publications in scientific journals

144. P. Paris, M. Aints, M. Laan, M. Kiisk, J. Likonen, J. Kolehmainen and S. Tervakangas. (2009). Laser ablation of thin tungsten layers deposited on carbon substrate. Fusion Engineering and Design, 84 (2009) 1465–1467.

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147. A. Lushchik, Ch. Lushchik, T. Kärner, P. Liblik, V. Nagirnyi, E. Shablonin, A. Shugai and E. Vasil'chenko. Franck-Hertz effect in cathodo- and photo-luminescence of wide-gap materials. Radiation Measurements (2009). Submitted for publication.

8.5.2 Conference Articles

148. M. Aints, M. Kiisk, M. Laan and P. Paris. Laser induced plasma spectroscopy for surface studies. Third Central European Symposium on Plasma Chemistry, Kyiv, Book of abstracts: invited lecture. 2009. Pp. 17–18.

149. M. Laan and P. Paris. Aints Testing of multilayer coatings by UV laser, 5th Euro Mediterranian Symposium on Laser Induced Spectroscopy, Tivoli, Abstracts. 2009. O16.

150. E. Shablonin, T. Kärner, P. Liblik, A. Lushchik, A. Maaroos, V. Nagirnyi, F. Savikhin, E. Vasil'chenko. Electron and hole processes in MgO crystals. International Baltic Sea Region conference "Functional materials and nanotechnologies", Riga, March 31 – April 3, 2009. (Poster)

151. A. Lushchik, Ch. Lushchik, T. Kärner, P. Liblik, V. Nagirnyi, E. Shablonin, A. Shugai and E. Vasil'chenko. Franck-Hertz effect in cathodo- and photo-luminescence of wide-gap materials, 7th International Conference on Luminescent Detectors and Transformers of Ionizing Radiation, Krakow, Poland, July 12–17, 2009. (Invited lecture.)

152. A. Lushchik, Ch. Lushchik, T. Kärner, V. Nagirnyi, E. Shablonin and E. Vasil'chenko. Impact and nonimpact creation mechanisms of radiation defects in ionic crystals. 14th International Conference on Radiation Physics and Chemistry of Inorganic Materials (RPC-14), Astana, Kazakhstan, October 6–10, 2009. (Invited lecture.)

153. E. Shablonin, T. Kärner, P. Liblik, A. Lushchik, A. Maaroos, V. Nagirnyi, F. Savikhin and E. Vasil'chenko. Electron and hole processes in MgO crystals. International Baltic Sea Region conference "Functional materials and nanotechnologies", Riga, March 31– April 3, 2009. (Poster)

APPENDIX A: INTRODUCTION TO FUSION ENERGY

A.1 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, geo-thermal, 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.

