ASSOCIATION EURATOM - VR
Swedish Fusion Research Unit

Annual Progress Report 2012
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On behalf of the Swedish Fusion Research Unit, we are pleased to present the Annual Progress Report for 2012 covering research carried out under the Contract of Association between the Swedish Research Council (VR) and the European Atomic Energy Community, EURATOM.

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Association EURATOM-VR
1 EXECUTIVE SUMMARY

1.1 Introduction

Controlled thermonuclear fusion offers the prospect of an intrinsically safe, virtually inexhaustible energy source. It is seen as potentially having a key role in the long-term energy system, primarily for base load electricity production, provided it can be developed to become economically competitive.

At the international level, the proof-of-principal experiment ITER now under construction in Cadarache, France, plays a key role in the development of fusion as an energy source. The mission of the ITER experiment is to:

- Demonstrate the capability of steady state fusion power production.
- Optimise burning plasma confinement under reactor conditions.
- Have dimensions comparable to a power station and produce about 500 MW of fusion power (10 times more power than needed to run it).
- Demonstrate or develop technologies and materials required for fusion power plants.

The Agreement on the Establishment of the ITER International Fusion Organisation for the Joint Implementation of the ITER Project is established between the seven participating Domestic Agencies, namely, the EU, Japan, USA, Russian Federation, China, South Korea and India.

The European Atomic Energy Community (EURATOM) is the Domestic Agency representing the European Union in the ITER International Organisation. A Joint Undertaking for ITER and the Development of Fusion Energy (Fusion for Energy or “F4E”) was approved by the European Council of Ministers in 2007. The objectives of F4E are:

1) To provide the contribution of EURATOM to the ITER International Organisation.
2) To provide the contribution of EURATOM to the Broader Approach (BA) activities with Japan for the rapid realisation of fusion energy.
3) To prepare and coordinate a programme of activities in preparation for the construction of a demonstration fusion reactor (DEMO) and related facilities including the International Fusion Materials Irradiation Facility (IFMIF).

A major component of the first F4E objective is to “in kind” procure, produce and provide the EURATOM components and equipment to the ITER Organisation and to prepare and coordinate EURATOM’s participation in the scientific and technical exploitation of the ITER project. The Fusion for Energy agreement covers 35 years from 2007 to 2041. The first ITER plasma is planned for 2020 and first deuterium-tritium operation is scheduled for 2026.

Under the responsibility of the European Domestic Agency, the preparation of the ITER site at Cadarache is well under way. In 2012, the first ITER building was handed over to the ITER Organization; the completed Poloidal Field Coils Winding Facility is a 257-metre-long facility where the winding and assembly operations for five of ITER's giant poloidal field coils will take place, beginning in 2013. The ITER Headquarters building was also completed on site at Cadarache, meaning that the ITER Organization could finally be united on a single campus. Work on the main tokamak pit and building continued, with seismic preparations, reinforcement and concrete works. The PRIMA Neutral Beam Test Facility (NBTF) was
launched in Padua, Italy. PRIMA is a test-bed for the development and testing of ITER’s powerful neutral beams, conceived to deliver 33MW of heating power to the ITER plasma. Slippages in the time schedule, partly due to the Japanese tsunami, were carefully assessed by the ITER Council and measures were put in place to prevent further slippage and recover some of the time lost.

The development of fusion power is a key action in the European Framework Programme and the research is co-ordinated and managed as a part of the EURATOM agreement. The delivery of the European contribution to ITER is the responsibility of F4E. However, a substantial support effort is required in the accompanying European fusion programme, which is co-ordinated by the European Commission under the auspices of EURATOM. The work is performed by national parties in the member states under Contracts of Association (CoA), which form bilateral agreements between EURATOM and the Program Owner of each participating state. The Contract of Association establishing the Swedish Research Unit (RU) in fusion is between the Swedish Science Research Council (VR) and EURATOM and it is valid until end 2013. The CoA defines the roles of the Association Steering Committee, the Research Unit and the leadership of the RU, the Head of Research Unit (HRU). The CoA also includes a Work Plan for the Association which normally spans several years.

There are a number of additional agreements between the European Fusion Associations. The European Fusion Development Agreement (EFDA) (valid until end 2013) provides a framework for coordinating activities which are included in the European fusion research programme:

- Co-ordinated activities in physics and emerging technology.
- The collective use of the JET facilities, which is the largest fusion experiment now in operation and is located in the UK.
- Training and career development of researchers, promoting links to universities and carrying out support actions.
- European contributions to international collaborations that are outside the Joint Undertaking for ITER and the Development of Fusion Energy.
- The long-term strategy of the European fusion programme is based on well-defined steps as outlined in the recently adopted “Roadmap for fusion energy” (see below).

Operation of present-generation experiments, in particular the JET experiment, has established a basis for the design of ITER. These experiments will now be used to plan for the exploitation of ITER. The results of the ITER project together with efforts carried out in parallel should enable the next step, the construction of a demonstration reactor, DEMO. The focus is now on ITER, however progress to fusion power plants includes additional elements:

1. a test facility for materials, the International Fusion Materials Irradiation Facility, IFMIF,
2. continued exploration of fusion facility concept improvements that may, in the longer term, be attractive as a basis for a fusion power plant,
3. continued development of technology required for a future electricity-producing power plant (DEMO).

A new EU Research and Innovation Framework Programme for the period 2014-2020 (Horizon 2020) is now in preparation. In view of the fact that both the Contracts of Association and the EFDA Agreement end in 2013, the discussion on the future organization and program of EU fusion research, including the European stakeholders in fusion (European Commission, the Associations, member states etc.) has continued in 2012. One important milestone in this process in the establishment of a Roadmap for fusion energy: “Fusion
Electricity - A roadmap to the realisation of fusion energy”\(^1\). The Roadmap proposes “an ambitious, yet realistic roadmap towards the demonstration of electricity production [from fusion] by 2050”. In parallel to the programmatic work on the Roadmap, the first steps towards a new organization of EURATOM fusion research were taken in 2012. These discussions will continue in more detail in 2013.

The Swedish fusion research unit encompasses a range of competencies that are important for the European fusion programme and for the ITER project. The Swedish Association has as its basic goal to make important contributions to the ITER project and to the long term goal of a prototype fusion reactor.

1.2 The Swedish Research Unit EURATOM-VR

The formation of a Swedish Fusion Research Unit (RU) is enabled by the Contract of Association between EURATOM and the VR. Swedish fusion research activities are carried out at four universities and one industry, which together form the Swedish Research Unit. The participating universities are: the Royal Institute of Technology (KTH) in Stockholm, Chalmers University of Technology (Chalmers) in Göteborg, Uppsala University (UU) and Lund University (LU). A group at Studsvik Energy AB is also a part of the Research Unit.

The activity of the Association EURATOM-VR is directed by a Steering Committee (SC), which in 2021 included the members: Vito Marchese (EU), Marc Pipeleers (EU), Johan Holmberg (VR) and Goran Bogdanovic (Ministry of Education). The VR-SC met on November 8, 2012, at KTH, Stockholm, for its annual meeting to review the activities and plans of the Swedish Association (Euratom-VR). At that meeting were also present Göran Ericsson (Head of Research Unit - HRU, Uppsala University), Pär Strand (deputy HRU, Chalmers), Per Brunsell (KTH), Per Karlsson (VR), Mikaela Laine (VR), Cecilia Mattsson (VR) and Francesco Romanelli (EFDA Leader, by video link).

Fusion research within the Swedish Association is mainly carried out at universities and is concerned with fundamental issues in transport, stability (including active control of instabilities), plasma wall interaction, plasma heating (mainly Ion Cyclotron Resonant Heating), energetic particles, and diagnostic development and implementations, in particular spectroscopy and neutron diagnostics. This research includes both experimental and theoretical work with a strong element of modeling, simulations and computer code development; this is emphasized by the fact that three of the university groups are actively participating in the work within EFDA’s Integrated Tokamak Modeling Task Force. Emerging Technology projects are in the area of tungsten and tungsten alloy development. Studsvik Energy AB has for many years been involved in fusion technology activities and is now focusing on work for ITER through contracts with Fusion for Energy, the European agency responsible for the EU responsibilities to the ITER International Organization.

The research activities within the RU are organized in a number of research projects which are presented in the Work Plan of the RU. These activities are well integrated into the EURATOM fusion programme and the activity is a part of the accompanying programme which supports the ITER project. It includes substantial participation in the EFDA JET project as well as collaboration with other Associations. A special feature of the Swedish fusion Research Unit is that it is a dispersed, university-based organization and involves student participation and education, mainly at PhD student level but also for Master’s degree projects.

1.3 Overview of research activities

The Contracts of Association and the EFDA Agreement provide the framework for the coordinated European fusion research activity. All EU member states with fusion research units participate in EFDA; in addition Switzerland is also a party. The EFDA leader during 2012 was Mr Francesco Romanelli. EFDA is organized in three departments, each led by a department head, for exploitation of JET, for ITER Physics and for Power Plant Physics and Technology. The EFDA leadership is aided by staff forming Close-Support Units at the EFDA-JET (Culham, UK) and IPP-Garching (Munich, Germany) sites.

The EFDA Steering Committee, made up of representatives from the Associations that are members of EFDA, functions as a management board for EFDA. The plans, programs and instrument for co-ordination of the work are put into a Work Plan prepared by the EFDA leadership and approved by the EFDA Steering Committee. The EFDA Work Plan normally spans several years, although in the present situation only to the end of 2013. An annual EFDA Work Programme, based on the Work Plan, is also prepared by the EFDA leadership and approved by the Steering Committee. The EFDA Work Programme together with the Work Plans for the Research Units is used as the basis for the annual Work Programmes prepared for each research unit. The Work Programme for the Swedish Research Unit is approved by the Association Steering Committee on an annual basis.

Over the last couple of years, the contribution of the Swedish RU to the coordinated Euratom fusion program has been quite stable at a level of about 50 person-years (py) per year. This contribution has been divided between the major areas of the EFDA Work Programme in the following way:

- Advancement of the ITER and DEMO Physics Basis: 32 py
- Development of plasma auxiliary systems: 10 py
- Concept improvements, fundamental understanding: 1 py
- Emerging technologies: 0.5 py
- Training &career development: 2.5 py
- Long term secondments: 2.5 py
- Other (central admin, Public info): 2.5 py

The total number of professionals involved in the RU program is about 80, of which about 20 are PhD students. The two major areas of activity are Provision of support to the advancement of the ITER Physics Basis and Development of plasma auxiliary systems, the latter being primarily focused on neutron and spectroscopy-based diagnostics.

As a university-based organization, training of PhD students (and to some degree Masters) is an important part of the work of the academic professional staff within the RU and this activity is fully integrated in the research projects of the Research Unit. The university academic staffs are also involved in undergraduate teaching; this is not included in the py accounting.

The activity of the Swedish RU is well integrated into the EFDA Work Programmes, as further detailed below. The EFDA Work Programme is organized into Task Forces (TF) for JET exploitation (TF-E1, TF-E2), Fusion Technology (TF-Fusion Technology) and for code development in the tokamak simulation field (“Integrated Tokamak Modeling Task Force”; ITM-TF), while the activity in “ITER Physics” is structured around 11 different Topical Areas. The work in the PPP&T department is organized in a number of large contracts, divided into sub-tasks. There is a Task Agreement for each of the above Task Forces and Departments, where the activity undertaken by each RU is specified.
The RU activity in the ITER Physics work programme in 2012 included tasks within most of the 11 Topical areas, for a total of 4.4 py Priority Support and 6.25 py Baseline support in named, specified contracts. The activity within the ITM-TF amounted to 2.01 py in Priority and 2.05 py in Baseline support contracts. The PPPT tasks summed up to 0.65 py Priority and 3 py Baseline support contracts. In addition, two RU researchers were continuing their Fusion Researcher Fellowships, and a small long-term activity within the Goal Oriented Training in Theory (GOTiT) (about 0.5 ppy per year) has also been continued in 2012.

The EFDA JET Work Programme specifies the exploitation of the jointly operated JET experiment. The JET activity comprises individual scientist’s contributions to the experimental campaigns, including both on-site work for specific JET experiments (ST Orders and Notifications) and preparations and analysis work at the home institute (Notifications), as well as work in technology (TF-FT) and in Enhancement projects. In 2012 the Swedish Association contributed about 697 person-days (about 2.8 py) for on-site ST Orders and Notification work as well as about 122 person-weeks (about 3.2 py) for work at the home institutes with preparations and analysis tasks connected to the JET experimental program (Notifications). In addition, Swedish researchers were involved in projects for JET Enhancements (“Upgrade of the Neutral Particle Analyzer”, “Vertical Neutron Spectrometer”) for about 0.25 py Priority Support and in Fusion Technology (“Material transport and erosion/deposition”, “Microbeam analysis and SEM/EDX analysis on cross section”, “Be-10 experiment”, “First test mirror at JET” and “Fuel ion ratio determination”) for about 0.2 py Priority and 1.35 py baseline support.

Summing up the RU involvement in named contracts within the European fusion program, a total of about 27 py are conducted under specific priority and baseline support tasks in 2012 (including JET Orders, Notifications and Fusion Fellowships). This corresponds to more than 50% of the total amount of the py’s contributed by the Association-VR to the fusion program.

Fusion for Energy Grants are not formally a part of the activities under the Euratom-VR Contract of Association, but the status of such grants is provided here for information. They show that Sweden is also taking an active part in the European fusion development on the level of direct involvement with F4E procurement and design tasks. Most of the grants in this area are/have been held by the Studsvik Energy AB company. In 2012, Studsvik worked on two main F4E contracts in the area of corrosion studies: F4E-GRT-243 “Corrosion assessment of water cooled components” and F4E-GRT-268 “Assessment of erosion corrosion parameters”; the total value of these two contracts amounted to 259 and 98 kEUR, respectively. In addition, in 2012 the Uppsala University neutron Diagnostic group has also obtained a contract with F4E as a “third-party” contributor to the Consortium of European fusion laboratories that has been awarded the F4E Framework Grant for the design of the ITER Radial Neutron Camera. The F4E contribution to the UU-ND group is about 170 kEUR over the contract period of 4 years.
1.4 Highlights of the research activity

Support to the advancement of the ITER physics base

Plasma wall interaction:
• Fusel retention and material mixing in tungsten-carbon-nitrogen-boron layers was determined in TEXTOR and ASDEX.
• Evolution of carbon and beryllium fluxes in the divertor during the JET-ILW operation was determined with spectroscopy.
• First Mirror Test in JET-ILW was performed. The optical performance of mirrors after short- and long-term exposures was not degraded.
• Laser-based methods for in-situ studies of wall components were tested on tokamak wall tiles and on laboratory-prepared targets.

Physics of plasma heating and current drive:
• Workflow, covering all types of heating and current drive, has been developed within the ITM and coupled to the European Transport solver.
• Investigation if ICRF scenarios for DEMO reveal only four possible frequency bands for fast wave current drive, although the current drive efficiency is likely to be comparable to other auxiliary schemes.
• Analyzed of the effect of rotation by ICRH on JET experiments show correlation with the electron temperature, independently of the heating scheme.

Plasma auxiliary systems

Neutron diagnostics, instrumental developments:
• Installation of high-efficiency neutron flux monitor (NE213) with the MPRu at JET.
• Design studies of backscatter Time-Of-Flight and Thin film Proton recoil 14 MeV neutron spectrometers for experiments at ITER.
• Conceptual design study of an upgraded neutron camera for MAST (started).

Neutron diagnostics, physics achievements:
• Studies of NBI driven fast ion redistributions with the MAST neutron camera.
• Determination of the fuel ion ratio (n_d-n_t) using the MPRu spectrometer.
• Modelling of the neutron energy spectrum from TT reactions in JET relevant plasma.

Concept improvements

A novel generalized weighted residual method, where the time domain is treated spectrally, has shown that resistive g-modes in the reversed-field pinch are stabilized by parallel and perpendicular heat conduction, but only for low beta and Lundquist numbers.

The major specialised equipment used by the Association includes:
• The EXTRAP T2R reversed-field pinch is located at KTH
• The UU-ND group has delivered and operated advanced neutron diagnostic instrumentation to JET and MAST
2 Support advancement of the ITER physics base

2.1 Energy and particle confinement and transport

2.1.1 Transport modelling

L. Fazendeiro, H. Nordman, A. Skyman (Ph D student), P. Strand, D. Tegnered (Ph D student), J. Weiland, M. Tendler

Introduction
This project is directed towards understanding the bulk transport in today’s fusion experiments and to find ways of improving the performance of a reactor. With “bulk transport” we here mean the transport of the thermal (or quasi thermal) particles. The main contribution to the transport originates from the turbulence in the plasma, driven by the free energy in the temperature and density gradients. The work is done in close collaboration with the experimental facilities and by participating in several international working groups, including JET task forces and the Integrated Modelling Task Force, (ITM).

Summary
The transport work during 2012 concerns main ion and impurity transport, effects of plasma flows and Geodesic Acoustic Modes, using fluid and gyrokinetic models. Much work was focused on comparisons between the computationally efficient fluid models of turbulence developed at Chalmers, suitable for use in analysis and predictions of fusion experiments like JET and ITER, and large scale kinetic turbulence simulations. We have continued to work on Predictive Transport Simulations of JET discharges within the EFDA-JET programme.

Theory

Geodesic Acoustic Modes (GAM’s): The geodesic acoustic mode (GAM) is the oscillatory counterpart of the zonal flow (m=n=0 in the potential perturbation, m=1, n=0 in the perturbations in density, temperature and parallel velocity) and thus a much weaker effect on turbulence is expected. Nevertheless, experimental studies suggest that GAMs are related to the L-H transition and transport barriers. The GAMs are weakly damped by Landau resonances and moreover this damping effect is weaker at the edge suggesting that GAMs are more prominent in the region where transport barriers are expected.

In particular, the electromagnetic effects on the generation of zonal flows and GAMs have been evaluated. In this work, the first demonstration of an electron branch of the geodesic acoustic mode (el-GAM) driven by ETG modes was presented. The frequency of the el-GAM is higher compared to the ion GAM by the square root of the ion-to-electron mass ratio. We have utilized a fluid model for the ETG mode based on the Braginskii equations with non-adiabatic ions including impurities and finite beta-effects. The dispersion relation for the non-linearly driven electron GAM is unstable with a growth rate depending on the saturation level of the ETG mode turbulence which is solved numerically. It is found that the magnetic safety
factor has a stabilizing effect on the el-GAM however the quantitative results are strongly dependent on the parameters. In the dispersion relation a set-off non-linear drive is present below which the el-GAM is stable. A new saturation mechanism for ETG turbulence through the interaction with el-GAMs, balanced by Landau damping, is found, resulting in a significantly enhanced ETG turbulence saturation level compared to the mixing length estimate.

Publications section 2.1.1

Peer reviewed journals

Presentations at international conferences and workshops


ELM Control by Resonant Magnetic Perturbations

M. Tendler

A theoretical model for the toroidal rotation spin-up and generation of the positive radial electric field during the stochastization of plasma edge is put forward. The equations for the toroidal velocity and for modification of the core radial electric field have been derived. The detailed comparison of the model results with the radial electric field and plasma potential measurements during MHD activity in the TUMAN-3M tokamak is assessed.

During rise of the MHD activity the change of the edge radial electric field from negative (directed inward) to positive (directed outward) values has been observed on many devices. There are also experimental evidence that MHD activity is associated with the rise of magnetic island at \( q=3 \) flux surface in the core few centimeters inside from the last close flux surface (LCFS), also rise of smaller islands at \( q=4 \) and \( q=2 \) surfaces, and formation of a stochastic layer in the LCFS vicinity. The model for the origin of the positive radial electric field during the rise of the MHD activity is put forward. It is based on the assumption of the existence of a strong electron radial flux associated with the formation of an ergodic layer. The radial electron flux requires the same radial flux of ions to provide the closure of the current. To create the positive radial ion current the radial electric field should become more positive. This situation is similar to the biasing experiments and corresponding theory has
been already developed by us before. In the extreme case, when the electron conductivity associated with the stochastic layer dominates over the ion conductivity, the radial electric field should become positive inside the stochastic layer. Most general equations for the toroidal rotation and the radial electric field are derived and final results are presented in the analytical form. The toroidal velocity saturates provided the stochastic conductivity increases and the stochastic layer is wide enough. The radial ion current generates toroidal rotation in the co-current direction by the toroidal $j \times B$ torque, so the ergodic layer becomes the source of the toroidal momentum. The co-current toroidal rotation should be transported outside the ergodic layer to the core by the turbulent viscosity thus creating the co-current spontaneous toroidal rotation in the center of a tokamak. The co-current toroidal rotation makes the radial electric field more positive also outside the ergodic layer and for sufficiently big toroidal rotation the radial electric field becomes positive also in the central regions in accordance with the observations.

Along the same lines, it was demonstrated on many tokamaks that the edge localized modes (ELMs) could be suppressed or mitigated by applying resonant magnetic perturbations (RMP) to the high confinement regime (H-regime) of a tokamak. The resonant coils for RMP are installed or planned on almost all large tokamaks: DIII-D, JET, MAST, ASDEX-Upgrade (AUG), NSTX and ITER. The widely accepted mechanism of ELMs suppression during RMP is the reduction of the pressure gradient in the pedestal region below the stability limit for type I ELMs. The main contribution to the pressure gradient decrease is the pedestal density drop – the so-called ‘pump-out effect’, while the pedestal temperature does not drop and might even increase. The new model invokes a perturbation of the magnetic field caused by polarised ELM’s plasma resulting in stochastization of plasma edge, thereby violating ambipolarity. The counter perpendicular current is carried by ions and provides for the “pump-out “ and the torque responsible for the spontaneous toroidal rotation. Hence, the project addresses the suppression of ELM’s by RMP. The issue of spontaneous rotation and ELM’s suppression is the first priority for the success of an implementation on ITER.

**2.1.2 Particle and impurity transport**

*T. Fülöp, I. Pusztai, S. Moradi, Ye. O. Kazakov, A. Mollén (PhD student)*

During 2012, we investigated impurity transport in the presence of poloidal asymmetries and in electromagnetic turbulence, and we studied the effect of impurity seeding on edge and core
confinement in JET discharges. Also, we considered finite orbit width effects in an H-mode pedestal in the presence of strong poloidal flow variation.

Effect of poloidal asymmetries
The effect of poloidal asymmetry on electrostatic turbulent transport was studied, including the effect of the $E \times B$ drift. The impurity transport was found to be sensitive to the magnetic shear and it changes sign in the presence of inboard accumulation. The impurity peaking factor was shown to be rather insensitive to collisions in both ITG and TE mode driven cases.

Impurity transport due to electromagnetic turbulence
Finite $E$ effects on the impurity peaking factor and the onset of the kinetic ballooning modes (KBMs) were studied using gyrokinetic simulations. We found that electromagnetic effects even at low $\beta$ can have significant impact on the impurity transport. The KBM instability threshold depends on the plasma parameters, particularly strongly on plasma shape. In KBM driven turbulence the impurity peaking factor is strongly reduced, with very little dependence on $\beta$ and the impurity charge.

Modelling of impurity seeded JET discharges
We investigated the balance between a degradation of the edge confinement and a potential reduction of the core turbulent transport due to the increase of the effective ion charge, based on a series of Ne seeded discharges conducted in JET. Our simulations recover the trend that the confinement degrades from pure deuterium plasma to neon seeded plasma, and it improves when D + Ne fuelling is replaced by pure Ne fuelling.

Neoclassical physics in an H-mode pedestal
We revisited our previous work considering the effects of a finite radial electric field on ion orbits in the banana and plateau regimes. The rapid variation of the poloidal ion flow coefficient and the electrostatic potential in the total energy modify previous evaluations of the ion flow, the bootstrap current, and the radial ion heat flux.

L. Fazendeiro, H. Nordman, A. Skyman (PhD student), P. Strand, D. Tegnered (PhD student)

Particle transport in ITG and TE mode driven turbulence was studied using fluid and gyrokinetic models. Quasi- and nonlinear simulations were performed using the gyrokinetic code GENE, studying the effects of the driving background gradients on the impurity transport and the importance of magnetic equilibrium model on the impurity transport.

It was seen that the the impurity density gradient corresponding to zero impurity flux, the so called peaking factor, was only weakly dependent on the impurity charge ($Z$) in both temperature and density gradient driven TE mode turbulence, with a saturation in peaking seen for very steep profiles. Evaluating the impurity and background density peaking self-consistently showed, that the impurity peaking is of the same order, but less pronounced than the steady state background peaking for the scenarios considered. It was also observed that the ITG and TE mode turbulence were both effective in the pump-out of He ash. The results were published in PoP and NF.

Studies continued with modelling of impurity transport at JET, focussing on the effect of geometry on the impurity transport in ITG mode dominated discharges. Results showed a
significant decrease in impurity peaking in the shaped equilibrium compared to the simpler s-alpha model, while the qualitative trend of the scaling with Z was preserved. These, and gyrokinetic results indicating an ETG mode driven pinch for barrier like conditions, were presented at EPS.

Figure 2.1.2-1 a) Scalings of impurity peaking factors with impurity charge Z, comparing the s-alpha equilibrium with a shaped equilibrium from JET discharge #63770. A considerable reduction in peaking is seen for the shaped equilibrium.

Figure 2.1.2-1 b) Scaling of impurity peaking factors with driving electron density gradient in TE mode turbulence. The three models employed (QL and NLGK, and fluid model) show qualitative and quantitative agreement, with a saturation of the impurity peaking for steep gradients.

J. Weiland

The work at ASIPP has been focused on particle transport in the collision dominated EAST plasma. The old collision model, derived in 1994, after minor modifications in the implementation, turned out to describe particle transport in EAST well. However, the main results on this were obtained during 2013. At the ITPA workshop in Hefei (April 2-5, 2012) continued work on the formation of internal and edge transport barriers in JET 69454 were presented. Because of the new correlation length, depending on flowshear, both internal and edge barriers are obtained in the same self consistent simulation without traces of barriers in the initial conditions. Separate simulations of internal and edge barriers were also published during 2012 in the new book. I have then collaborated with the Lehigh group (Bethlehem PA) on the implementation of the new Weiland model in the Multi Mode Model MMM8.1). Rather much work was also spent during 2012 on the implementation of the new Weiland model in the JET code.
Publications section 2.1.2

Books

Peer reviewed journals


Presentations at international conferences and workshops


12. I. Pusztai, A. Mollén, T Fülöp and S Moradi, Poloidally varying equilibrium potentials and their effect on impurity peaking, Joint International Tokamak Physics Activity Topical Group Meeting, San Diego CA (USA), 15-18 October 2012.


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**ITPA Hefei**  

**ICTP Trieste**  


**APS 2012**  


### 2.1.3 Integrated modelling

*P. Strand, D. Yadykin*

During 2012 the Association has had a continued strong commitment to the Integrated Tokamak Modelling Task Force and remains active in all Integrated Modelling Projects (IMP’s) as well as the ITER Scenario Modelling Group. Chalmers are actively participating in the leadership of IMP 12 (Equilibrium, MHD, and Disruptions) where Dmitriy Yadykin is continuing deputy project leadership whereas KTH has a leadership role in IMP 5 (Heating and current drive) where Thomas Johnson is a deputy project leader in IMP5 in charge of integration of H&CD codes into the ITM-TF infrastructure.

Activities related to ITM were in IMP12 devoted to the maintenance of the MARS-F and CarMa code and to the verification of the elements of the equilibrium-MHD stability chain. The integration of the Kepler actors for the equilibrium reconstruction code (EQUAL), the equilibrium refinement code (CHEASE) and the MHD stability code (MARS-F) were performed providing equilibrium-MHD stability chain allowing MHD stability analysis of the tokamak equilibrium taking data from the experimental data base of the particular device.
First verification results were obtained by interchanging actors for the equilibrium refinement codes (CHEASE, HELENA, SPIDER, CAXE) and MHD stability codes (MARS, MARS-F, KINX) for the circular plasma cross-section (TORE SUPRA tokamak).

Work has progressed in IMP3 and IMP4 on providing transport models through the TCI (Transport Code Interface) module. This module is also utilized in ISM activities as well. Currently we are supporting WEILAND; GLF23, RITM and EDWM models and a new NCLASS module. Preparatory work is underway to expand relevant modules (EDWM, NCLASS) to support multiple charge state descriptions for impurity species which would be important for ILW and other ITER relevant developments.

Publications section 2.1.3

Peer reviewed journals

2.1.4 Pedestal properties and confinement in JET plasma with carbon wall and ILW

L. Frassinetti
The focus of this work was to characterize the confinement and the pedestal properties of the plasma in JET with the new ITER-like wall (ILW) and to compare it with plasma produced with the previous carbon wall (CFC). The work was focused also on the study of the edge localized modes (ELMs) on the pedestal and on the ELM comparison between CFC ILW plasmas. Part of the work describes the behaviour of electron temperature and density during RMP experiments for ELM mitigation.

Confinement and pedestal characteristics in JET with CFC wall and ILW

The comparison was performed on a database composed of approximately 100 H-mode CFC shots and 400 H-mode ILW shots characterized by neutral beam heating only and Type-I ELM. The results show that high triangularity baseline plasmas seem to underperform with the ILW compared to CFC wall mainly because of the lower pedestal Te, see figure 2.1.4.1. Preliminary results suggest that the N\textsubscript{2} seeding in high δ BLs increases the pedestal height, the stored energy and the confinement to values comparable to the CFC plasma. For low triangularity baseline plasmas, the confinement is similar in ILW and CFC shots, provided a low gas rate. At high input power, ILW Hybrids plasmas have confinement relatively similar to the corresponding CFC plasmas. ILW hybrids with low confinement are related to low pedestal Te due to low input power and/or high gas fuelling.

Figure 2.1.4-1. Electron temperature and electron density at the top of the pedestal for CFC plasma (open symbols) and ILW plasmas (full symbols).
ELM effect on the pedestal parameters and energy losses in ILW plasma

The effect of the ELMs on the pedestal temperature and on the energy ELM losses have been studied and compared in plasmas with CFC wall and ILW. The comparison was performed on a subset of high triangularity baseline discharges with Ip=2.5MA and P_{NBI}=15MW. The results shows that the time scale of the pedestal temperature collapse is much faster in CFC plasmas (<0.5ms) than in ILW plasmas (=2-3ms), see figure 2.1.4.2. The ELM energy losses are significantly smaller with the ILW (=0.15MJ) than in the CFC wall (=0.4MJ). Preliminary results show that ELMs in ILW high δ BL plasmas with N\textsubscript{2} seeding seem to recover a behaviour similar to CFC ELMs.

RMP effect on pedestal profiles during an ELM

RMPs with n=2 field have been applied to high collisionality H-mode ILW plasmas to study the possibility of ELM mitigation and/or suppression. Our work was focused on the RMP effect on electron density and temperature profiles at the pedestal. The drop of the pedestal temperature during the RMP experiment is less than 3%, while it is ~ 16% for the unmitigated ELMs. There is no drop in the core electron density and temperature with RMP current up to 88 kAt. The influence of the n = 2 field on the edge pedestal can be also neglected as seen in figure 2.1.4.3.

Although the pedestal density and temperature vary slightly due to non-stationary features of the discharge, the pedestal pressure remains the same within the measurement error.

Publications section 2.1.4

Peer reviewed journals

Presentations at international conferences and workshops


2.2 MHD stability and plasma control

2.2.1 Active MHD mode control

P. Brunsell, E. Olofsson (PhD student), L. Frassinetti, J. R. Drake
In collaboration with:
W. Suttrop, V. Igochine, Max-Planck-Institut für Plasmaphysik, Garching
A. Soppelsa, T. Bolzonella, G. Marchiori, G. Manduchi, Consorzio RFX, Padova
C. R. Rojas, H. Hjalmarsson, EES/Automatic Control, KTH

The general goal of the research program at KTH on MHD stability and plasma control is the development of methods applicable to both tokamak and reversed field pinch devices. Finding optimized methods for active suppression of resistive wall modes remains the primary target.

The EXTRAP T2R reversed field pinch has been utilized for the development and testing of various algorithms. The process control system strategy has been adapted for RWM mode control; system identification followed by controller design based on the identification results. A specific application for the work is the active RWM stabilization at the ASDEX Upgrade tokamak.

Figure 2.2.1-1. EXTRAP T2R device at Alfvén Laboratory KTH

The main parameters of the device are listed in Table 2.2.1-1.
Table 2.2.1-1. EXTRAP T2R parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Notation</th>
<th>Value</th>
<th>Unit</th>
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<td>Major radius</td>
<td>R</td>
<td>1.24</td>
<td>m</td>
</tr>
<tr>
<td>Minor radius</td>
<td>a</td>
<td>0.183</td>
<td>m</td>
</tr>
<tr>
<td>Wall diffusion time</td>
<td>( \tau_v )</td>
<td>6.3</td>
<td>ms</td>
</tr>
<tr>
<td>Plasma pulse length</td>
<td>( \tau_d )</td>
<td>&lt;100</td>
<td>ms</td>
</tr>
<tr>
<td>Plasma current</td>
<td>( I_p )</td>
<td>&lt;150 kA</td>
<td></td>
</tr>
<tr>
<td>Plasma electron temperature (typical)</td>
<td>( T_e )</td>
<td>300 eV</td>
<td></td>
</tr>
<tr>
<td>Plasma electron density (typical)</td>
<td>( n_e )</td>
<td>( 1 \times 10^{19} ) m(^{-3})</td>
<td></td>
</tr>
</tbody>
</table>

A MHD mode control system is based around an array of control coils placed outside the conducting shell. Arrays are distributed over the toroidal surface as shown in Fig. 2.2.1-2.

The main features of system are:
- 128 magnetic flux loop sensors at 4 poloidal and 32 toroidal positions inside the thin shell.
- 128 active saddle coils at 4 poloidal and 32 toroidal positions outside the thin shell. Saddle coils and sensor flux loops are pair-connected at each toroidal position to form 64 independent \( m=1 \) coils and sensors.
- 32 power amplifiers units providing at total of 64 independent channels. Audio amplifiers are used with output power of 800-1200 Watt providing maximum radial magnetic field at the coil centre of about 3 mT.
- An integrated digital controller unit, contained in one VME bus crate including CPU board, ADCs and DACs. Control algorithms are implemented in software.

Measurement of resistive wall mode plasma response

A reliable method for measuring and extracting the resistive wall mode plasma response has been adapted to EXTRAP T2R and tested (Ref. 1). The algorithm, referred to as the Subspace Identification Method (SIM), estimates the multi-variate plasma response measured with the discrete array of 64 sensors, as a result of small "dithering" perturbations using the array of 64 active coils. Since there are unstable modes, the plasma response must be obtained during closed-loop operation.

Specifically, the usage of SIMs turns out to be efficient for multivariate signals of the present sizes and lends itself to (i) computational statistics to determine accuracy and (ii) cross-validation methods for model order determination. When applying the SIM, the resistive wall mode response is approximated as a linear time-invariant multi-input multi-output (MIMO) system. The starting point is a "black box" state space model with \( n \) internal states and unknown system matrices. Initially, also the order \( n \) of the state space system, i. e. the number of unknown states is undetermined.
Two sets of experimental data from T2R were analyzed in this work: (i) a vacuum-obtained, and (ii) a plasma-obtained set. First the model order $n$ is chosen in order to have optimum prediction accuracy. Too high model order results in over fitting to the specific dataset used for identification, too low model order may lead to a significant bias error. A cross-validation technique is utilized to determine the optimum model order based on the acquired data set. It is found that a good choice would be in the range $350 < n < 600$, and $n = 500$ was then used.

The transfer function of the model can be decomposed in a set of eigenmodes. For visualisation of the MHD spectral density, a method of bootstrap replication and smoothing is applied. The basic idea is to separate the measured signals into (i) vacuum diffusion and (ii) plasma response. The stable vacuum part can be obtained in open-loop configuration and its transfer function is denoted $G_0$, see Figure 2.2.1-3. If $G_1$ denotes the sum of (i) and (ii) as obtained from the plasma experiment signals, the internal structure is assumed to be $G_i = (I + \Gamma) G_0$ where the plasma response eigenvalues are retained in $\Gamma$.

The result of system identification is shown in Figure 2.2.1-4. The eigenvalue stability criterion is $|\rho| < 1$ as implied by the conversion between discrete- and continuous-time $\gamma$ growth rates:

$$\gamma = \tau_s^{-1} \ln |\rho|$$

where $\tau_s$ is the sampling interval. The observed branching in Figure 2.2.1-4a of the vacuum system eigenvalues can be attributed to horizontal gaps in the resistive shell (giving different penetration times for vertical and horizontal magnetic field components). Qualitatively good agreement is observed between plasma experiment (Figure 2.2.1.4b,c) and theory.

**Attempts at few coils and low-coverage resistive wall mode stabilization**

The reversed-field pinch features multiple current driven RWM instabilities at any plasma pressure. The EXTRAP T2R device incorporates for stabilization of the unstable RWM spectrum an array of 64 independent active control coils that fully covers the toroidal wall. The unstable part of the RWM spectrum consists of $m=1$ modes with varying toroidal mode numbers (in total about 15 unstable modes). An attempt to stabilize the full spectrum of these modes using both i) incomplete coverage and ii) few coils has been carried out on T2R. The T2R study attempts to make effective use of randomized coil subsets for the full multimode RFP instability problem. Two empirically derived centralized model-based control algorithms are compared with a baseline decentralized intelligent shell type feedback. One interesting finding of this study is that the model-based controllers appear to outperform the decentralized intelligent shell method. However, experimental stabilization could not be achieved for the coil array subset sizes considered in this first study, in spite of the fact that numerical simulations of the models were predicting stabilization. The number of output channels (active coils) of the controllers is reduced using a random sampling methodology. Several subsets were tested in each case. Neighbouring coils were also bundled together to form larger coils. The subsets are characterized by two numbers; Degrees-of-freedom: DOF ($1<\text{DOF}<64$) (Number of independent coils), Areal fraction covered by coils: $c$ ($0<c<1$).
Since coils were bundled together, the DOF may be smaller than the actual number of physical coils used. The baseline controller used as a reference is the intelligent shell controller, a model-free, decentralized PID array with DOF=1-64, 0<c<1. Recent system identification results have been exploited for the design of the model-based controllers. The first is a multi-variable controller (MVC) specially designed for each coil selection. Linear-quadratic-Gaussian control (LQG) design followed by aggressive model reduction was used to obtain a controller which could be deployed in the real-time control computer. The implemented controller has 64 inputs, 16 outputs, 8 states, and uses pairs of bundled coils (DOF=16, c=0.5). The second model based controller is a static–output feedback controller (SOF), designed in a similar way as the MVC, but it requires less real-time computation allowing deployment of a controller with 64 inputs, 24 outputs, 0 states, and uses pairs of bundled coils (DOF=24, c=0.75). Note that the requirements for real-time computations severely limited the complexity (number of states) of the model-based controllers.