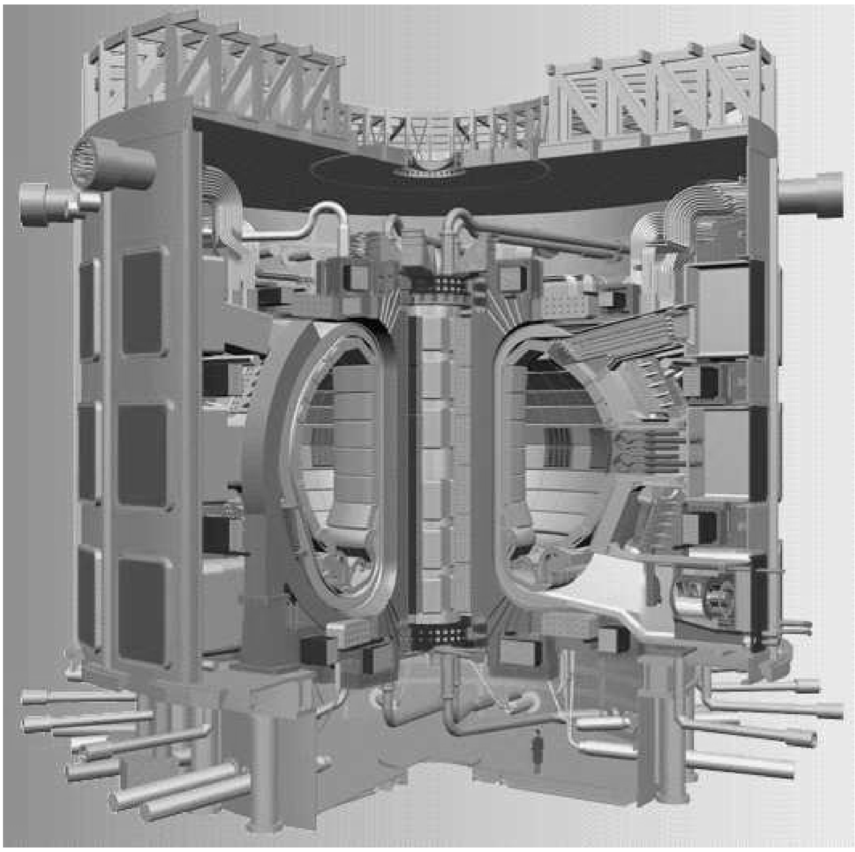

Figure A1. A design model for the experimental fusion reactor ITER, which is under construction in Europe (Cadarache, France) as world wide collaboration.

A.2 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, 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.

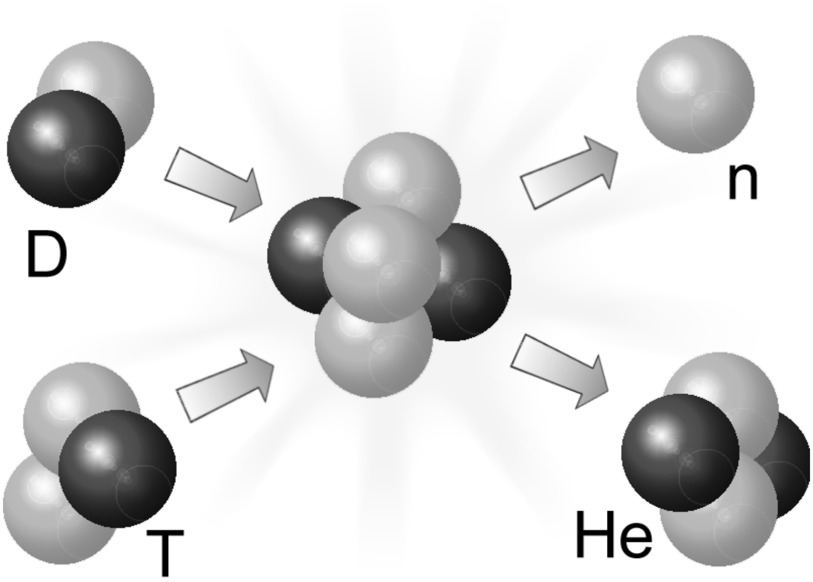

Figure A2. In a fusion reaction, deuterium (D) and tritium (T) fuse together forming a helium nucleus (4He) and releasing a large amount of energy which is mostly carried by the neutron (n).

A.3 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 the Associations and Euratom takes care of overall physics co-ordination in Europe, facilitates the joint exploitation of the JET facilities and the 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 early 2007 and is coming fully operational in 2008. The main task of "Fusion for Energy" is to provide European in-kind contributions for ITER being one of the Domestic Agencies for ITER including component and system procurements 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.

A.4 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 Dr. Kameda Ikeda and the deputy director general is Dr. Nobert Holtkamp who is responsible of the ITER construction. In the end of 2009 the project staff exceeded 445 persons. The total number of personnel will be close to 600.