**ASDEX-Upgrade enhancement project**

The on-going ASDEX Upgrade enhancement project for active MHD control is carried out in collaboration between Max-Planck-Institut für Plasmaphysik and includes 24 in-vessel saddle coils with power supplies. KTH involvement is mainly in the design of the RWM controller. At present, 16 coils have been installed at poloidal positions above and below the midplane, and manufacture of power amplifiers is ongoing at Max-Planck-Institut für Plasmaphysik.

**Publications section 2.2.1**

**Peer reviewed journals**


2.2.2 External magnetic perturbation effects on plasma rotation


The work tried to exploit the capabilities of the EXTRAP T2R feedback system to address key issues related to external magnetic perturbations and error fields. In particular, the screening of a resonant perturbation by the plasma flow, the effect of resonant and non-resonant perturbations on the plasma velocity, comparison with neoclassical toroidal viscosity torque and the identification of error fields have been studied.

**Resonant magnetic perturbation screening**

Resonant magnetic perturbations (RMPs) are a promising tool for mitigation and/or suppression of edge localized modes (ELMs) and for the optimization of neoclassical tearing mode stabilization. However, the RMP penetration into the plasma might be screened by the plasma flow, limiting the capabilities of the technique.

Experimental results show that with high flow the RMP has a smaller influence on the TM amplitude than at low rotation, see the example in figure 2.10. Preliminary numerical simulation of EXTRAP T2R plasmas obtained with the NIMROD code show that in the high rotation case the plasma remains in the (fully) screened state until the velocity is sufficiently slowed, while in the lower rotation case the reconnection occurs soon after the RMP application.

The work is in collaboration with V. Izzo from University of California-San Diego.

**Torque produced by a resonant magnetic perturbation**

It has high relevance for the tokamak community to understand the underlying physics related to the plasma flow braking by an external magnetic perturbation. The braking can be due to the interaction of the static perturbation resonant harmonic with the rotating plasma mode and/or to the neo-classical toroidal viscosity (NTV) torque due to the non-resonant harmonics generated as side-band effects related to the small number of active coils. The example in figure 2.2.2.2 shows the plasma velocity without perturbation (dashed line) and plasma velocity at several time instant when a resonant perturbation is applied. While the velocity is clearly localized at the resonance (vertical dashed line), the braking is extended till the plasma core.

![Figure 2.2.2.1](image)

**Figure 2.2.2-1.** Dependence of the TM amplitude on the plasma velocity without (open symbols) and with a 0.6mT (1,-12) RMP. And time evolution of the TM amplitude and phase at three different levels of velocities.

![Figure 2.2.2.2](image)

**Figure 2.2.2-2.** Experimental braking torque produced by a non resonant perturbation (red dots) compared with the theoretically expected NTV torque (black dots).
**Torque produced by a non-resonant magnetic perturbation**

Experiments similar to those conducted for a RMP, have been performed by applying a non-resonant magnetic perturbations (non-RMP). This work has experimentally quantified the torque produced by a non-resonant perturbation. The results show that the non-RMP torque is not localized in any specific position but affects the entire core and that the torque decreases as the perturbation harmonic is more far from the resonance. Theoretical results show a qualitative good agreement between the experimental torque and NTV theory, both concerning the radial shape of the torque density and the effect of the non-RMP harmonic, see figure 2.2.2.3.

The work is in collaboration with Y. Sun from the Institute of Plasma Physics, Chinese Academy of Sciences.

**Error field identification**

Error fields (EFs) are known to lower confinement in toroidal plasmas and, in general, to lower their rotation. Additionally, EFs can seed magnetic islands by EF penetration or cause locking of pre-existing islands, often resulting in disruptions. Compensation of error fields in tokamaks in ITER are therefore of great importance. In this work a new non-disruptive error field (EF) assessment technique not restricted to low density and thus low beta was demonstrated at the EXTRAP-T2R reversed field pinch. The technique exploits a set of active coils to simultaneously create a known static error field and the probing external field with growing amplitude and rotating phase that will be used to identify the static error field. From the measured radial field, it was possible to identify the harmonic and the phase of the error field. Figure 2.2.2.4 shows the results concerning the phase identification.

The work is in collaboration with F. Volpe from Columbia University.

**Publications section 2.2.2**

**Peer reviewed journals**

1. L. Frassinetti, S. Menmuir, K.E.J. Olofsson, P.R. Brunsell, J.R. Drake
Presentations at international conferences and workshops


5. L. Frassinetti, Olofsson K.E.J.O, Setiadi C, Fridström R.,Brunsell P.R., Drake J.R., Volpe F.A. “Wall diffusion time in EXTRAP T2R and possible applications to tokamaks” 54th Meeting of the APS Division of Plasma Physics, November 2012, Providence, USA

6. F. A. Volpe, L. Frassinetti, E. Olofsson, P. Brunsell and J. Drake “Error Field Assessment from Driven Mode Rotation: Results from Extrap-T2R Reversed-Field-Pinch and Perspectives for ITER” 54th Meeting of the APS Division of Plasma Physics, November 2012, Providence, USA

2.2.3 MHD stability

C. Wahlberg (UU), in collaboration with CRPP Lausanne and UKAEA Culham

The main focus of this work is on global MHD instabilities in the core region of low-shear tokamaks and the influence of toroidal plasma flows on such instabilities. The activity during 2012 has dealt both with Kelvin-Helmholtz like instabilities in low-shear plasmas with strongly sheared toroidal plasma flows, and with the appearance of a 3D helical core in static, ITER like hybrid scenarios.

In [1], a Kelvin-Helmholtz like instability of tokamak plasmas with strongly sheared toroidal flows and low magnetic shear in the core region was studied analytically and numerically. The analytical theory generally shows good agreement with the numerical calculations based on the DIVA and CASTOR-FLOW codes, and many characteristic features and parameter dependences of the flow-driven instability, such as an eigenmode structure peaking at the position of largest flow shear, and insensitivity of the growth rate to the plasma beta and to the details of the safety factor profile in the low-shear region, can be understood from the analytical theory. From an asymptotic expansion of the growth rate for large rotation frequencies, the drop in the dynamic pressure from the flow across the region of strong flow shear can be identified as one of the major driving mechanisms of the instability. In addition
to the relationship with the KH instability, the mode can therefore also be interpreted as a kind of infernal or quasi-interchange instability, driven by the drop in the dynamic pressure associated with the plasma flow.

In [2], MHD stability of ITER like hybrid scenarios, characterized by weak, reversed shear and $q$ near unity, was studied with particular attention to ideal internal kink modes and infernal modes. Numerical simulations for ITER like equilibria with weakly hollow $q$ profiles were carried out using the 3D equilibrium code ANIMEC. These simulations showed the presence of a 3D helical core with the characteristics of a saturated internal kink mode. The internal kink perturbation has also been investigated nonlinearly using an ideal version of the XTOR code. A scan in the current was performed and it was found that with the minimum of $q$ above unity, the helical distortion shows good agreement with the results provided by the ANIMEC simulations, while for $q_{\text{min}}$ below 1, XTOR gives a residual distortion in contrast with the ANIMEC results. Moreover, infernal mode stability in hybrid scenarios was in [2] studied analytically, extending the quasi-interchange model with the inclusion of resistive as well as electron and ion diamagnetic effects.

Y. Liu, D. Yadykin

The research activity in 2012 covers: a) analytic theory development; b) numerical code development together with extensive computer simulations; c) investigation of the 3D equilibrium for JET tokamak; d) wall characterization for JET tokamak.

a) The theory part of the work is reported in Ref. [3], which is based on analytically tractable cases. We show two possible mechanisms of modifying the tearing index, namely by invoking either the kinetic physics or by the active control using magnetic coils. The possibility of controlling the tearing index can be essential for the NTM instability control. The magnetic feedback schemes, studied in this work, are found to be generally stabilizing for the tearing index. The drift kinetic effects from both thermal particles and hot ions tend to reduce the power of the large solution from the outer region. This generally leads to an increase of the tearing index, for the toroidal analytic equilibria considered.

b) The second work [4] studies the penetration dynamics of the resonant magnetic perturbation (RMP) field through the edge region of the plasma. These RMP fields are applied in tokamaks in order to mitigate ELMs. The simulations are performed in full toroidal geometry, under realistic plasma conditions in MAST experiments. The physics associated with several aspects of the RMP penetration, including the plasma response and rotational screening, the resonant and non-resonant torques and the toroidal momentum balance, are highlighted. In particular, the plasma response is found to significantly amplify the non-resonant component of the RMP field for some of the MAST plasmas. A fast rotating plasma, in response to static external magnetic fields, experiences a more distributed electromagnetic torque due to the resonance with continuum waves in the plasma. At fast plasma flow (such as for the MAST plasma), the electromagnetic torque is normally dominant over the neoclassical toroidal viscous (NTV) torque. However, at sufficiently slow plasma flow, the NTV torque can play a significant role in the toroidal momentum balance, thanks to the precession drift resonance enhanced so-called superbanana plateau regime.
c) Investigations of the 3D equilibrium for the JET tokamak were performed by the plasma boundary reconstruction using array of the magnetic sensors (flux loops) calibrated by direct kinetic measurements at one spatial location (High Resolution Thompson Scattering diagnostic). Reconstruction is done when external non-axisymmetric magnetic field distortion is applied using Error Field Correction Coils (EFCC). It is found that the plasma boundary displacement is proportional to the currents in the EFCCs. Maximum plasma boundary displacement is $\Delta r = 6 \text{ cm}$ for $\text{IEFCC}=3\text{kA}$. Journal publication is in preparation.

d) Wall characterization of the JET tokamak were performed by measuring the magnetic field penetration time through the conducting structures. Two methods were applied: penetration time measurement during the slowing down phase of the Neoclassical Tearing Mode (NTM) rotation; penetration time measurement in vacuum during decay phase of the applied external magnetic field. It is found that the penetration times are quit different for two methods (~5.5 and ~20 ms respectively). This could be caused by the fact that the conducting structures ‘seen’ from inside and outside are different. The work is ongoing and the comparison with the model results (CarMa code) is seen as the next step.

**Publications section 2.2.3**

**Presentations at international conferences and workshops**


**Peer reviewed journals**


2.3 Power and particle exhaust, Plasma-wall interaction

2.3.1 Plasma-wall interaction

M. Rubel, D. Ivanova, P. Petersson, G. Possnert, A. Garcia-Carrasco

Plasma-wall interactions (PWI) comprise all processes involved in the exchange of mass and energy between the plasma and the surrounding wall. Two inter-related aspects of fusion reactor operation - economy and safety - are the driving forces for studies of PWI. The major issues to be tackled are: (i) lifetime of plasma-facing materials (PFM) and components (PFC), (ii) accumulation of hydrogen isotopes in PFC, i.e. tritium inventory; (iii) carbon and metal (Be, W) dust formation. PWI is one of the primary areas where integration of the Physics and Technology programmes is being achieved. The work at KTH in the field of PWI and fusion-related material physics has been fully integrated with the international fusion programme: (i) EU Fusion Programme, (ii) International Tokamak Physics Activity (ITPA), (iii) Implementing Agreements of International Energy Agency (IEA). It is demonstrated by the participation in:

- EFDA-JET Work Programme: Task Forces and JET Enhancements (Phase 1 and Phase 2) including the ambitious ITER-Like Wall (ILW) Project, i.e. full metal wall at JET.
- EFDA Work Programme on Power Plant Physics and Technology (PPPT)
- EFDA-JET Fusion Technology Programme.
- ITPA activities: (a) SOL and Divertor Physics; (b) Diagnostics.
- IAEA and IEA activities.

Experimental work is carried out at home laboratory, JET, TEXTOR and ASDEX-U. The research programme is concentrated on:

- Material erosion, migration and re-deposition.
- Fuel retention studies and fuel removal techniques.
- Dust generation processes in fusion devices.
- Characterization of plasma-facing materials and components including testing of high-Z metals.
- Test of diagnostic components.
- Development and characterization of wall materials for ILW at JET.
- Development of diagnostic tools for PWI studies.

Tracer Techniques for Material Migration Studies: Nitrogen-15

Plasma edge cooling by impurity is needed especially in the operation with high-Z metal plasma-facing components. Nitrogen seeding is used for that purpose. Some of the injected gas is retained in PFC. Quantitative determination of the deposition can only be achieved by ex-situ analysis of wall components. This is complicated by the fact that the adsorption of air nitrogen may have an impact on the measurements. For that reason Nitrogen-15 rare isotope (natural abundance 0.37%) was used. The first experiments with N-15 as a material migration marker were done in TEXTOR using a roof-shaped test limiter, shown in Figure 2.4.1-1. The main image shows the exposed probe, whereas the fresh unexposed W and C stripes are in the insert in the upper left corner. Limiter position in the tokamak is indicated by arrows and the analysed spots on both materials are marked with the numbered circles. It was composed of a graphite holder and four stripes: two made of tungsten and two made of graphite. The assembly was inserted into the machine from the top and placed in the scrape-off layer (SOL).
plasma, and exposed to 18 discharges (112 s) in total $3.38 \times 10^{21}$ N-15 atoms were injected. The exposures were followed by IBA studies performed at the 5MV Tandem Accelerator in Uppsala University by means of time-of-flight heavy ion elastic recoil detection (ToF-HIERDA) with 26 MeV $^{127}\text{I}^{7+}$ ions.

In Figure 2.3.1.1 one perceives that after exposure most of the originally shiny W surface is coated with a blackish deposit containing mainly carbon eroded both locally from the adjacent plate and from all main toroidal and poloidal limiters of TEXTOR which are made of graphite. Only a small area on the top of the limiter remains brighter than the rest. These two distinct areas, the net erosion zone on top and net deposition below, are associated with differences in particle fluxes (and related heat) reaching the plates during the exposure. ToF-HIERDA spectra shown in Figure 2.3.1.2 reveal the presence of two nitrogen isotopes, thus proving that a certain fraction of the gas injected for edge cooling remains in the vessel either as co-deposited atoms or compounds (such as C-N, W-N) formed on PFC under plasma impact. The quantitative data for all four analysed points are collected in Table 2.3.1-1.

![Figure 2.3.1-1: Roof-shaped test limiter with tungsten and carbon stripes after exposure to plasma in TEXTOR. Location of the limiter in the tokamak is shown by arrows and the analysed spots on both materials are marked with numbered dots.](image)

**Table 2.3.1-1:** Quantitative composition (all concentrations $10^{15}$ cm$^{-2}$) of co-deposits determined with ToF-HIERDA in erosion and deposition zones on graphite and tungsten surfaces exposed in TEXTOR.

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<th>Point 3</th>
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<td>3.6</td>
<td></td>
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Progress Report 2012 of the Fusion Association EURATOM-VR

Figure 2.3.1-2: Time-of-flight HIERDA spectra recorded with a 26 MeV $^{127}$I$^+$ beam for co-deposits on surfaces exposed to the TEXTOR plasma on a test limiter: (a) graphite plate; (b) tungsten plate.

In summary, the measurements have allowed for a firm statement on the in-vessel retention of nitrogen by co-deposition or by the compound formation with the PFC material. This causes the “memory” effect of nitrogen in plasma. Understanding of the process may help developing tokamak operation scenarii and defining limits regarding nitrogen injection. This first and successful experiment with nitrogen-15 opens new possibilities in material migration studies in controlled fusion devices. It should also be noted that HIERD analysis lead to detection of helium in tungsten. This is the first measurement of that kind on metals exposed to tokamak plasma.

**Impact of Thermal Treatment and ICWC on Fuel Inventory in Co-deposits**

Curtailing of in-vessel fuel inventory in fusion devices is essential in D-T plasma operation. The issue becomes particularly important with carbon plasma-facing components (PFCs). Currently considered basic schemes for reduction of fuel aim either at the desorption of hydrogen-containing species or at removal of the entire fuel-rich co-deposit. The first approach is based on surface heating by photonic means, long-term annealing of PFCs. Ion cyclotron wall conditioning (ICWC) is also proposed as a fuel removal technique but no detailed surface analysis of wall components has been carried out so far after high power radio-frequency (RF) pulses. Secondly, after PFCs cleaning by whichever technique, the fuel-depleted layers will remain in the vessel and they would be repeatedly exposed to plasma. The question is how do such layers respond to plasma during the repeated exposure? To address those two issues, systematic studies have been done to assess: (i) the efficiency of ICWC and (ii) fuel re-absorption by thermally treated co-deposits exposed to plasma after cleaning.

The investigation was done with deposit-covered specimens obtained by sectioning graphite tiles from the TEXTOR tokamak: the main toroidal pump limiter at ALT-II (Advanced Limiter Test II) and inner bumper limiter being a shield of the dynamic ergodic divertor (DED). All specimens were analysed after tiles’ retrieval from the tokamak and then at all stages of the experimental procedure by means of gas-phase and material research methods: thermal desorption spectrometry (TDS), ion beam techniques and microscopy (SEM). For thermal treatment a number of 1cm x 3cm plates were cut from the deposition zone of the ALT-II. Outgassing of each sample was performed at 1273 K with synchronous monitoring of masses M2 (H$_2$) M3 (HD), M4 (D$_2$) and masses M19 - M20 corresponding to D-containing
water and C\textsubscript{1} hydrocarbons. For exposure in TEXTOR the outgassed plates were mounted on a holder attached vertically to the side of the test limiter (shaped as a single-roof block) to face the ion flux. The holder was made of a pure graphite plate which then served as a reference surface in the retention studies. The test limiter was positioned in the scrape-off layer (SOL) plasma at radial position \( r = 48.5 \) cm, i.e. 2.5 cm behind the last closed flux surface. The exposure was performed as a parasitic experiment during the commissioning of a charge exchange recombination spectrometer. The experimental program comprised 8 discharges (40 s in total), both ohmic and auxiliary heated by the two neutral beam injectors. The main plasma parameters were: the toroidal magnetic field strengths \( B_t = 2.2-2.6 \) T, line averaged electron density \( n_e = 2.5-3 \times 10^{19} \) m\textsuperscript{-3}, plasma current \( I_p = 350-400 \) kA.