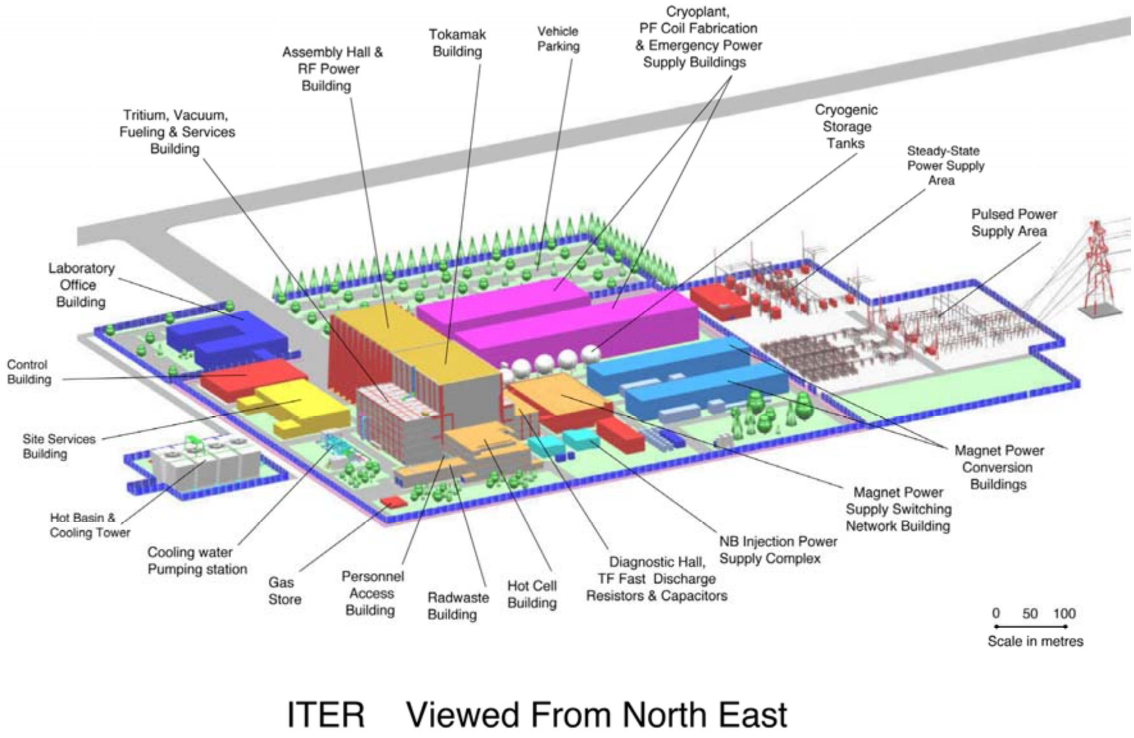

Figure A3. Lay-out of the ITER site and buildings at Cadarache.

APPENDIX B: INSTITUTES AND COMPANIES

B.1 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. +358 105 2151; Fax. +358 105 215903
www.tekes.fi

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Hannu Juuso	hannu.juuso(at)tekes.fi

B.2 Finnish Fusion Research Unit of the Association Euratom-Tekes

VTT, Technical Research Centre of Finland

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

Seppo Karttunen	seppo.karttunen(at)vtt.fi
Jukka Heikkinen	jukka.heikkinen(at)vtt.fi
Jari Likonen	jari.likonen(at)vtt.fi
Seppo Tähtinen	seppo.tahtinen(at)vtt.fi

VTT Production Systems
Tuotantokatu 2
P.O. Box 17021, FI-53851 Lappeenranta, Finland
Tel. +358 20 722 111; Fax. +358 20 722 2893

Veli Kujanpää	veli.kujanpaa(at)vtt.fi

VTT System Engineering
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Mikko Siuko	mikko.siuko(at)vtt.fi

VTT Nuclear Energy
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VTT Sensors
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Jukka Kyynäinen	jukka.kyynarainen(at)vtt.fi

Helsinki University of Technology (TKK)

From 2010:
Aalto University School of Science and Technology
Department of Applied Physics
P. O. Box 14100, FI-00076 AALTO, Finland
Tel. +358 9 47001; Fax. +358 9 4702 3195
www.aalto.fi

Rainer Salomaa	rainer.salomaa(at)tkk.fi
Taina Kurki-Suonio	taina.kurki-suonio(at)tkk.fi

Tampere University of Technology (TUT)

Tampere University of Technology
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(at)tut.fi
Jouni Mattila	jouni.mattila(at)tut.fi

Lappeenranta University of Technology

Laboratory of Machine Automation
Skinnarilankatu 34, P.O. Box 20, FI-53851 Lappeenranta, Finland
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www.lut.fi

Heikki Handroos	heikki.handroos(at)lut.fi

University of Helsinki

Accelerator Laboratory
P.O. Box 43, FI-00014 University of Helsinki, Finland
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www.beam.helsinki.fi

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Kai Nordlund	kai.nordlund(at)helsinki.fi