The exposure to ICWC discharges was done with a 5cm x 5 cm sample cut from the DED tile. As in the previous case, the plate was installed vertically on a complex test limiter holder and inserted from the bottom. ICRF pulses were generated using two antennae (50 kW each) in hydrogen (8x10\textsuperscript{-2} Pa) under \( B_t = 0.23 \) T. The entire programme comprised 550 pulses lasting 0.5 s, 40 pulses of 0.2 s and 45 of 2 s duration. In a given cycle, from 5 to 100 pulses, power was injected every 20 s.

The initial fuel content in thick co-deposited layers on the ALT-II tiles is in the range 7-11\%, i.e. the deuterium-to-carbon concentration ratio (D/C) is about 0.1, as studied in detail after several long-term campaigns in TEXTOR. As determined with NRA they contained around \( 4.7 \times 10^{18} \) cm\textsuperscript{-2} D atoms layer of up to 7 \( \mu \)m. Thermal treatment enhances surface roughness and layer brittleness leading eventually to flaking and detachment of co-deposits, i.e. dust formation. These effects additionally complicate the subsequent analyses and handling of the deposit-containing samples. To find possible differences in the fuel content between the original co-deposits and layers exposed to deuterium after outgassing the following features were measured: (a) surface content of deuterium and depth distribution up to the accessible information depth with NRA; (b) total D amount and desorption characteristic with TDS.

**Re-absorption experiments in TEXTOR:** The deuterium radial distribution and content determined by NRA in the re-exposed ALT-II deposit and in the graphite holder are plotted in Fig. 2.3.1-3(a). Images of the re-exposed sample and the pure graphite holder are shown in Fig. 2.3.1-3(b) and 2.3.1-3(c), respectively. Arrows indicate the direction of the analysis with a \( ^{4}\text{He}^{+} \) beam. The growth of a new deposited layer was observed on the reference graphite plate. Concentration of D atoms along the plate drops exponentially with a characteristic e-folding length \( \lambda = 0.9-1.0 \) cm. This value is in agreement with earlier measurements using surface collectors. The retention profile on the re-exposed fragment of ALT-II has a plateau region which matches the surface structure and corresponds to the area with the remaining co-deposited layer. Fuel retention in the re-exposed deposit is \( 1.2 \times 10^{17} \) D cm\textsuperscript{-2}. This quantity is significantly smaller than the retention in the reference graphite placed at the same radial distance from the plasma: \( 3.3-1.5 \times 10^{17} \) D cm\textsuperscript{-2}. The areas where deposits peeled off also show a lower level of fuel retention in comparison to pure graphite. In the area where the transition between the deposition and erosion zones of the original ALT-II tile starts, the concentrations of D atoms in the studied sample and the reference plate become almost the same. A similar flat profile and lower absolute values of fuel retention were observed in the second experiment in TEXTOR. Depth profiles of the D atoms show broader distribution of fuel species in the flaking porous deposits than in the pure graphite. The release of selected species was studied: HD (M3) D\textsubscript{2} (M4) and M19 and M20 which represent a mixture of C\textsubscript{1} hydrocarbons and deuterated water (HDO, D\textsubscript{2}O). The most important feature is that the
release occurs predominantly in the temperature range of 700 K – 900 K with a peak value around 750 K. Spectra obtained for the re-exposed plate have followed the same trend as measured for the original limiter tile, i.e. single broad desorption peak (650-1000 K) with the maximal desorption rate for M3 and M4 occurring at around 750 K. However, the desorbed amount of HD and D₂ is 30-40 times smaller than from the original sample, thus indicating that fuel-depleted layers are not immediately re-saturated during consecutive exposure to plasma.

**Figure 2.3.1-3:** (a) Deuterium content in the re-exposed deposit and reference plates after 40 seconds of exposure to SOL plasma in the TEXTOR tokamak; (b) Photo of the re-exposed specimen with the remaining deposit; (c) The pure graphite holder after the exposure. Arrows indicate the direction of the NRA scan.

**Fuel release by ICWC:** Several DED were retrieved from TEXTOR after several years of operation and analysed in detail with NRA for deuterium content. One such pre-characterised tile is in Fig. 2.3.1-4(a) and a piece of that tile after exposure to ICWC pulses is shown in Fig. 2.3.1-4(b). Whereas plots in Fig. 2.3.1-4(c) show the deuterium content measured before and after that experiment. One perceives the decrease in fuel content following the ICWC in hydrogen. The drop is by a factor of more than 2. These are the first data of that kind obtained after cleaning a long-term wall component from a tokamak. These results are encouraging but still more detailed research is needed especially when it comes to the release of fuel from remote areas where the greatest deposition and fuel inventory has been observed. They are not accessible by ICWC.

**Figure 2.3.1-4:** (a) DED tile as retrieved from TEXTOR; (b) specimen sectioned from the tile and exposed to ICWC pulses; (c) deuterium content on the DED tile before after ICWC pulses.

A positive result obtained by ICWC-induced cleaning should not overshadow the fact that this is an early result. At least a few other points should be carefully assessed: (a) toroidal uniformity of release; (b) depth of fuel release and (c) re-saturation of the layers during repeated exposure to fusion plasma.
Publications section 2.3.1

Peer reviewed journals


Presentations at international conferences and workshops


2.3.2 In-situ dust diagnostics and study of dust dynamics in SOL plasmas

*S. Ratynskaia, H. Bergsäker, I. Bykov, L. Vignitchouk, P. Tolias*

The possible accumulation of dust, particularly at hot surfaces, is a critical issue for ITER and other future big devices. The presence of dust in the plasma may also interfere with plasma confinement and other operations aspects. The most common diagnostics for dust in fusion plasmas include tracking of glowing particles with fast cameras, laser scattering and simply collecting and analysing the dust that has accumulated at different places in a device after extended periods of operation. Laser ablation methods are sometimes envisaged for the in situ removal of fuel trapped in thick deposited layers in fusion devices. However, laser ablation does produce dust. In order to assess laser ablation methods it is necessary to characterise the dust that is emitted.

Another diagnostic technique is to collect dust in a controlled way with silica aerogel collectors, preferably with time resolution. This technique allows counting of particles that are moving in the edge plasma, even if it is not glowing, and analysis of individual particles to determine their size distribution, composition and other properties. The silica aerogel collectors also make it possible to estimate the particle velocities, since fast particles penetrate into the ultra low density material without being significantly damaged, and the penetration depth is related to the particle velocity.

The experimental campaign in 2012 included dust collection experiments in TEXTOR, where intrinsic and injected dust was collected with silicon collectors in the scrape-off layer, while the effects of dust injection were studied with spectroscopy, fast cameras and laser scattering close to the injection point. For the first time dust moving in both the toroidal directions and in the poloidal directions were collected. Another experiment, which was carried out in 2012, was to intercept dust that was emitted from laboratory laser ablation of deposited layers from TEXTOR limiter tiles. The particle velocities could be inferred from the impact features and the fuel content of individual dust grains could be measured using microbeam NRA.
Another part of the 2012 experimental program was a dedicated study of metal particle impact at different surfaces, in a velocity range from a few m/s up to several 100 m/s, using a mechanical launching device.

In order to use experimental data for predictions about dust behaviour in new conditions, such as in ITER, comprehensive models are necessary. The main efforts in the modeling part of the 2012 program were to develop an existing dust dynamics model to include more sophisticated treatment of collisions between particles and the vessel walls, and to adapt the code to be able to simulate dust dynamics in the TEXTOR tokamak and in the T2R reversed field pinch device. Figure 2.3.2-3 shows examples of simulated particle trajectories in TEXTOR, given a specific set of assumptions. Tungsten particles were injected from a port at the top of the machine and could be collected at Si surfaces using a fast probe system, as explained above.
**Publications section 2.3.2**

**Peer reviewed journals**


**Presentations at international conferences and workshops**


**2.4 Physics of fast particles, heating and current drive**

*T. Hellsten, T. Johnson, A. Hannan (PhD student), J. Höök (PhD Student), Q. Mukhtar (PhD student), S. Tholerus (PhD student)*

The research is focused on studying wave-particle interactions relevant for fusion experiments, in particular for heating, current drive and excitation of waves by fast particles. The group develops codes for predicting the effects of ICRH, and validates them against experiments. The program is well integrated into the European fusion program through participation in e.g. the Integrated Tokamak Modeling Task Force, the exploitation of the JET facility and PPPT.

The main codes developed by the group are PION, FIDO, SELFO, SELFO-light and RFOF. PION was the first self-consistent code for modeling ICRH and NBI heating using simplified models and is used routinely at JET (developed by L.-G. Eriksson and T. Hellsten). For more advanced modelling the Monte Carlo code FIDO was developed to calculate the distributions of resonant ions taking into account effects of finite orbit width, RF-induced spatial transport and interaction between MHD waves and fast ions. By coupling the FIDO and wave code LION the self-consistent ICRH code SELFO was developed. Recently the SELFO-light code has been developed which is similar to LION, but with a more advanced wave solver. This model is particularly suitable for large machines like ITER and DEMO.
Exploitation of JET

Work has continued on the analysis and modelling of JET experiments carried out in 2009 and 2010, primarily related to experiments on intrinsic and RF induced plasma rotation and ICRF scenarios for the non-activated phase of ITER.

Experiments on intrinsic plasma rotation have been analysed. It has been shown that in JET this rotation is very different from what is predicted by commonly used scaling laws; the JET results suggest that the predictions for the rotation in ITER might be strongly overestimated [4]. In search for a deeper understanding of this rotation, experiments have shown that there is a clear correlation between the plasma rotation and the electron temperature, independently of the heating scheme used [3]. In addition, experiments on the ICRF scenarios for the non-inductive phase of ITER has been analysed [12-13], including the possibility to generate two mode conversion layers in the plasma [14].

ICRH scenarios for DEMO and the SELFO-light code

The SELFO-light code, which is less advanced than SELFO and RFOF, is a code suitable for routine analysis [1]. The code has been tested and used for studies of fast wave current drive for DEMO. Both SELFO-light and SELFO use the global wave solver LION for calculating the wave field, which is based on finite element. A problematic issue in modelling wave propagation in plasmas is the spatial dispersive effects. New methods suitable for FEM codes to include have been developed to take into account these effects [15].

Modelling of current drive scenarios for DEMO has been done with SELFO-light in order to identify potential scenarios [2]. It was found that because of the strong damping by alpha particles only four scenarios could be found. The optimum toroidal mode number, which is critical for the design of the antenna, is determined by a phase velocity of about 1.23 times the thermal velocity. At higher phase velocities the fraction of power damped by ion cyclotron damping increases and at lower phase velocities the fraction of power absorbed by trapped electrons increases.

![Figure 2.4-1: Fast wave current drive efficiency for different DEMO designs as a function of the wave frequency. Four frequency bands can be identifies as candidates for fast wave current drive in DEMO.](image)
**ITM task force**

The group participates in the Integrated Tokamak Modelling Task Force, where Thomas Johnson is Deputy Project Leader for IMP5: the integration project for heating, current drive and fast particle effects. The main contributions have been in the development of the ITM infrastructure, the integration of heating and current drive codes into the European Transport Solver (ETS), the adaptation of codes to the ITM infrastructure and the development of advanced Fokker-Planck models.

**IMP5 infrastructure**

The developments of the IMP5 infrastructure during 2012 has been focussed the 4.10a version of the ITM data structures and the development of generic tools for handling objects within this data structure. These changes have been implemented by Thomas Johnson. In addition a number of generic structures, used outside the IMP5, has been implemented, along with related data-processing tools and documentation. In addition, tools for e.g. generating and merging data structures have been developed.

**Heating and Current drive workflow**

The workflow for heating and current drive, IMP5HCD, has been upgraded to work in 4.10a and developed further during 2012. As a result the workflow now works as a standard module in the ETS workflow.

![Workflow diagram](image)

**Figure 2.4-1:** Work flow for heating and current drive. The picture illustrates how the workflow is partitions. On the top one finds physics modules separated into three categories Waves/Sources/Fokker-Planck models. Inside the Waves-model the workflow is further separated into IC/EC/LH waves. Finally each wave heating scheme may be represented by different physics models, e.g. the EC-wave model EVE shown above
**RFOF an library for RF modelling in orbit averaged Monte Carlo codes**

The work on RFOF has continued and the library is now part of two orbit following Monte Carlo codes, ASCOT (TEKES/Finland) and SPOT (CEA/France). In particular, the wave-interface has been developed, including the reading of LION output files. The coupling to ASCOT has been developed in collaboration with TEKES, including the implementation of a scheme for Marker-weighting in ASCOT that is required to runt ICRF scenarios ASCOT.

### 2.4.1 Mutual effect of impurities and ICRH

*Ye Kazakov, I Pusztai, T Fülöp*

There is a wealth of experimental evidence of the mutual effect of ICRF heating and impurities in fusion plasmas. During 2012, we continued and extended our research on the enhancement and optimization of the ICRH performance in tokamaks, and modelled the effect of the off-axis low field side ICRH on the transport of high-Z impurities. These activities were in line with the envisaged research plan specified by the EFDA Fusion Researcher Fellowship for Ye Kazakov.

**ICRH-driven poloidal asymmetries**

We investigated the poloidal asymmetries in impurity density driven by the low field side ICRF heating. These asymmetries are considered to be a contributing mechanism to the observed reduction of impurity transport in ICRH-heated plasmas. The ratio of the perpendicular to the parallel temperature of the resonant minority ions was identified to be the main parameter governing the impurity asymmetry strength. Through numerical simulations with the TORIC-SSFPQL code, the temperature anisotropy of minority ions was shown to increase with ICRH power and decrease with increasing plasma density and temperature, fast wave toroidal wavenumber, minority and impurity concentrations. With respect to plasma shaping, the elongation of the flux surfaces was shown to lead to the reduction of the reached anisotropy.

**ICRH efficiency in plasmas with multiple mode conversion layers**

High plasma contamination with impurities can lead to the appearance of the supplementary mode conversion layer in the plasma. This was experimentally shown to occur in (³He)-H ICRH experiments performed at JET. Unavoidable presence of C⁶⁺ ions in the discharges gave rise to two mode conversion layers rather than a single one. This resulted in very different dynamics of wave absorption, which was observed at the low and high helium-3 concentrations. Such a non-trivial dependence of ICRH performance on the concentration of impurity ions could be qualitatively explained by the recent analytical theory of mode conversion in plasmas with two evanescence layers.

**Minimizing parasitic ICRH absorption by fast particles in D-T plasmas**

In view of the foreseen D-T campaign at JET, we evaluated ICRH scenarios relevant for this phase. D minority heating in D:T=20:80 and ³He minority heating in D:T=50:50 plasmas were shown not to suffer much from the parasitic absorption by fast particles (fusion-born alphas and NBI-produced fast ions), and thus these scenarios can be used for maximizing the
fraction of thermal ion heating. A theory, which explained strong absorption by minority ions predicted by the TOMCAT and TORIC codes, was developed, and the interference effect was shown to be responsible for the absorption enhancement.

**Publications section 2.4**

**Peer reviewed journals**

9. L J Höök et al, submitted to *Computer Physics Communications*


*Presentations at international conferences and workshops*


### 2.5 Energetic particle physics

#### 2.5.1 Physics of burning fusion plasmas

*M. Lisak, R. Nyqvist (PhD student) and F. Håkansson (PhD student)*

**Introduction**

One of the main objectives of tokamak devices such as JET and the next generation experiment ITER is the study of alpha particle production and confinement, which are of fundamental importance for heating, burn control and alpha particle diagnostics. ITER will contain large populations of fusion born alpha particles, which may excite wave instabilities due to the deviation of their distribution from thermodynamic equilibrium. The presence of thermonuclear instabilities may in turn enhance transport of the energetic particles, thereby degrading the plasma heating and fusion yield. Many aspects of fast ion collective effects are presently well understood, including excitation of MHD modes such as fishbone oscillations and toroidicity-induced Alfvén eigenmodes (TAEs). However, a currently "hot" topic is the role of kinetic and nonlinear Alfvén instabilities. Promising topics for future advances include quantitative modeling of frequency shifting energetic particle modes.

The research programme of the group focuses on the study of stability and transport in magnetically confined fusion plasmas, with a particular emphasis on fast particle effects. The aim is to develop and improve theoretical models within this area, in order to explain experimentally observed phenomena in existing devices and make predictions for future ones. The research activity is based on close collaboration with JET-EFDA (Culham Science Centre, UK), the Institute of Advanced Fusion Studies at the University of Texas (Austin, USA) and the West Pomeranian University of Technology (Szczecin, Poland).
VR Association Work Programme

Radiative Damping of Low Shear Toroidal Alfvén Eigenmodes
Radiative damping of TAEs is caused by non-ideal coupling to radially propagating, kinetic Alfvén waves (KAWs) that carry away parts of the mode amplitude from the TAE main mode body. A significant asymmetry is found between the damping rates of even and odd TAEs, with eigenfrequencies below and above the central TAE gap frequency, respectively. For the even TAE, the coupling results in two non-overlapping, outgoing fluxes of KAWs that propagate away from each other and the TAE. In contrast, the odd TAE couples to KAWs that initially propagate towards each other, overlap and form an interference pattern. As a result, the outgoing KAW flux is negligibly small, as is the rate of radiative damping. The indicated up/down asymmetry (with respect to the mode frequency) suggests that odd TAEs may be destabilized by fusion born alpha particles more easily than the more commonly observed even TAE.

Adiabatic Description of Long Range Frequency Sweeping
Magnetically confined plasmas typically exhibit a wide range of kinetic instabilities. For example, in externally heated plasmas, fast ions often excite plasma eigenmodes in the Alfvénic frequency range. The role of dissipation in such systems is far from trivial. Near the instability threshold, when the linear growth rate due to the kinetic drive just barely exceeds the damping rate due to dissipation, a commonly observed phenomenon is the spontaneous formation of phase space structures (so called holes and clumps) in the fast particle distribution function. Such scenarios correspond to a transformation from unstable plasma eigenmodes to beam-like, self-sustained energetic particle modes (EPMs) with time dependent frequencies, and experimental observations of frequency sweeping events that have been attributed to EPM formation are abundant, see e.g. Figure 2.5.1-1. Recently, emphasis has been put on asymmetric and long-range frequency shifts (see e.g. Figure 2.5.1-1 b), and an efficient analysis tool has been developed to handle such events. The model takes advantage of the fact that after the rapid hole/clump formation stage, the EPMs evolve slowly as compared with the mode oscillations.

![Figure 2.5.1-1. a) Spectrogram showing frequency sweeping TAEs on MAST. b) Spectrogram of n = 0 modes on JET. These modes sweep over an extended frequency range.](image)

Accounting for long-range effects such as a finite frequency shift, a global shape of the unperturbed fast particle distribution and particle trapping in the wave field, the model can accurately track modes over large frequency spans, thus permitting quantitative analysis of sweeping rates and amplitude evolution. The model predicts asymmetric frequency shifts for a
number of reasons and can be used to describe transitions from monotonic to transient sweeping.

**Publications section 2.5.1**

**Peer reviewed journals**


**Presentations at EPS conferences**

**Presentations at international conferences and workshops**


**Licentiate theses**

**2.5.2 Runaway electrons**

*T. Fülöp, G. Papp (PhD student), J. Rydén (MSc student), E. Nilsson (MSc student)*

Due to a sudden cooling of the plasma in tokamak disruptions a beam of relativistic runaway electrons is sometimes generated, which can cause damage to plasma facing components through highly localized energy deposition. During 2012, we assessed the effect of resonant magnetic perturbations on runaway losses in ITER, we investigated kinetic instabilities driven by runaway electrons in near-critical field and we calculated the distribution and synchrotron radiation emitted by runaway positrons in tokamak disruptions.