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www.fi.tartu.ee
Madis Kiisk madis.kiisk(at)fi.tartu.ee
Marco Kirm marco.kirm(at)ut.ee

B.4 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(at)fi.abb.com

Company: **Adwatec Oy**
Technology: Remote handling, water hydraulics, actuators and drives
Contact: Adwatec Oy, Polunmäenkatu 39 H 9, FI-33720 Tampere, Finland
Tel. +358 3 389 0860; Fax. +358 3 389 0861
www.adwatec.com
Arto Verronen rto.verronen(at)adwatec.com

Company: **Aspocomp Oy**
Technology: Electronics manufacturing, thick film technology, component mounting (SMT), and mounting of chips (COB) in mechanical and 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(at)aspocomp.com

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(at)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(at)delfoi.com

Company: **DIARC Technology Oy**
Technology: Diamond like DLC and DLC (Si, D) doped carbon coatings plus other coatings with potential plasma facing material in thermonuclear fusion machines
Contact: Diarc Technology, Olarinluoma 15, FI-02200 Espoo, Finland
Tel. +358 9 2517 6130; Fax. +358 9 2517 6140
www.diarc.fi
Jukka Kolehmainen jukka.kolehmainen(at)diarc.fi

Company: **Ekono-Electrowatt/Jaakko Pöyry Group**
Technology: International consulting and engineering expert within the Jaakko Pöyry Group serving the energy sector. Core areas: management consulting, hydropower, renewable energy, power & heat, oil & gas, project services for nuclear safety and industrial processes
Contact: P.O. Box 93, Tekniikantie 4 A, FI-02151 Espoo, Finland
Tel. +358 46911; Fax. +358 9 469 1981
www.poyry.com
Vilho Salovaara vilho.salovaara(at)poyry.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(at)elektrobit.com

Company: **Enprima Oy**
Technology: Design, engineering, consulting and project management services in the field of power generation and district heating, EPCM services
Contact: P.O. Box 61, FI-01601 Vantaa, Finland
Tel. +358 40 348 5511; Fax. +358 9 3487 0810
www.enprima.com
Jarmo Raussi jarmo.raussi(at)enprima.com

Company: **Finpro**
Role: Industry activation and support
Contact: Finpro, P.O. Box 358, Porkkalankatu 1, FI-00181 Helsinki
Tel. +358 204 6951; Fax. +358 204 695200
www.finpro.fi
Markus Ranne markus.ranne(at)finpro.fi

Company: **Fortum Nuclear Services Oy**
Technology: Nuclear engineering
Contact: Fortum Nuclear Services Oy, Keilaniementie 1, Espoo,
FI-00048 Fortum, Finland
Tel. +358 10 4511; Fax. +358 10 453 3403
www.fortum.com
Herkko Plit herkko.plit(at)fortum.com

Company **High Speed Tech Oy**
Technology: Copper to stainless steel bonding by explosive welding
Contact: High Speed Tech Oy, Tekniikantie 4 D, FI-02150 Espoo, Finland
Fax. +358 9 455 5267
www.highspeedtech.fi
Jaakko Säiläkivi jaakko.sailakivi(at)highspeed.sci.fi

Company: **Hollming Works Oy**
Technology: Mechanical engineering, fabrication of heavy stainless steel structures
Contact: Puunaulakatu 3, P.O. Box 96, FI-28101 Pori, Finland
Tel. +358 20 486 5040; Fax. +358 20 486 5041
www.hollmingworks.com
Jari Mattila jari.mattila(at)hollmingworks.com

Company: **Hytar Oy**
Technology: Remote handling, water hydraulics
Contact: Hytar Oy, Ilmailukatu 13, P.O. Box 534, FI-33101 Tampere, Finland
Tel. +358 3 389 9340; Fax. +358 3 389 9341
Olli Pohls olli.pohls(at)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(at)instrumentti-mattila.fi

Company: **Japrotek Oy**
Technology: Designs and manufacturing of stainless steel process equipment such as columns, reactors and heat exchangers
Contact: Japrotek Oy, P.O. Box 12, FI-68601, Pietarsaari, Finland
Tel. +358 20 1880 511; Fax. +358 20 1880 415
www.vaahtogroup.fi
Ulf Sarelin ulf.sarelin(at)vaahtogroup.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(at)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(at)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(at)kempower.fi

Company: **Luvata Oy**
Technology: Superconducting strands and copper products
Contact: Luvata Oy, Kuparitie, P.O Box 60, FI-28101 Pori, Finland
Tel. +358 2 626 6111; Fax. +358 2 626 5314
Ben Karlemo ben.karlemo(at)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 9 2248 7323; Fax. +358 9 2248 7341
www.mansner.com
Sami Mansner sami.mansner(at)mansner.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(at)marioff.fi

Company: **Metso Materials Technology Oy**
Technology: Special stainless steels, powder metallurgy, component technology/ engineering, design, production and installation
Contact: Metso Materials Technology Oy, P.O. Box 1100,
FI-33541 Tampere, Finland
Tel. +358 20 484 120; Fax. +358 20 484 121
www.metsopowdermet.com
Jari Liimatainen jari.liimatainen(at)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(at)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(at)patria.fi

Company: **PI-Rauma Oy**
Technology: Computer aided engineering with CATIA
Contact: PI-Rauma Oy, Mäntyluoto, FI-28880 Pori, Finland
Tel. +358 2 528 2521; Fax. +358 2 528 2500
www.pi-rauma.fi
Matti Mattila matti.mattila(at)pi-rauma.com

Company: **Platom Oy**
Technology: Remote handling, thermal cutting tools and radioactive waste handling
Contact: Platom Oy, Graanintie 5, P.O. Box 300, FI-50101 Mikkeli, Finland
Tel. +358 44 5504 300; Fax. +358 15 369 270
www.platom.fi
Miika Puukko miika.puukko(at)platom.fi

Company: **PPF Products Oy**
Service: Industry activation and support
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Tel. +358 3 434 1970, +358 50 40 79 799
Pertti Pale pertti.pale(at)surffi.net

Company: **Prizztech Oy**
Role: Industry activation and support
Contact: Teknologiakeskus Pripoli, Tiedepuisto 4, FI-28600 Pori, Finland
Tel. +358 2 620 5330; Fax. +358 2 620 5399
www.prizz.fi
Jouko Koivula jouko.koivula(at)prizz.fi

Company: **Rados Technology Oy**
Technology: Dosimetry, waste & contamination monitoring 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(at)rados.fi

Company: **Rejlers Oy**
Technology: System and subsystem level design, FE modelling and analysis with ANSYS, studies and technical documentation, installation and maintenance instructions, 3D modelling and visualisation of machines and components.
Contact: Rejlers Oy, Myllykatu 3, FI-05840 Hyvinkää, Finland
Tel. +358 19 2660 600; Fax. +358 19 2660 601
www.rejlers.fi
Jouni Vidqvist jouni.vidqvist(at)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(at)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(at)selmic.com

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(at)solving.fi

Company: **Sweco PIC Oy**
Technology: Consulting and engineering company operating world-wide, providing consulting, design, engineering and project management services for industrial customers in plant investments, product development and production
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Kari Harsunen kari.harsunen(at)sweco.fi

Company: **Tampereen Keskustekniikka Oy**
Technology: Product development, design, production, marketing, and sales of switchgear and controlgear assemblies
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Tel. +358 3 233 8331
www.keskustekniikka.fi
Reijo Anttila reijo.anttila(at)keskustekniikka.fi

Company: **Tankki Oy**
Technology: Production and engineering of stainless steel tanks and vessels for use in different types of industrial installations
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Tel. +358 6 510 1111; Fax. +358 6 510 1200
Jukka Lehto jukka.lehto(at)tankki.fi

Company: **TVO Nuclear Services Oy**
Technology: Nuclear power technologies; service, maintenance, radiation protection and safety
Contact: TVO Nuclear Services Oy, FI-27160 Olkiluoto
Tel. +358 2 83 811; Fax. +358 2 8381 2109
www.tvo.fi
Antti Piirto antti.piirto(at)tvo.fi

Company: **TP-Konepaja Oy / Arelmek Oy**
Technology: Heavy welded and machined products, DTP2 structure
Contact: TP-Konepajat Oy / Arelmek Oy, PL 23, FI-33701 Tampere, Finland
Tel. +358 40 8318001
www.tpyhtio.fi
Jorma Turkki jorma.turkki(at)tpyhtio.fi