**Effect of resonant magnetic perturbations on runaways**

The effect of resonant magnetic perturbations (RMP) on the net radial transport of runaway electrons (RE) was calculated by simulating the runaway electron drift orbits in magnetostatic perturbed field with the ANTS (plasma simulatioN with drifT and collisionS) code. The RMP influences the time dynamics and preferred loss directions of the REs. Interestingly, the loss patterns do not depend on the particle energies and starting positions. The particle radial
steps are correlated with the local radial magnetic perturbation component, which makes the transport chaotic, but deterministic.

**Interaction of electromagnetic waves and suprathermal electrons in the near-critical electric field limit**

Using a suprathermal electron distribution appropriate for the case when the electric field is near-critical we investigated the frequencies, wave-numbers and propagation angles of the most unstable waves, using a general dispersion relation. We found that the threshold for destabilization of the extraordinary electron is more likely to be destabilized than the whistler wave found in earlier work.

**Runaway positrons in fusion plasmas**

We determined the positron distribution, the fraction of runaway positrons and the parametric dependences of their synchrotron radiation spectrum. Apart from its intrinsic interest, detection of radiation from positrons could be a diagnostic tool to understand the properties of the medium they propagate through.

**Publications section 2.5.2**

**Peer reviewed journals**


**Presentations at international conferences and workshops**


**Master’s theses**


3 Plasma auxiliary systems - diagnostics

3.1 Neutron diagnostics

3.1.1 Instrumental developments for JET and MAST

Modeling the neutron spectrum from the t-t reaction

J Eriksson, S Conroy, G Ericsson, C Hellesen

The neutron energy spectrum from the T(t,2n)4He (t-t) reaction has been modeled for JET relevant fuel ion distributions [1,2]. This is to form a starting point for the investigation of the possibility to obtain fast ion information from the t-t neutron spectrum in a future deuterium-tritium campaign at JET. The t-t spectrum is more challenging to analyze than the d-d and d-t cases, since this reaction has three (rather than two) particles in the final state, which results in a broad continuum of neutron energies rather than a peak. However, the presence of various final state interactions might still allow for spectrometry analysis. Interactions between one of the neutrons and the $^4$He give rise to a short-lived $^5$He resonance that results in a more peaked component in the neutron spectrum, as seen in Figure 3.1.1-1. In particular, highly energetic fast ions, such as the ones produced by NBI and harmonic ICRH, give strong signatures in the neutron spectrum.

![Figure 3.1.1-1](image)

**Figure 3.1.1-1.** Calculated neutron energy spectra from the t-t reaction from a thermal plasma at 10 keV (black solid line), a NBI heated plasma (blue dashed line) and a plasma heated with NBI and 3rd harmonic ICRH (red dash-dotted line). (a) No final state interactions. (b) The peak that is obtained when a $^5$He resonance is produced.

Fuel ion ratio measurements with neutron emission spectrometry

C Hellesen, J Eriksson, F Binda, S Conroy, G Ericsson, A Hjalmarsson, M Skiba, M Weizsflog and JET-EFDA contributors

The fuel ion ratio ($n_t/n_d$) is of central importance for the performance and control of a future burning fusion plasma, and reliable measurements of this quantity are essential for ITER. A method to measure the fuel ion ratio by comparing the thermal and beam-thermal neutron emission intensities, measured by a high resolution neutron spectrometer, has been developed.
The method has been applied to NBI heated deuterium tritium (DT) plasmas at JET, using data from the MPR spectrometer. The trend in the results is consistent with Penning trap measurements of the fuel ion ratio at the edge of the plasma, but there is a discrepancy in the absolute values, especially for high tritium densities, as can be seen from Figure 3.1.1-2. It is suggested to further validate this method by comparing it to the traditionally proposed method to estimate $n_t/n_d$ from the ratio of the thermal DD and DT neutron emission components.

Figure 3.1.1-2. Fuel ion ratios derived from the MPR spectrometer for four JET discharges (points with error-bars). For comparison, the fuel ion ratio measured in the divertor by the Penning trap is shown in solid blue.

**Peer reviewed journals**


**Presentations at international conferences and workshops**


**Licentiate thesis**


**Neutron Diagnostic at MAST**

**M.Cecconello, S.Sangaroon, I. Wodniak**

MAST experimental campaign from 2011 continued into 2012 and the neutron camera was extensively used in during this last part of the campaign to complete the measurements for off-axis current drive with neutral beam injection and its effect on the fast ions redistribution.
The results obtained from 2011 and 2012 were presented at different conferences and published in scientific journals. The neutron camera detector response function and efficiency was studied with the help of computer codes using the Monte Carlo method, in particular MCNP, NRESP and NEFF. These codes were used to obtain the response function matrix which when applied to the neutron source energy spectrum with the appropriate acquisition threshold provided a good match to the experimentally observed recoil proton pulse height spectra as shown in figure 3.1.1-3.

Figure 3.1.1-3. Left panel: detector efficiency estimates using NRESP and MCNP for different detector thresholds. Right panel: comparison between experimentally measured pulse height spectra of the recoil protons and simulated ones using the response function matrix obtained via NRESP.

Data analysis and modelling
TRANSP is the main code used in the data analysis of the neutron camera data on MAST: its standard output includes the neutron emissivity averaged on the poloidal flux surfaces. This 2D neutron emissivity profile is then used with the 2D solid angle map of the field of views to estimate the expected counts at the detector. Any anisotropy in the neutron emissivity arising from the presence of trapped fast ions is therefore lost. A collaboration with PPPL was then started in order to obtain a special output in which the non-flux averaged neutron emissivity projected on a poloidal plane was provided. The results are shown in figure 3.1.1-4 where the contribution of trapped fast ions is clearly seen. The flux and non flux-surface-averaged neutron emissivities are then used to model the profile of neutron emission measured by the neutron camera as shown in figure 3.1.1-5. Typically better agreement is found when using the non-flux averaged quantity. Initial activities have been started in collaboration with CCFE for the modelling of the neutron emissivity profile using LOCUST and HAGIS.
Figure 3.1.1-4. TRANSP simulated neutron emissivity profiles non flux-averaged (left panel, special TRANSP output), average over the flux surfaces (middle panel, standard TRANSP output) and their difference (right panel) clearly showing the localized contribution of trapped fast ions.

Figure 3.1.1-5. Neutron emissivity profile on MAST as a function of the impact parameter (inboard for low impact parameter values, outboard for large) at two different times using the flux averaged (blue and purple curves) and the non flux-averaged (red and green curves) neutron emissivity profiles obtained from TRANSP.

Neutron camera upgrade for MAST Upgrade

MAST will undergo a major upgrade starting from 2013 and lasting for 2 year. The main components that will be changed in the upgrade are the central columns and the toroidal field coils, the position of the poloidal field coils, the divertor geometry (super-X) and the spatial distribution and number of the neutral beam injector heating system. MAST Upgrade will be a device with higher performances than MAST which will results in a higher neutron yield. Based on the experience gained so far with the current neutron camera, the conceptual design of a neutron camera upgrade has started. Different solutions are being considered including two equatorial sets of lines of sight one of which is offset in vertical direction by 65 cm and one vertical set of lines of sight. The equatorial sets are made up of 8 to 10 lines of sight thus allowing the measurement of the full profile in a single pulse contrary to what can be done
currently on MAST. The vertically shifted set of lines of sight is intended to measure the fast ion population produced by the off-axis NBI. The vertical set of lines of sight is intended to measure the plasma position and radial redistribution of the fast ions.

![Conceptual design of the neutron camera upgrade for MAST Upgrade](image)

**Figure 3.1.1-6.** Conceptual design of the neutron camera upgrade for MAST Upgrade: three set of lines of sight are considered, two equatorials with one offset by 65 cm to observe the fast ion populations from the off-axis NBI, and one vertical.

**Preparation of MAST experimental campaign for 2013**

During 2012, a series of meetings where held at CCFE with the scope of preparing the experimental campaign for 2013. Uppsala University was involved in these preparatory meetings and put forward three proposals for dedicated experiments in the field of fast particles aimed at characterizing the neutron emission on MAST, the effect of fish-bones, long lived modes and saw-teeth. The proposals were among those approved to be carried out.

**Peer reviewed journals**

3. "Observation of fast ion behaviour with a neutron emission profile monitor in MAST", M. Cecconello et al. 2012 Nucl. Fusion 52 094015

**Presentations at international conferences and workshops**

Study of the detector efficiency of the MAST neutron camera


The determination of the absolute efficiency of the neutron detectors used in the NC at MAST is necessary for an accurate comparison of the experimental data with the measurements predicted by theoretical modeling of the neutron emission. The detector efficiency of the EJ301 liquid scintillators used in the NC is calculated using a combination of theoretical models to describe the detectors' properties and experimental measurements done at MAST. The detector efficiency has been calculated using the Monte Carlo code NRESP and a theoretical expression which takes multiple neutron scattering on H and C into account. Good agreement is found between NRESP and the theoretical value with $\varepsilon = 13.78 \pm 0.76 \%$ and $\varepsilon = 7.40 \pm 0.50 \%$ for energy thresholds at 0.11 MeVee and 0.38 MeVee respectively, corresponding to neutron energies of 0.7 MeV and 1.5 MeV.

A comparison between the neutron yield estimated from the NC and that measured with a calibrated fission chamber has been performed. Based on the neutron emission profiles measured with the NC, the neutron yield has been calculated including neutron absorption along the flight path and the detector efficiency. For a series of plasma discharges, the results were compared to the yield as measured with the fission chamber, see figure 3.1.1-7b. The observed time span includes sawtooth oscillations as observed with SXR and the electron temperature (figure 3.1.1-7a). The average proportionality constant between the predicted total neutron yield measured with the NC ($Y_{\text{model}}$) and the fission chamber ($Y_{\text{FC}}$) is $Y_{\text{model}} / Y_{\text{FC}} \approx 0.94 \pm 0.05$ for the whole time interval shown in figure 3.1.1-7b. The result confirms that the detector efficiency as calculated for the NC detectors are correct within the experimental uncertainty.

**Figure 3.1.1-7:** (a): Time traces of SXR (black) and electron temperature (blue) for plasma discharge 26448. (b): Total neutron yield measured with the MAST fission chamber (black) and the NC (red).
**Upgrading the Control and Monitoring system for the TOFOR neutron time-of-flight spectrometer at JET**

**Johan Valldor-Blücher, Matthias Weiszflog, Göran Ericsson**

The TOFOR time-of-flight spectrometer consists of two sets of scintillator detectors, a first scatterer (S1, 5 detectors) exposed to the collimated neutron beam and a second one (S2, 32 detectors) to detect the scattered neutrons after a well-defined flight distance, see figure 3.1.1-8. The scattering processes are registered as light pulses by photo multiplier tubes (PMTs) attached to the detectors. Each scattering process is recorded as a “time stamp” by the data acquisition (DAQ) system. The flight times are obtained as the time difference between pairs of time stamps.

TOFOR is equipped with a Control and Monitoring (C&M) system with the purpose to monitor the gain and timing stability of the individual detectors. The timing properties of the electronics receiving the PMT signals generally depend on the amplitude of the incoming signal. For precise time measurements, a detailed knowledge of this relationship is required.

![Figure 3.1.1-8: The TOFOR time-of-flight spectrometer (left) and a schematic view of the detectors and the neutron flight path (right)](image)

The upgraded C&M system enables, in contrast to the original version, to measure the time difference between the detector signal after being processed by the DAQ system and an electric synchronization pulse for different pulse amplitudes of the detector signal. The system comprises a pulsed laser (wavelength 531 nm, pulse duration 0.65 ns FWHM, pulse repetition rate 4.88 kHz), a step motor controlled polariser to vary the light intensity and a PMT, not influenced by the position of the polariser, to create the synchronization pulse. The TOFOR detectors are, via light fibres, illuminated with the laser light that went through the polariser.
Figure 3.1.1-9: Time difference between detector output signal and synchronization pulse as function of pulse amplitude. The absolute value of the time difference is cable dependent, only the change is relevant.

Performance tests of the upgraded C&M system show that its time resolution is about 0.1 ns and the time stability is better than 0.12 ns over more than 24 hours. First tests of the PMT pulse height dependence performed with the new C&M system and one spare PMT, show that the timing of that PMT is stable within about 0.25 ns when varying the pulse amplitude between -5 mV and -300 mV, see figure Figure 3.1.1-9.

The upgraded C&M system is now installed at TOFOR. The timing properties of the individual TOFOR detectors still needs to be analysed.

**A fully digital data acquisition system for TOFOR**

Mateusz Skiba, Sean Conroy, Göran Ericsson, Carl Hellesen, Anders Hjalmarsson, Matthias Weiszflog

The current DAQ system of TOFOR employs analogue electronics (e.g. constant fraction discriminators) to determine the time of the detector signals. The time information is then stored without any correlation it with other information, e.g. the pulse height. It is also impossible to determine if two detector signals, one from S1 and one from S2, were caused by the same physical neutron. Therefore, coincidences between un-associated neutrons will contribute to the TOF spectrum, and give rise to a flat, count rate-dependent background of random coincidences.

To address this issue, a new fully digital DAQ system is currently in development, with a prototype, 12 channel system, being evaluated in parallel with the old one. With the new DAQ system, it is possible to obtain correlated time and pulse height information. This data can be used to discriminate random events based on known relations between neutron energy (TOF), deposited energy (pulse height) and the geometry of TOFOR (flight distance) in the TOF spectrum. Investigating the effects of such background discrimination on TOF spectra, one can note that the signal-to-background ratio can be improved significantly in low-energy (high TOF) parts of the spectrum. This opens up the possibility to study weak spectral components at high count-rate with the TOF technique.
In particular, with an upgraded DAQ system, it will be possible to distinguish and perform spectroscopy on a relatively weak 2.45 MeV DD neutron peak that would otherwise be hidden by the strong background component generated by 14.0 MeV neutrons in future JET DT plasma scenarios.

The background discrimination technique enabled by correlated time and energy information was tested on modelled data from various scenarios with different relative concentrations of deuterium and tritium in the JET plasma, resulting in varying relative intensities of 2.5 MeV DD and 14.0 MeV DT neutrons. The results were compared to experimental data collected using the prototype digital DAQ system currently in development (Figure 3.1.1-10). It is concluded that a fully digital DAQ system will allow TOFOR to function as a broadband DD and DT spectrometer in the upcoming JET DT experimental campaign.

Figure 3.1.1-10: A comparison of modelled and experimental TOF data with un-discriminated (red) and discriminated (black) TOF spectra. a) Modelled DT data, b) Modelled DD data, c) Experimental TOFOR data from JET campaigns C31 and C32. The 2.45 MeV DD neutron peak is visible in all spectra at 65 ns, to the right in the figure. The 14.0 MeV DT neutrons correspond to the 27 ns peak to the left in Fig. 6 a). The accidental background is visible as a flat contribution in all three un-discriminated (red) spectra. The effects of the discrimination are evident in the black spectra, as is the similarity between modelled data in figure b) and experimental data in figure c).

Modelling the neutron and gamma fluences for the low energy Neutral Particle Analyzer at JET (JW12-EDT-ISU)

N. Dzysiuk, S. Conroy, G. Ericsson

The Joint European Torus is equipped with numerous diagnostics. One is the Neutral Particle Analyzer (Isotopes Separator). This diagnostic is designed to perform measurements of absolute fluxes of neutral particles emitted from the plasma. Besides providing absolute values it has the ability to distinguish the hydrogen isotopes and hence to study the isotopic composition of the plasma. The Isotope Separator Upgrade Feasibility Study (ISU) project is one part of the JET component of the EFDA 2012 Work Programme which includes 4 enhancement projects. Three of this set of diagnostic enhancements have been grouped into a package referred to as EDT (Enhancements for DT Operations).
The performance of the low energy NPA (KR2) is likely to be limited during the anticipated DT campaign in the present state of the diagnostic. The aim of ISU project is to plan for the necessary and needed work to obtain the best possible scientific results. The general planning involves essential maintenance and repair tasks as well as a plan for upgrading the detector and data acquisition system of the KR2. The plan for hardware upgrade will be supported by modeling of the radiation fields at this diagnostic. The ISU project also aims to improve on the analysis of the KR2 data.

The first stage of this work is the development of the computer model of the KR2 diagnostic. This task was accomplished with the MCNPX code based on the Monte Carlo approach. MCNPX is a general code for calculating the time-dependent continuous-energy transport of neutrons. The code is well suited to simulate complicated particle transport because it uses continuous cross section data. It treats an arbitrary three-dimensional configuration of materials in geometric cells. In order to reproduce the real features of this diagnostic the available information on geometry, materials, and constituents was used. The MCNP model of the NPA diagnostic is presented in Fig. 3.1.1-11.

![Figure 3.1.1-11: The MCNPX 3D model of the KR2 diagnostic](image)

The left panel of Fig.11 shows NPA without shielding while right panel shows the diagnostic inserted into the shield.

In Fig. 3.1.1-12 there are neutron spectra calculated with the described NPA model. These calculations have been performed for the case when NPA is in Octant3 of the Torus Hall. It is clearly visible that neutron attenuation takes place. The shielding is sufficient to suppress the neutron flux by a factor of ~15. The 14 MeV flux incident on the detectors is reduced from $1.6 \times 10^{-11}$ to $1.0 \times 10^{12}$ (n/cm$^2$ per JET neutron) (see Fig.12). Total fast flux (>1 MeV) is reduced by factor 8 ($7.2 \times 10^{11}$ to $9.1 \times 10^{12}$), and attenuation improves rapidly at lower energies.
Design of a Backscatter 14 MeV Neutron Time-of-Flight Spectrometer for Experiments at ITER

N. Dzysiuk, C. Hellesen, S. Conroy, G. Ericsson, A. Hjalmarsson, M. Skiba

A backscatter time-of-flight neutron spectrometer (bTOF) is investigated that could potentially be integrated into the Radial Neutron Camera (RNC) at ITER to provide high resolution neutron spectrometry of 14 MeV neutrons. The instrument is based on two sets of scintillators, a first scatterer exposed to a collimated neutron beam and a second detector set placed in the backward direction (see Fig. 3.1.1-13 left). The scintillators of the first set are enriched in deuterium to achieve neutron backscattering.

Through elastic n,d scattering in D1, a fraction of the incoming neutron’s energy is transferred to a deuteron recoil, n + d → d_R + n', which is detected as a scintillator light pulse (“start” signal). The second detector is an ordinary plastic scintillator (D2) placed at a known distance L upstream of D1 and with a suitable hole to allow the collimated neutron “beam” to pass unhindered. D2 records a fraction of the backward scattered neutrons within a fixed solid angle through elastic proton recoils, n,p (“stop” signal). The energy of the initial, incoming
neutron can thus be determined based on geometry and time information \((t_{\text{tof}} = t_{\text{stop}} - t_{\text{start}})\). This spectrometer is rather insensitive to 2.5-MeV neutrons so that 14-MeV neutrons can be measured even in a relatively high flux of 2.5 MeV neutrons. The n,d backscattering geometry has significant advantages at 14 MeV compared to the conventional n,p forward scattering technique. The cross section for n,d elastic scattering is peaked in the backward direction which provides high efficiency (Fig.13). A preliminary design of optimal geometry for the two scintillator sets has been obtained by Monte Carlo simulations based on the MCNPX code.