Company: **Woikoski Oy**
Technology: Production, development, applications and distribution of gases and liquid helium
Contact: Voikoski, P.O. Box 1, FI-47901 Vuohijärvi, Finland
Tel. +358 15 7700700 Fax. +358 15 7700720
www.woikoski.fi
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Title

FUSION YEARBOOK
Association Euratom-Tekes
Annual Report 2009

Abstract

This Annual Report summarises the fusion research activities of the Finnish and Estonian Research Units of the Association Euratom-Tekes in 2009. The Estonian Research Unit was established by the Agreement between Tekes and the University of Tartu in 2007. The emphasis of the new EFDA is in exploiting JET and co-ordinating physics research in the Associations. In addition, emerging technology and goal oriented training activities are under EFDA. The activities of the Research Unit are divided in the fusion physics under the Contract of Association and EFDA. New R&D Grant work on remote handling for ITER divertor maintenance launched by the Joint Undertaking “Fusion for Energy” started in 2008 and is running to 2010.

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

- Heat and particle transport, MHD physics and plasma edge phenomena
- Plasma-wall interactions and material transport in SOL region
- Code development and diagnostics.

Association Euratom-Tekes participated actively in the EFDA JET Workprogramme 2009 and exploitation of JET facilities in experimental campaigns C20–C27. Three persons were seconded to the CCFE operating team, two physicists in codes & modelling and one engineer in remote handling. In addition, Tekes Association participated in the 2009 experimental programme of ASDEX Upgrade (AUG).

The Technology work is carried out at VTT, Aalto University School of Science and Technology, 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 is focused on the remote handling, vessel/in-vessel materials and components plus some activities in physics integration and JET Technology:

- Divertor Test Platform (DTP2) at VTT in Tampere for remote handling of divertor maintenance and development of water hydraulic tools and manipulators
- Development of advanced welding methods and IWR cutting/welding robot
- Application of powder HIP method for fabrication of ITER vessel/in-vessel 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
- Upgrading of the JET NPA diagnostics
- Feasibility study for micromechanical magnetometers.

A major PI/PR occasion was the inauguration of the ITER divertor test platform DTP2 at VTT in Tampere, 29 January 2009.

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May 2010

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Commissioned by
Tekes, Euratom

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This Annual Report summarises the fusion research activities of the Finnish and Estonian Research Units of the Association Euratom-Tekes in 2009. The Estonian Research Unit was established by the Agreement between Tekes and the University of Tartu in 2007. The emphasis of the new EFDA is in exploiting JET and co-ordinating physics research in the Associations. In addition, emerging technology and goal oriented training activities are under EFDA. The activities of the Research Unit are divided in the fusion physics under the Contract of Association and EFDA. New R&D Grant work on remote handling for ITER divertor maintenance launched by the Joint Undertaking "Fusion for Energy" started in 2008 and is running to 2010.

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

- Heat and particle transport, MHD physics and plasma edge phenomena
- Plasma-wall interactions and material transport in SOL region
- Code development and diagnostics.

Association Euratom-Tekes participated actively in the EFDA JET Workprogramme 2009 and exploitation of JET facilities in experimental campaigns C20–C27. Three persons were seconded to the CCFE operating team, two physicists in codes & modelling and one engineer in remote handling. In addition, Tekes Association participated in the 2009 experimental programme of ASDEX Upgrade (AUG).

The Technology work is carried out at VTT, Aalto University School of Science and Technology, 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 is focused on the remote handling, vessel/in-vessel materials and components plus some activities in physics integration and JET Technology:

- Divertor Test Platform (DTP2) at VTT in Tampere for remote handling of divertor maintenance and development of water hydraulic tools and manipulators
- Development of advanced welding methods and IWR cutting/welding robot
- Application of powder HIP method for fabrication of ITER vessel/in-vessel 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
- Upgrading of the JET NPA diagnostics
- Feasibility study for micromechanical magnetometers.

A major PI/PR occasion was the inauguration of the ITER divertor test platform DTP2 at VTT in Tampere, 29 January 2009.

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