The spectrometer performance is a tradeoff between resolution and efficiency. Thicker D1 and D2 detectors give higher efficiency but degraded resolution. Similarly, a shorter distance between D1 and D2 \((L)\) gives higher efficiency but degraded resolution. Thus a suitable balance has to be found to assure a performance at the required level. Energy resolution and detection efficiency are the two most crucial characteristics of the system and have to meet the set requirements. In this study the parameter driving the overall design effort is a required energy resolution of \(\Delta E/E < 5\%\) (FWHM). A suppression of accidental background was accomplished by requiring a correlation between the D1 energy deposition and the \(t_{\text{TOF}}\), as given by the kinematics of n,d scattering into the acceptable angular range.

The first results indicate that the bTOF spectrometer could deliver an energy resolution \(\Delta E/E = 4.9\%\) (FWHM) combined with an efficiency of about 0.065%. This was obtained with a geometrical configuration with a first scatterer \((\text{D1}, \text{"start"})\) of total thickness of 4.5 cm, divided into 5 layers of 0.9 cm, and a second detector \((\text{D2}, \text{"stop"})\) with a total thickness of 4 cm, segmented into 4 layers of 1 cm; the distance between D1 and D2 is 165 cm. The spectrometer is characterized by rather compact size, low weight and reasonable cost (similar to the TOFOR spectrometer at JET). Further work is needed for the detailed design of the D1 and D2 assemblies which is necessary to assess the maximum coincidence count rate capability of the system.

Finally, based on the flight time spectra after pulse height selection, the detection efficiency is calculated as the ratio of counts in the selected from the TOF spectrum time window to the number of incident neutrons. The dependencies of the energy resolution \(\Delta E/E (1\sigma)\) and the total detection efficiency on different geometrical parameters are presented in Fig. 3.1.1-14. The resolution was determined with an uncertainty about 3.8 % while the efficiency is defined with an uncertainty of less than 2 %. It was defined as a standard deviation obtained from several Monte Carlo runs. A correction for a D1 edge effect was implemented; this takes into account the fact that deuteron recoils produced close to the upper edge of the D1 scintillator will not deposit their full energy in the detector and thereby fail to fulfill the kinematical requirement. The analysis has been performed in 3 steps:

1. Select a resolution (here \(\Delta E/E (1\sigma) = 2.6\%)\) and mark the corresponding contour line in the plot of D1 thickness versus D1-D2 distance (flight path \(L\)) - Fig. 3.1.1-14a.
2. Map out the resolution contour line from Fig. 3.1.1-14a onto the efficiency contours in Fig. 3.1.1-14b and identify the flight path \(L\) that gives the highest efficiency. In this case \(L=165\) cm gives an efficiency of 0.065%.
3. Figs 3.1.1-14a and 3.1.1-14b are simulated for a D2 thickness of 4 cm. The contours in Figs 3.1.1-14c and 3.1.1-14d are obtained for a 160 cm flight path. An improvement in resolution can be achieved by dividing the D2 in 1 cm segments; by following the red arrows from D2=4cm to D2=1cm we obtain an improvement in resolution dE/E(1σ) from 2.6% to 2.1 %. The latter value corresponds to a dE/E=4.9% (FWHM), i.e., it fall within the set design requirement.

**Figure 3.1.1-14.** Energy resolution and detection efficiencies as functions of detector thicknesses and distance. See text for details.

**JET Vertical Neutron Spectrometer project (JW12-EDT-VNS)**

*Federico Binda, Sean Conroy, Göran Ericsson, Jacob Eriksson, Carl Hellesen, Anders Hjalmarsson*

The Vertical Neutron Spectrometer (VNS) project (JW12-EDT-VNS) concerns the installation of a compact broadband neutron spectrometer at JET in view of a future DT campaign. The spectrometer will be of liquid scintillator type and placed in a vertical line of sight above the KM11 (TOFOR) spectrometer and should be able to measure both 2.5 MeV and 14 MeV neutrons.

The Uppsala University neutron group is involved in development of tools for the forward fitting analysis of the data that will be collected. In preparation for this, a library of neutron spectral components calculated using the TRANSP and CONTROLROOM codes has been
produced. Before the final installation of the VNS detector, this library will be used in the analysis of data from the Compact Neutron Spectrometer (CNS - a detector of the same type of the VNS, already installed at JET but in a tangential line of sight) with the aim of testing the tools for the VNS data analysis.

An example of a spectrum and its components is shown in Figure 3.1.1-15. The project also involves an additional installation of a diamond detector, along the same line of sight as the VNS. The Uppsala University will be involved in a preliminary phase of the diamond detector sub-project during the present DD campaigns. The idea is to install the diamond detector in the back of the KM9 (MPRu) neutron spectrometer, using a space available for test installations.

![Figure 3.1.1-15: Calculated spectral components and total neutron spectrum for the CNS detector, JET pulse #82723.](image)

**TPR performance and conceptual design**

*Anders Hjalmarsson and the Uppsala University Neutron Diagnostic group*

The Thin film Proton Recoil (TPR) neutron spectrometer concept is based on neutron-proton elastic scattering in a thin polyethylene foil. A fraction of collimated incoming neutrons will interact in the foil generating recoil protons. By performing energy measurement on the produced recoil protons, energy information of the incoming neutrons can be deduced. Measurement of the recoil proton energy is obtained by an annular detector positioned around the neutron beam and at some distance down stream the scattering foil.

During 2012 the Monte Carlo code used for performance calculations of a TPR spectrometer has been modified. The modification was implemented to investigate the energy resolution, $\sigma/E$, and detection efficiency, $\varepsilon$, for a TPR operating at atmospheric pressure instead of vacuum. The effect of operating at atmospheric pressure was simulated with the Stopping and Range of Ions in Matter (SRIM) code and the results was incorporated into the TPR Monte Carlo code.

For comparison of $\sigma/E$ and $\varepsilon$ of a TPR operating at atmospheric pressure and vacuum, an annual silicon detector with a thickness of 2mm and fixed inner and outer radii of 24 and 48 mm, respectively was implemented in the model. The polyethylene foil has a fixed area of 10
cm² and the thickness was varied between 0.05 to 0.4 mm. In the calculations the foil-to-detector distance was varied from 150 to 950 mm. A comparison of the performance calculations of operating a TPR at atmospheric pressure and vacuum is shown in Figure 3.1.1-16. In Figure 3.1.1-16a the Pareto frontier corresponding to optimum \( \varepsilon \) for given \( \sigma/E \) is shown for both cases. The vacuum case is represented by points connected with the red line and the atmospheric pressure case is represented with points connected with the black line. In figure 3.1.1-16b the TPR settings of foil thickness versus foil-to-detector distance is shown corresponding to the Pareto frontier shown in Figure 3.1.1-16a.

![Figure 3.1.1-16](image)

**Figure 3.1.1-16.** (a) Monte Carlo results in form of Pareto frontiers for a TPR system operating at atmospheric pressure and vacuum. The Pareto frontiers connected with a black line correspond to atmospheric pressure and the once connected with the red line correspond to the vacuum case. The color coded points in (a) are related to a specific setting of a TPR system as shown in (b), the line color coding is the same as in (a).

Based on the Monte Carlo results a conceptual design of a TPR system has been finalized. In the design a number if design criteria was taken into consideration,

- Vacuum compatibility, the system should be able to run both in air and vacuum conditions.
- Rotating target wheel with four positions for 10 cm² polyethylene foil with different thicknesses, one position for alignment cross hair and one position for a calibration source.
- Detector support mounted on a rail system in order for easy change of detector-to-foil distance together with a cross hair for alignment purposes.
- Annular silicon detector based on the Micron S1 design.
- Flange for turbo pump mounting on the vacuum chamber.
- Flexibility to achieve at least four different operational settings, **high resolution** FWHM/E = 2.5 %, \( \varepsilon=5\times10^{-5} \) cm², **high efficiency** FWHM/E = 10 %, \( \varepsilon=5\times10^{-4} \) cm², “Alpha knock-on”, FWHM/E = 6 %, \( \varepsilon=2\times10^{-4} \) cm² and **DD high efficiency**, FWHM/E = 10 %, \( \varepsilon=1\times10^{-4} \) cm².

The activity on the TPR system modelling and conceptual design was performed under the Topical Group Diagnostics WP11-DIA-03-04-01/VR.
3.1.2 Integrated Tokamak Modelling, ITM

S. Conroy

The work here is related to the calculation of fusion product spectra in arbitrary directions from an underlying set of distribution functions of reactants. The plasma is represented as a set of volume elements (voxels) each containing a distribution of the reacting particles. Random particles from the underlying distributions are reacted and the energy and intensity in a direction determined. The determination is fully relativistic. A previously determined solid angle of the detector under investigation per voxel allows for the finding of the fusion product flux and energy spectrum for any plasma.

The work this year consolidated the progress from last year, moving on from the proof of principle work to the integration into the ITM workflow system. FORTRAN code has been developed which can use an arbitrary line of sight and calculate the neutron flux from Maxwellian plasmas at specific detectors. A second set of routines allow the determination of alpha particle distributions from DT reactions in the plasma.

3.2 Plasma Spectroscopy

3.2.1 Beryllium and the ITER-like Wall at JET

C. Jupén and P. Jönsson

Spectra produced at the JET tokamak by the newly installed Iter Like Wall (ILW) with beryllium and wolfram being wall and divertor coatings have been analysed by means of Czerny Turner spectrometers covering the spectral range from VUV up to the infrared wavelength region. In the case of neutral beryllium, Be I, with the ground state 1s²2s²¹S₀, 2s-2p outer shell excited auto-ionizing states of the 1s²2p3l character lying between 1 and 3 eV above the lowest ionization limit 1s²2s²²S₁/₂ have been analysed according to the degree of auto-ionization. Our calculations show extremely high auto-ionization rates for 2/3 of the total 1s²2p3l ¹L±(L±1) states of Be I being in the range of 10¹⁴ s⁻¹ far too high for observation of these 2/3. This means that no ELMs might be created by means of Be I. Our calculations are in accordance with both observations and calculations by Mohamed et al by their experiment carried out at the ion storage ring CRYRING by studying recombination spectra of Li-like Be ions.

Inner-shell 1s-2p excited auto-ionizing states of Be I, Be II and Be III lying between 118 and 126 eV above their ground states, producing saw-teeth, have indirectly been observed by 2s-2p cascade transitions at 2650.62 Å in Be I, at 3130-3131 Å in Be II and 3722 Å in Be III, respectively. Observations at JET show connection between ELM and saw-teeth. It is worth to know that saw-teeth normally a function of electron temperature, at a certain electron density (nₑ) at which collision rates are overlapping the auto-ionization rates induce oscillation between the counteracting auto-ionization and dielectronic recombination being in phase with ELMs.
4 Concept improvements

4.1 Computational methods and beta limits

J. Scheffel, A. Mirza (PhD student)

In collaboration with
D. D. Schnack, Univ. Wisconsin-Madison, USA

During 2012, we have published important results within the two areas of this project. The first research area concerns confinement limits of the the reversed-field pinch (RFP). In particular, pressure-driven resistive instabilities are studied. These modes are absent in the tokamak and there were earlier indications that heat conduction effects could remove them also in the RFP. The second research area concerns a new method for solving problems with strongly separated time scales related to fusion transport. The time domain of the corresponding partial differential equations is here given a spectral representation. We report on new findings and developments below.

**Theoretical and numerical modelling of RFP confinement**

Relatively limited physical effects have been included in numerical computations of RFP confinement because of the complexity of the strongly nonlinear MHD phenomena and the strongly separated Alfvén and resistive time scales. In this study we extend the understanding of operational limits of confinement, in particular those related to resistive pressure driven instabilities.

Classical linearized resistive magnetohydrodynamic (MHD) stability theory predicts unstable pressure-driven modes even at low plasma beta values for the RFP because of its unfavourable curvature and strong poloidal magnetic field. These resistive g-modes undermine energy confinement and are detrimental to the RFP reactor potential.

In the classical analysis, one aspect is common, which is the usage of the adiabatic energy equation, ignoring the contribution due to thermal conduction effects. However, in more recent analysis, stabilization of pressure-driven modes is demonstrated through inclusion of thermal conductivity. In the present work, we compare the results obtained from both classical and thermal conduction modified boundary layer stability analysis (delta prime method) with those from a time-spectral resistive linearized MHD code (GWRM; see below). Ohmic heating and thermal conduction effects are also included in the calculations. We have found that thermal conduction effects stabilize pressure-driven resistive g-modes only for very low values of plasma beta; see Figure 1. In addition, analytical and numerical investigation of the
equilibrium reveal that, for reactor relevant values of Lundquist numbers $S_0$ and tearing mode stable plasmas, the scaling $\gamma \propto S_0^{-4/5}$ for the growth rate of these modes is weaker than that for the adiabatic case $\gamma \propto S_0^{-3}$. Thus the stabilizing effects, due to heat conduction in the energy balance, on resistive pressure driven modes in the RFP are small at reactor relevant conditions. It is possible, though that the relatively large Larmor radius in the RFP may have a stabilizing effect on the resistive pressure gradient driven instabilities. This will be included in our future work.

**The Generalized Weighted Residual Method (GWRM)**

Temporal and spatial subdomain techniques have been evaluated during 2012 for a time-spectral method for solution of initial-value problems. The most interesting feature of this method is that it solves partial differential initial-boundary value problems non-causally. This means that there are no time step restrictions; indeed time steps are not used at all. For example, linear problems are solved in a single Gauss matrix elimination step and nonlinear problems are solved iteratively in spectral space. The spectral method, called the generalised weighted residual method (GWRM), is a generalisation of weighted residual methods to the time and parameter domains. A semi-analytical multi-variable (in time, spatial dimensions and main parameters) Chebyshev polynomial ansatz is employed, and the problem reduces to determine the coefficients of the ansatz from linear or nonlinear algebraic systems of equations. In order to avoid large memory storage and computational costs, it is preferable to subdivide the temporal and spatial domains into subdomains. Methods and examples to show how this can be achieved are now published.

Two example applications are used; the nonlinear Burger equation and a rather demanding system of 14 coupled resistive MHD equations, including parallel and perpendicular heat conductivity (see above). Three different methods employing spatial subdomains were introduced. Whereas the first method involves simultaneous solution of all, global Chebyshev coefficients, the other two have the potential of being computationally less demanding because their corresponding Chebyshev coefficient matrix equations are iterated separately at each iteration step. It was found that temporal subdomains are essential for efficiency for both high accuracy and extended time computations. Solving a stiff ordinary differential equation it was shown that an adaptive GWRM time domain formulation compared well with commercial software both regarding efficiency and accuracy.

During 2012, preparations have been made for application of the GWRM to problems in transport problems including turbulence, where the potential of the method will be fully explored. In collaboration with Prof. Hans Nordman (Chalmers, Gothenburg) a set of nonlinear drift wave turbulence equations, developed for studying ion temperature gradient driven turbulence in tokamaks, are presently being solved.

**Publications section 4.1**

**Peer reviewed journals**


**Presentations at international conferences and workshops**


5 Emerging technology

5.1 Development of laser techniques for in-situ wall characterisation

P. Petersson and M. Rubel

Plasma-wall interaction processes will become much more important in ITER and future power plants due to the large increase of particle fluence on the wall, the higher energy deposition during transients and the use of tritium. ITER reaches in few pulses the particle fluence comparable to that of present large devices within about 1 operational year, and about 100 times higher plasma energy content. The main issues are the induced wall erosion and the associated material deposition, which determine the lifetime of internal components and the in vessel T inventory, and thus the availability of the device.

Laser techniques are promising candidates for in situ wall characterization. This paper summarizes results of an R&D program performed in the EU to evaluate their perspectives for ITER and future reactors. Three different techniques have been analysed with respect to their applicability and limitations with the main objective to develop a conceptual design of a laser based monitor integrated into an ITER port plug. The basic concept of laser-based in situ diagnostics of first wall surfaces in fusion devices is to heat small spots (∼ 0.5-1 cm² in ITER) on the first wall by intensive laser radiation and to monitor the released hydrogen isotopes and the ablated wall material by spectroscopy, either during or between plasma discharges. For the methods discussed in this contribution, the laser light is guided from outside the biological shield by a mirror system through a window onto the wall. In Laser Induced Desorption Spectroscopy (LIDS) laser pulses of 1.5-5 ms duration thermally desorb the retained fuel from the irradiated wall spot. The released hydrogen is spectroscopically detected from characteristic hydrogen line radiation in the edge of the running tokamak plasma. In Laser Induced Ablation Spectroscopy (LIAS) laser pulses in the ns range ablate the material from the wall spot and the ablated material together with the incorporated fuel is detected in a similar way as in LIDS in the edge plasma. The third method, Laser Induced Breakdown Spectroscopy (LIBS), uses a ns laser pulse to ablate material (similar conditions as in LIAS) and to produce a laser induced plasma whose characteristic line radiation is used as a fingerprint of the composition of the ablated material. LIBS can be used with and without plasma in between discharges, in high vacuum (< 10⁻⁵ mbar) and also under high magnetic field conditions (5T in ITER).

A broad international effort has been taken to develop and test the techniques. One part of EU programme has been related to a proper characterisation of targets before and after irradiation with laser beams. VR has been involved the study of morphology changes on PFC surfaces from the TEXTOR tokamak and special laboratory-prepared coatings irradiated by laser pulses of different power. The layers deposited on tungsten (polished and non-polished) contained tungsten, carbon and co-deposited deuterium (up to 10% at). This also included reference targets with diamond-like (DLC) tungsten-carbon-aluminum (W-C-Al) coatings used to optimize the irradiation conditions and to facilitate calibration in studies of mixed layers. Two aspects of laser–material interactions were determined: (a) the efficiency of fuel removal; (b) the damage caused by laser pulses of various energy both to the coatings and substrates. The latter included dust generation. Materials were examined before and after
irradiation using high energy ion beam and microscopy methods. Species liberated from surfaces to the gas phase were determined by optical spectroscopy. Several results are summarized below.

(a) Laser-induced desorption with a power density of 20-80 kW cm$^{-2}$ results in deuterium removal and does not cause melting of the layer, but the lateral pattern is not uniform.

(b) The desorption from carbon substrates is complete, while the incomplete release was observed from tungsten targets. Desorption profiles were measured with nuclear reaction analysis.

(c) In laser-induced ablation with power density of 1-2 GW cm$^{-2}$ on the area of about 0.2 cm$^2$ the layers are partly removed and partly fused with the substrate material. Melting and cracking also leads to the coating detachment in the vicinity of the irradiated spot.

**Publications section 5.1**

**Presentations at international conferences and workshops**


**5.2 Modelling of ODS steels in thermal and irradiation conditions**

**P. Olsson, A. Claisse**

Ferritic/Martensitic (F/M) steels are considered as candidate materials for application in future fusion reactor systems. However, in order to withstand the intense operating environment, standard F/M steels need to be modified. Steels with embedded dispersed nano-metric oxides – Oxide Dispersion Strengthened (ODS) steels – have been shown to meet most of the design criteria for a fusion reactor. However, these nano-composite steels are relatively new types of materials and have not yet been subjected to long enough tests of their durability, especially since they are under continued development. Modeling of the basic interactions of radiation induced point defects and the solutes present in the steel due to the presence of the oxides could give clues to aid the development and to make tentative predictions on long term behavior of the steels under irradiation.

KTH follows an ab initio based scheme for atomistic modeling of the ODS particle behavior in steel matrices under neutron irradiation conditions. The starting point is to determine what
the basic interaction parameters are between ODS solutes in an iron matrix and to expand from there the parameter set, in order to obtain as realistic a picture as possible. Electronic structure theory can provide quantitative insight into the nano-scale interactions that govern the microstructure evolution over long times under irradiation. These interactions can be made into a database for larger scale stochastic modeling schemes, such as atomistic kinetic Monte-Carlo (KMC), where the nucleation and formation, evolution, disintegration etc. of the oxide particles can be simulated.

We have determined a database of basic interaction parameters for ODS relevant solutes in bcc Fe, ODS solute interactions with point defects and ODS solute migration barriers. We have developed a KMC model that can be used to simulate the evolution of the material under both thermal and irradiation conditions.

The most important finding is the determination of the crucial role of vacancies in the stabilization of the ODS clusters. Without a supersaturation of vacancies during nucleation, the clusters will be planar and not spherical. This is due to the oxygen-oxygen interaction in the bcc Fe matrix, see Figure 1, where the diametrically differently interacting 4a and 4b configurations forces any ODS cluster to nucleate in a planar form, unless a vacancy is present in the center.

![Figure 1. The DFT predicted oxygen-oxygen interaction in bcc Fe. The blue circles highlight the stable binding, planar oriented, configurations and the red circle the strongly repulsive configuration.](image)

**Publications section 5.2**

**Peer reviewed journals**


5.3 High purity ODS-tungsten materials

M. Muhammed, S. Wahlberg, M. A. Yar.

Tungsten based materials are being considered as candidates for armour material in experimental (ITER) and commercial fusion reactor, but poor material properties are major hurdles. The less ductile nature or brittleness of tungsten materials is an obstacle during their processing as well as for their deployment in such extreme environment with high temperature and neutron radiation.

Material’s properties are directly related to its composition (purity) and microstructure. In recent years, some research has showed that mechanical properties in tungsten can be improved through grain-refinement. Further, nanostructured materials also show higher radiation resistance. Therefore research has been focused on the development of nanostructured but thermally stable oxide dispersed strengthened (ODS) tungsten composites with reduced brittleness. On one hand, plasma-wall interaction studies are progressive for evaluation of different tungsten based materials by high heat load testing and neutron radiation damage. On the other hand, on the basis of results, research is also proceeding to develop new techniques for fabrication and processing of tungsten based materials.

KTH is contributing for development of new powder metallurgy routes to fabricate high purity tungsten based materials with tailored microstructure. In this project we developed specific chemical powder metallurgical methods for the fabrication of nanoscale tungsten based powders.

Various chemical routes have been developed and studied for fabrication of both La and Y doped W powders and ODS-W composites sintered by spark plasma process (SPS) have been characterized using high resolution electron microscopy and micro-mechanical testing. Major findings have been published in well know journals of related field as mentioned below. Among various powder fabrication methods, tungstic-acid based routes produced final material (W-Y₂O₃ 1 wt.%) with desired microstructure and better mechanical properties. Elastic and fracture properties using micro-mechanical indentation have been studied to determine the effects of grain refinement. Final evaluation of developed material is performed by thermal-shock testing in hot cell-electron beam facility at Forschungszentrum–Jülich, Germany. Major achievements regarding this research topic are listed below;

- Novel chemical routes have been developed to fabricate nanostructured tungsten powders and ODS-W composites with high homogeneity and uniform dispersion of oxides.
- Optimization of sintering (SPS) conditions for high density ODS-W-Y₂O₃ composites.
- Coarse grain W-Y₂O₃ (1 %wt.) material demonstrated better micro-mechanical properties as compared to fine grain material.
- New mixed oxides of W-O-Y identified during HR-SEM/TEM analysis.
- Developed material evaluated for armour material application.
- Evaluation by high heat load testing of developed W- 1 wt. % Y₂O₃ materials, suggestion are given to reduce the oxide contents.
Developed W-Y₂O₃ Composite

Material after thermal-shock testing.

Publications section 5.3

Peer reviewed journals


6 EFDA JET

The Swedish Association is heavily involved in the JET activity. Most aspects of the scientific programme in support of JET have been included in earlier sections of this Report covering the activities within the Work Programme of the Association. In this section the contractual basis for the JET activity is presented in more detail. In addition, some aspects of the involvement in the JET Enhancements and Task Force Fusion Technology, not covered elsewhere, are described.

The major upgrade of the JET machine to install the “ITER-like wall” was successfully concluded in mid 2011. JET campaigns started in August 2011 with a programme of mixed restart and experiments. After about one year of operation in experimental campaigns C28-C30c, JET went into shutdown in the end of July 2012. Work in 2012 (C29-C30c) covered the period Jan 3 – July 27 and has been focused on continued careful exploitation of the newly installed ITER-like wall. Research groups from VR participated in a number of active, parasitic and back-up experiments. VR scientists also acted as Scientific Coordinators, Diagnostic Coordinators and control room experts for various diagnostic systems. The VR commitment to the JET experimental campaigns in 2012 amounts to about 697 person days (ST Order days and some JET Notifications). In addition, VR scientists conducted work in support of the JET campaigns under Notifications at their home institutes for about 122 person-weeks.

The Swedish Association is involved in the JET Enhancement Programme for DT operations in the areas of “Neutral Particle Analyzer upgrade” and “Vertical Neutron spectrometer”.

The Swedish RU is involved in the JET Fusion Technology programme in several areas; “Material transport and erosion/deposition”, “Microbeam analysis and SEM/EDX analysis on cross section”, “Be-10 experiment”, “First test mirror at JET” and “Fuel ion ratio determination”.

The involvements of the Swedish RU in the EFDA JET Notifications and Orders as well as in JET Task Force Fusion Technology in 2011 are summarized in Table 6.1.

<table>
<thead>
<tr>
<th>EFDA Task Agreement</th>
<th>Title / Subject</th>
<th>Key persons, Groups</th>
<th>Period (Notification/Orders)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JW12-FT-JET</td>
<td>FT-3.71 Material transport erosion/deposition</td>
<td>KTH (Rubel)</td>
<td>2012 (Baseline support)</td>
</tr>
<tr>
<td>---</td>
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</tr>
<tr>
<td></td>
<td>FT-3.74 Microbeam analysis and SEM/EDX analysis on cross section</td>
<td>KTH (Bergsåker)</td>
<td>2012 (Notif: 10 kEUR, Orders 2 kEUR)</td>
</tr>
<tr>
<td></td>
<td>FT-3.75 Be-10 experiment</td>
<td>KTH (Bergsåker)</td>
<td>2012 (Notif: 10 kEUR, Orders 3 kEUR)</td>
</tr>
<tr>
<td></td>
<td>FT-4.24 First mirror tests at JET</td>
<td>KTH (Rubel)</td>
<td>2012 (Notif: 15 kEUR, Orders 15 kEUR)</td>
</tr>
<tr>
<td></td>
<td>FT-5.44 Fuel ion ratio determination</td>
<td>UU (Eriksson, Hellesen)</td>
<td>2012 (1 py Baseline support) Ext. to 2013</td>
</tr>
<tr>
<td></td>
<td>JW12-EDT-VNS: Vertical Neutron Spectrometer</td>
<td>UU (Eriksson, Hellesen, Binda)</td>
<td>Continuing in 2013 and beyond</td>
</tr>
</tbody>
</table>

### 6.1 EFDA JET Enhancements

Two tasks within the JET Enhancement Task Agreement (JW12-EDT) were carried out by the Uppsala University Neutron Diagnostic group. They are described in Section 3.2 “Neutron Diagnostics”, under headline “Modelling the neutron and gamma fluencies for the low energy Neutral Particle Analyzer at JET (JW12-EDT-ISU)” and headline “JET Vertical Neutron Spectrometer project (JW12-EDT-VNS)”.

### 6.2 Fusion Technology at JET

#### 6.2.1 First Mirror Test

*M. Rubel, D. Ivanova, P. Petersson*

Windows and so-called first mirrors are essential plasma-facing components (PFC) in all optical spectroscopy and imaging systems used for plasma diagnosis both in laboratory applications and in controlled fusion devices. The installation of more than eighty metallic first mirrors is planned in the International Thermonuclear Experimental Reactor (ITER). Detailed knowledge of their performance is crucial for reliable controlling of plasma operation thus having ultimate impact on the reactor safety and the quality of scientific work. Plasma-wall interaction (PGI) phenomena leading to material erosion and migration may be decisive for the state of mirror surfaces and the degradation of their properties. To recognize the extent of changes a thorough First Mirror Test (FMT) has been carried out at the JET tokamak (Joint European Torus) on the request of the ITER Design Team. The major goals of the test are to assess the optical performance, i.e. reflectivity, and – by detailed surface analyses – to determine the surface morphology in order to understand the causes of reflectivity changes.
Up to date, FMT has been the most comprehensive study program of mirror behaviour in fusion environments. JET is the most appropriate device for such activity because of the best possible today proximity to reactor conditions: divertor configuration, high power and long pulse operation in the presence of beryllium (Be) on the first wall. Both short- and long-term exposures can be performed during selected pulses or entire campaigns, respectively. The test has comprised a series of steps to ensure maximum outcome for ITER: (i) selection of materials for mirrors, (ii) selection of relevant location on the main chamber wall and in the divertor of JET, (iii) design and manufacture of mirror carriers, (iv) pre-characterisation of reflectivity and surface properties of the tested mirrors, (v) installation of the optical system for studies of mirrors contaminated by beryllium and tritium during the exposure in JET, (vi) detailed reflectivity and surface studies of the exposed mirrors, (vii) the test of photonic and mechanical cleaning methods. The test units with mirrors are installed in JET in the vicinity of other erosion-deposition probes in order to enhance the information on the effects of PWI processes.

The test in JET with carbon walls was completed in 2009. The next phase of the test was continued in JET-ILW and the first step of the program was finished in 2012. Two major types of experiments were done under ILW conditions with test mirrors: short- and long-term exposures. The short-term exposure was accomplished for three polycrystalline Mo (Mo-poly) mirrors inserted from top of the torus using the reciprocating probe as a carrier. The probe head was modified for that purpose: stainless steel with three channels for cylindrical mirrors. Images in Figure 6.2.1-1 (a-d) show details of the probe head assembly, the entire 505 mm long probe and its position in JET indicating the maximum radial position with respect to mushroom limiters. The specimens were placed 5-7 cm in the shadow of mushroom limiters and exposed during 71 pulses for approximately 1200 s (0.3 h).

Before and after exposure mirrors underwent detailed surface analysis using optical techniques to determine total and specular reflectivity, microscopy for surface topography, sputter-assisted X-ray photoelectron spectroscopy (XPS) and a number of ion beam analysis (IBA) including accelerator-based methods and secondary ion mass spectrometry (SIMS).

Figure 6.2.1-1: The assembly of mirrors on the reciprocating probe head: (a) holder with three installed mirrors; (b) the stainless steel probe head with installed mirrors; (c) position in JET; (d) entire probe assembly.
All specimens exposed in the main chamber, both the long-term samples from the midplane holders on the outer wall and the short-term probes, look clean and shiny after exposure. Plots in Fig. 6.2.1-2 show reflectivity of the mirrors after exposure using the reciprocating probe. Data before and after exposure are plotted. One may infer that no optical degradation occurred. On the surface there are only minor amounts of carbon, nitrogen and oxygen as detected by HIERDA. The concentration of carbon does not exceed $4 \times 10^{15}$ at cm$^{-2}$ and nitrogen is below $1.5 \times 10^{15}$ cm$^{-2}$. The layer thickness does not exceed 10 nm. No beryllium has been found. Similar results have been obtained after long-term exposure of the mirrors from main chamber wall. These data are important for development of diagnostic system in ITER.

![Figure 6.2.1-2: Reflectivity of mirrors after short-term exposure using a reciprocating probe head as a holder. Data before and after exposure are plotted.](image)

### 6.2.2 Materials migration studies in JET using microanalysis and $^{10}$Be marker

**H. Bergsåker, I. Bykov, P. Petersson, G. Possnert**

The erosion and migration of first wall material gives rise to several critical plasma-surface interactions issues for ITER and for other future big and high duty cycle fusion devices. The balance between erosion and deposition at different surfaces in the device determines the net erosion rate and consequently the life time of the plasma facing component. Deposition of thick layers at some surfaces is linked with co-deposition of fuel and consequently to the tritium inventory in a reactor. The build-up of thick deposited layers also entails dust production due to subsequent breaking and flaking of the layers. Materials migration and mixing may also modify the erosion rate and other surface properties. To study these issues at JET, microscopy, ion beam analysis techniques and SIMS have been frequently used for post mortem analysis of plasma facing surfaces. In JET with carbon wall, layers with thicknesses up to about one mm are produced in the divertor over extended periods of plasma operation.

Microbeam analysis reveals that deuterium trapping at the divertor surfaces is nonuniform on a microscopic scale. Figure 6.2.2-2 shows an example of locally enhanced Deuterium trapping, which can be associated with structural features. Figure 6.2.2-3 shows Be segregated at the layer surface, while D is found mainly within a pit in the substrate.

The Be distribution can be explained by negligible physical sputtering of Be due to the low electron temperature, whereas carbon is eroded chemically. The higher D-concentration
within the pit in the substrate is probably due to reduced ion flux in such geometrically protected pockets. Locally enhanced D-retention has also been found in dust particles that have been buried within the deposited layers.

An isotopic marker experiment has been designed to study the migration of beryllium from the main chamber to the divertor in JET with ITER-like wall. One of the beryllium tiles at the inner wall in JET has been enriched with $^{10}$Be through irradiation with thermal neutrons in a fission reactor. The tile was installed in JET in 2011 and exposed to the plasma throughout the first period of operations with ITER-like wall. Figure 6.2.2-4 shows a numerical simulation predicting the 3D large scale redistribution of the marker using the ASCOT code, with a particular set of assumptions.

Using the extremely sensitive accelerator mass spectrometry (AMS) method, the $^{10}$Be content in re-deposited beryllium layers all over the JET can be investigated after the first JET shut down in summer 2012, down to five orders of magnitude dilution with respect to the primary marker tile. Several numerical models exist for the materials migration and mixing problem in JET with ITER-like wall and the marker experiment is designed for comparison with the numerical models. During the shutdown from July 2012 samples could be taken from the surfaces for $^{10}$Be analysis by accelerator mass spectrometry (AMS). Due to the limited
availability of Be tiles for analysis, a new, non-destructive sampling method was developed. Samples of about 200 µg beryllium had to be taken at every sampled position. It was found that the sampling could most conveniently be done using SiC abrasive paper. The parameters were optimized and the method, including sample handling and transport could be approved for JET use. In the first version, sampling is made in the Be handling facility at JET, not in the JET vessel, but the sampled tiles can go back into the vessel again and continue to be used after sampling.

**Figure 6.2.2-5.** Surface sampling with abrasive paper. About 4 µm thick samples can be taken.

**Figure 6.2.2-6.** Castellated IWGL tile with sampled spots visible.

Following AMS analysis of at least 60 of the samples from the main chamber, the marker redistribution is to be compared with the ASCOT simulations. Comparison can also be made...
with 3D ERO simulations of the local erosion and deposition around the primary source tile. Later on, complete tiles from the divertor and from the main chamber will also become available for analysis, and depending on the results the data may also be comparable with WALLDYN simulations, including a more sophisticated treatment of surface processes, but with less elaborate geometry (2D).

**Publications section 6.2.2**

*Peer reviewed journals*


*Presentations at international conferences and workshops*

2. Poster presentation: “Microanalysis of deposited layers in the divertor of JET following operations with carbon wall” H. Bergsåker et al. 20th International Conference on Plasma-Surface Interactions in Controlled Fusion Devices, Aachen, May 2012


**6.2.3 Developments in neutron diagnostic methods**

A task in neutron diagnostics within the TF-FT program was carried out by the Uppsala University Neutron Diagnostic group. The work is described in Section 3.2 (Neutron Diagnostics” under headline “Fuel ion ratio measurements with neutron emission spectrometry”.


7 EFDA non-JET work: ITM-TF, “ITER Physics” and PPP&T

The non-JET activities of EFDA are structured within the Departments for “ITER Physics” and “Power Plant Physics and Technology” (PPP&T). Within the EFDA Coordinated Activities in ITER Physics there is one Task Force with specified activity in the Work Programme: Task Force Integrated Tokamak Modelling (TF-ITM). The rest of the activities are structured into 11 cross-cutting topical research areas, which each involve several of the Task Forces and Topical Groups previously active within the programme.

The topical research areas are given in Table 7.1, which also includes the VR contact person for each area. VR is active in almost all of these activities (TF-ITM and 9 out of 11 Topical research areas). In particular, the Deputy TF-ITM Leader for ICRH Heating, Current Drive and Fast Particles is Thomas Johnson (KTH), Deputy TF-ITM Leader for MHD stability chain is Dimity Yadikin (Chalmers) and the Deputy TF-PWI Leader is Marek Rubel (KTH). Table 2.2 gives an overview of the activity in the Task Force Integrated Tokamak Modelling:

In addition, VR has contributed significantly to the activities within the EFDA programme for Goal Oriented Training in Theory (GOTiT). VR also had two researchers in the Fusion Researcher Fellowship programme, Sara Moradi and Yevgen Kazakov, both from Chalmers.

<table>
<thead>
<tr>
<th>Nb</th>
<th>Topical area description</th>
<th>Nb</th>
<th>Topical area description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Prediction of Material Migration and Mixed Material</td>
<td>A7</td>
<td>Disruptions, prediction, avoidance, mitigation and</td>
</tr>
<tr>
<td></td>
<td>Formation</td>
<td></td>
<td>consequences</td>
</tr>
<tr>
<td></td>
<td>Marek Rubel (KTH)</td>
<td></td>
<td>Tünde Fülöp (Chalmers)</td>
</tr>
<tr>
<td>A2</td>
<td>Shaping and controlling performance limiting</td>
<td>A8</td>
<td>Physics of the Pedestal and H-mode</td>
</tr>
<tr>
<td></td>
<td>instabilities</td>
<td></td>
<td>Tünde Fülöp (Chalmers)</td>
</tr>
<tr>
<td></td>
<td>Per Brunsell (KTH)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A3</td>
<td>Fuel Retention and Removal</td>
<td>A9</td>
<td>Fast Particles</td>
</tr>
<tr>
<td></td>
<td>Marek Rubel (KTH)</td>
<td></td>
<td>Mietek Lisak (Chalmers)</td>
</tr>
</tbody>
</table>
A4  Plasma rotation  
Thomas Johnson (KTH)  

A10  Particle transport, fuelling and Inner Fuel Cycle modelling  
Hans Nordman (Chalmers)  

A5  Core electron heat transport and multi-scale physics  
Pär Strand (Chalmers)  

A11  Operation with metallic plasma facing components including High Power ICRH  
Yevgen Kazakov (Chalmers)  

A6  Pedestal instabilities (ELMs), Mitigation and Heat loads  
Lorenzo Frassinetti (KTH)  

7.1 Task Force Integrated Tokamak Modeling

Table 7.2 gives an overview of the activity in the Task Force Integrated Tokamak Modelling:

<table>
<thead>
<tr>
<th>Activity</th>
<th>Description</th>
<th>Commitment (in PY)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WP12-ITM-TFL Task Force Leadership</td>
<td>T.Johnson, KTH, Deputy TFL-IMP5 D.Yadikin, Chalm., Dpt TFL-IMP12</td>
<td>0.25 priority 0.25 priority</td>
</tr>
<tr>
<td>WP12-ITM-EDRG Experiments and Diagnostics ...</td>
<td>ACT3 Synthetic diagnostic (Uppsala University)</td>
<td>0.20 priority</td>
</tr>
<tr>
<td>WP12-ITM-IMP12 MHD Equilibrium, stability and disruptions</td>
<td>ACT1 Int. CarMa code .. (Chalmers) ACT1 Control workflow (Chalmers) ACT3 Ver., valid. IMP12 (Chalmers)</td>
<td>0.15 priority 0.15 priority 0.25 priority</td>
</tr>
<tr>
<td>WP12-ITM-IMP3 Transport code and discharge ...</td>
<td>ACT1 Maint., dev.,verify (Chalmers)</td>
<td>0.08 priority</td>
</tr>
<tr>
<td>WP12-ITM-IMP4 Transport processes and Micro ..</td>
<td>ACT4 Maint. &amp; standards (Chalmers)</td>
<td>0.08 baseline</td>
</tr>
<tr>
<td>WP12-ITM-IMP5 Heating, Current Drive, Fast Particles</td>
<td>ACT1 Creation, test, bench-marking of Kepler Actors (KTH) ACT1 ARENA code int. (Chalmers) ACT1 Benchmarking (UU) ACT2 Integr. of modules (KTH) ACT3 Dev &amp; integr. (KTH) ACT4 Fast part. codes (KTH)</td>
<td>0.30 baseline 0.05 priority 0.50 baseline 0.20 baseline 0.20 priority 0.25 priority 0.45 baseline 0.10 priority 0.10 baseline</td>
</tr>
<tr>
<td>WP12-ITM-ISM ITER Scenario Modelling</td>
<td>ACT1 Support validation (Chalmers) ACT2 Development scen. (Chalmers)</td>
<td>0.30 baseline 0.50 baseline</td>
</tr>
<tr>
<td>TOTAL 2012</td>
<td></td>
<td>2.01 PY priority 2.05 PY baseline</td>
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</tbody>
</table>
7.2 Topical areas in “ITER Physics”

Table 7.3 gives an overview of the activity in the EFDA department for ITER Physics.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Description</th>
<th>Commitment (PY) (k€ for hardware)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WP12-IPH-A01-2-07</td>
<td>Properties of material mixture ... (KTH-PWI)</td>
<td>1.10 baseline 0.70 priority</td>
</tr>
<tr>
<td>WP12-IPH-A02-2-2-01</td>
<td>Dev. of system identification tools for RWM ... (KTH-MHD)</td>
<td>0.30 priority</td>
</tr>
<tr>
<td>WP12-IPH-A02-2-2-04</td>
<td>Assess impact of coil coverage for RWM feedb cntrl ... (KTH-MHD)</td>
<td>0.20 priority</td>
</tr>
<tr>
<td>WP12-IPH-A02-2-3-01</td>
<td>Study influence of external 3D fields on MHD ... (KTH-MHD)</td>
<td>0.20 baseline 0.40 priority</td>
</tr>
<tr>
<td>WP12-IPH-A02-2-3-02</td>
<td>Error field assessment and correction ... (KTH-MHD)</td>
<td>0.20 baseline 0.35 priority</td>
</tr>
<tr>
<td>WP12-IPH-A03-2-07</td>
<td>Studies of re-saturation effects after photonic ... (KTH-PWI)</td>
<td>0.40 baseline 0.20 priority 8 k€ hardw. priority</td>
</tr>
<tr>
<td>WP12-IPH-A03-2-08</td>
<td>Characterization of laser ablated dust, ... (KTH-PWI)</td>
<td>0.10 baseline</td>
</tr>
<tr>
<td>WP12-IPH-A03-2-13</td>
<td>Optical and microscopic investigation of dust ... (KTH-PWI)</td>
<td>0.05 baseline</td>
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<tr>
<td>WP12-IPH-A03-2-17</td>
<td>Dust production by fuel removal methods: photonic ... (KTH-PWI)</td>
<td>0.50 baseline 0.20 priority 8 k€ hardw. priority</td>
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<td>WP12-IPH-A03-2-18</td>
<td>Time resolved dust collection and dust characteriz ... (KTH-PWI)</td>
<td>0.50 baseline</td>
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<tr>
<td>WP12-IPH-A03-2-21</td>
<td>Provide experimental input for multi machine ... (KTH-PWI)</td>
<td>0.05 baseline</td>
</tr>
<tr>
<td>WP12-IPH-A03-3-07</td>
<td>Study of fuel removal efficiency and homogeneity... (KTH-PWI)</td>
<td>0.45 baseline 0.15 priority 10 k€ hardw. priority</td>
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<tr>
<td>WP12-IPH-A04-1-05</td>
<td>Study the relation between mode conversion and rotation</td>
<td>0.15 baseline</td>
</tr>
<tr>
<td>WP12-IPH-A04-2-09</td>
<td>Stiffness of ion temperature with influence of rotation</td>
<td>0.40 baseline</td>
</tr>
<tr>
<td>WP12-IPH-A06-2-13</td>
<td>Experimental study of RMP penetration and screening in EXTRAP T2R</td>
<td>0.10 baseline 0.20 priority</td>
</tr>
<tr>
<td>WP12-IPH-A06-2-15</td>
<td>Study the influence of RMPs on</td>
<td>0.20 baseline</td>
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</table>
7.3 Power Plant Physics and Technology

The PPPT work is structures into six different Project Areas: System Design Integration (SYS), Power Exhaust Physics and Integration Studies (PEX), Design Tools and Methodologies (DTM), Design Assessment Studies (DAS), Materials (MAT) and Socio-Economic Research in Fusion (SERF). The VR Association has a small but increasing activity within a few topics in this field. In addition, the Association participates in the activity on Emerging Technology System Integration, Dust and Tritium Management.

Table 7.4 gives an overview of activity in the EFDA Coordinated Activities in PPPT.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Description</th>
<th>Commitment (in PY)</th>
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<tr>
<td>WP12-MAT-01-HHFM Tungsten and Tungsten Alloys Development</td>
<td>03/02 Armour materials optimization (KTH, Functional materials)</td>
<td>2.80 baseline</td>
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<tr>
<td>WP12-MAT-01-IREMEV-01-01</td>
<td>Phase Stability and Bonding (KTH, Reactor physics)</td>
<td>0.15 priority</td>
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<tr>
<td>WP12-MAT-01-IREMEV-01-02</td>
<td>Evolution of microstructure (KTH, Reactor physics)</td>
<td>0.10 priority</td>
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<tr>
<td>WP12-DAS-HCD-IC-02-01</td>
<td>Revisiting the low harmonics range for the DEMO 2 case</td>
<td>0.10 priority</td>
</tr>
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</table>
7.4 Goal Oriented Training in Theory (GOTiT)

Table 7.5 gives an overview of VR participation in Goal Oriented Training in Theory as included in definitive version of task agreement, 14 July, 2008, which now has been extended to 30 June 2012. The activity is conducted by personnel at KTH, Stockholm.

<table>
<thead>
<tr>
<th>Activity</th>
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<tbody>
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<td>WP08-GOT-GOTiT</td>
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<td>0.4 (mentoring) 2.0 (trainees)</td>
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<tr>
<td></td>
<td>3.1.1.2 MHD, waves fast particles – ICRH (KTH)</td>
<td></td>
</tr>
<tr>
<td>TOTAL 2008 - 2012</td>
<td></td>
<td>2.4</td>
</tr>
</tbody>
</table>

7.5 Programme for Fusion Researcher Fellowships

Table 7.8 gives an overview of VR participation in the programme for Fusion Researcher Fellowships in 2012. Both Fellows are active at Chalmers Technical University.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Description</th>
<th>Commitment (in ppy, prelim.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WP11-FRF-VR/Moradi, S. Fusion Researcher Fellowship July 2011 – June 2013</td>
<td>Transport study of intrinsic and seeded impurities through scenario modelling</td>
<td>1.0 (131 kEUR total)</td>
</tr>
<tr>
<td>WP12-FRF-VR/Kazakov, Y. Fusion Researcher Fellowship April 2012 – March 2014</td>
<td>Efficient heating and decontamination: mutual effect of ICRH and impurities in tokamaks</td>
<td>1.0 (131 kEUR total)</td>
</tr>
<tr>
<td>TOTAL in 2012</td>
<td></td>
<td>2.0</td>
</tr>
</tbody>
</table>
8 ITPA and IEA activities

8.1 Overview of ITPA activities

The International Tokamak Physics Activity (ITPA) provides a framework for internationally coordinated fusion research activities. The ITPA continues the tokamak physics R&D activities that have been conducted on an international level for many years. This has resulted in establishing a broad physics basis essential for the ITER design and useful for all fusion programs and for progress toward fusion energy generally.

The ITPA operates under the auspices of ITER. The Participants in the ITPA are the Members of ITER. The organizational structure of the ITPA consists of a Coordinating Committee (CC) and several Topical Physics Groups. The role of the ITPA Coordinating Committee is to oversee the Topical Physics Groups in conducting their tasks and to interface the ITPA with the ITER Organization. It is composed of three representatives from each Participant and ITER.

Representatives of the ITPA and the experimental fusion facilities meet annually with the International Energy Agency (IEA) to encourage collaborations. The IEA sponsors several Implementing Agreements that foster joint collaborations. The resulting process has grown to involve all the IEA implementing agreements and nearly all tokamaks.

Each year, the ITPA prepares a report on the previous year and a proposal for a set of joint experiments for the coming year. The proposals are discussed with the world's tokamak program leaders, and commitments are sought from the various tokamak program leaders. An international participant team is identified and a spokesperson defined. The tokamak leaders seek to implement these joint experiments within their normal experimental planning processes.

Since 2008 there has been an increased focus on addressing remaining uncertainties in the physics related to ITER design and operation as well as issues relating to a future electricity-producing power plant (DEMO). The Swedish Research Unit has participation in the following ITPA Topical Groups:

- Diagnostics
- MHD, Disruptions & Control
- Scrape Off Layer and Divertor
- Transport and Confinement

See respective Sections for the scientific information related to the Swedish ITPA activities.

J. Weiland (Chalmers) participated in the meeting of the ITPA “Transport and Confinement” topical group in Hefei, China, April 1-5 2012. One presentation was given, which presents simulation results of both the internal barrier and edge barrier on JET pulse #69454. These simulations are self-consistent including ion and electron temperatures as well as poloidal and toroidal momenta. All traces of barriers were removed from the initial conditions. The internal barrier was triggered by the spin up of poloidal momentum (Reynolds stress) which agreed well with the experimental spin up. Also the edge barrier was triggered by a spin up of poloidal momentum but here we do not have experimental data:
Within the ITPA on MHD, **D.Yadykin (Chalmers)** has contributed to Working Group 12 on “3d distortion of the plasma boundary in the presence of saturated MHD instabilities or applied resonant magnetic perturbations”. In this project, studies of the 3D distortion of the plasma boundary were performed at JET when external magnetic perturbations are applied. It was found that the plasma boundary displacement has linear dependence on the current in the external coils (in agreement with the previously obtained numerical predictions). Presentation for the WG 12 final meeting is in preparation.

In the IEA Implementing Agreement on Fusion Nuclear Reactor Technology (Annex II) **M.Rubel (KTH)** is Leader in Subtask 3, “Plasma-Surface Interaction including Tritium Retention and Tritium Removal”. A presentation was given at the yearly Ex-Co meeting:

- “Tritium retention and removal studies – recent progress”, M. Rubel, H. Ding, R. Dorner, Suk-Ho Hong, S. Suzuki, Executive Committee Meeting of IEA Implementing Agreement on Fusion Reactor Nuclear Technology, Liege, Belgium, September 2012

**M.Rubel** is also a member of the IAEA Coordinated Research Project on Dust in tokamaks.

**S.Conroy and G.Ericsson** of the Uppsala University – Neutron Diagnostics group are members of the Neutron Working Group within the ITPA-Diagnostics.
9 Other activities

9.1 Training and education

**PhD training**
The physics programme of the Swedish Fusion Research Unit is university based. There are PhD programmes at Chalmers, KTH and UU. During 2012 there were 22 PhD students included in the Research Unit. On average there are about 3 to 4 PhD examinations per year. This is slightly less than in previous years, due to a decrease in funding for PhD students. However there is no difficulty in recruiting students when funding is available.

**Master's programmes**
In addition to the PhD programme the three universities have Master of Science programmes where students can select fusion plasma physics topics for their thesis work. Annually there are about 15 MSc thesis students.

9.2 Public information

Within the European Fusion Development Agreement (EFDA) there is one public information officer representing each member country. The Swedish Public Information Network (PIN) representative is J. Scheffel at the Division of Fusion Plasma Physics, KTH in Stockholm.

J. Scheffel co-chairs the EFDA PIN working group Strategy, the aim of which is to set more focus on active public relations within the EU rather than to the earlier more passive roles, working with public information only. Media, stake-holders and politicians are target audiences. For active participation in discussions, debates and media, a data base of information is being developed to cover the following missions: "Prepare for unpleasant questions and discussions", "Strengthen competencies in energy scenarios" and "Prepare list of spin-offs". This involves the construction of a wiki, being accessible for anyone working within EFDA, being in the need for relevant fusion information. Any EFDA subject expert could contribute in order to make the database a reliable tool for information on also detailed matters as, for example, those related to tritium (start-up amounts, production, accidents) and to candidate fusion concepts such as inertial fusion.

The Swedish PIN activities include substantial contact with media and the general public and are, during periods, carried out in the form of lobbying, concentrated towards contact with government, parliament and energy administrators with the intention of strengthening fusion funding. The national funding for fusion is unchanged since the early 1990’s, and the situation is quite difficult with regards to retaining competence and enrolling younger scientists. The Swedish Energy Authority has a mission to consider fusion but has so far in practice not supported fusion research.

The year 2012 has been a year with substantial contact also with the public. There is a strong interest in fusion among school pupils and university students, most likely because of the debate on global warming and the energy future.
Performed PIN activities

The EFDA Public Information network (PIN) met at Culham, UK in June 2012 to discuss common strategies with respect to fusion information and lobbying.

The PIN group “Strategy”, where the Swedish PIN representative is a member, met in December 2012 to discuss the Mission Statement for moving from PI towards more proactive PR activities.

Lobbying

- Personal contact with politicians and administrators in the energy sector
- Articles on fusion, to Swedish newspapers or produced by independent journalists

Contacts with the public

- Long interview with Swedish PIN officer in the Swedish national radio programme “Institutet”.
- Interview with Swedish PIN officer for the Swedish national radio programme “Vetenskapsradion”.
- Discussions with the French Embassy, Stockholm, in order to invite a leader of the inertial fusion LMJ project in Bordeaux, France. An invited Public talk by Dr Thierry Massard was given at the Royal Institute of Technology on 29 February 2012.
- A debate article on fusion was published in the widely read weekly newspaper Ny Teknik: http://www.nyteknik.se/asikter/debatt/article3459027.ece in response to a critical article on fusion, referring to political arguments of a person involved in fission research.
- Alfvén lecture ”Putting the Sun into a Box” by Dr G. F. Matthews, JET-EFDA Culham Science Centre, UK, at the Royal Institute of Technology, Stockholm.
- Lectures on fusion to school children, students, associations and at other universities
- Cooperation with the science center “House of Science” on tutorship for several groups of upper secondary pupils doing project work in fusion

Contacts with students, taking university courses

- Several students at KTH Royal Institute of Technology, studying to become upper secondary school teachers, take a course on fusion and energy
- A popular university summer course at KTH on energy includes lectures on fusion. J. Scheffel gives these lectures.
- A set of 10 short lectures on fusion and the global energy situation has been video recorded by J. Scheffel at KTH.
Appendix I: Fusion for Energy Grants

The European domestic agency for ITER, the “Joint Undertaking for ITER and the Development of Fusion Energy”, called “Fusion for Energy” or F4E, has the responsibility for procuring the necessary research and development as well as the equipment for ITER. F4E can provide support to groups in the member states in the form of Grants, which cover 40% of the costs of the Research and Development. Procurement of hardware, often directed towards industry, is normally covered by 100%.

This F4E activity is not a part of the EURATOM fusion programme, which provides support to the fusion research Associations as established in the Contract of Association and the European Fusion Development Agreement. However it is important that the EURATOM programme maintains an effective contact with F4E since the EFDA has a focus where preparations for ITER have the highest priority. Therefore information of the Association VR activity for F4E is provided here for information.

In 2012, three different F4E contracts were active within the Swedish Fusion Research Unit. Two of these were held by Studsvik AB and concerned work in the field of corrosion studies. The third contract was held by Uppsala University Neutron Diagnostics as a third party contributor to the Consortium of European fusion laboratories that was awarded the Framework Grant for design and development of the ITER Radial Neutron Camera.

The F4E grants held by the Swedish RU are summarized in Table I.1.

<table>
<thead>
<tr>
<th>Contract No.</th>
<th>VR group</th>
<th>Title</th>
<th>Type</th>
<th>Amount (F4E contr) k€</th>
</tr>
</thead>
<tbody>
<tr>
<td>F4E-GRT-243 (ES-MF)</td>
<td>Studsvik</td>
<td>Corrosion assessment water cooled comp’s</td>
<td>Grant</td>
<td>224</td>
</tr>
<tr>
<td>F4E-GRT-243 (DNO 451)</td>
<td>Studsvik</td>
<td>Corrosion assessment water cooled comp’s</td>
<td>Grant dev.</td>
<td>35</td>
</tr>
<tr>
<td>F4E-GRT-268</td>
<td>Studsvik</td>
<td>Assessment of erosion corrosion parameters</td>
<td>Grant</td>
<td>98</td>
</tr>
</tbody>
</table>
Appendix II:
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Cover Picture:

Simulated neutron emissivity profiles in MAST, using the transport code TRANSP. Non flux-averaged (left panel, special TRANSP output), average over the flux surfaces (middle panel, standard TRANSP output) and their difference (right panel) clearly showing the localized contribution of trapped fast ions.

Compiled from contributions from the research groups of the Swedish Fusion Research Unit

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