ASSOCIATION EURATOM - VR
Swedish Fusion Research Unit

Annual Progress Report 2013
Cover Picture:

Dispersion relations for the Resistive Wall Mode (RWM) in the fusion device EXTRAP T2R at the KTH Royal Institute of Technology in Stockholm. Left: empirical. Right: theoretical.

Responsibility for the information and views set out in this report lies entirely with the authors. In particular, any mentioning of resources (PPY and EUR) in this report should be seen as indicative only and not as a commitment by the European Commission.

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

Göran Ericsson  
Head of the Swedish Fusion Research Unit  
Department of Physics and Astronomy  
Ångstrom Laboratory  
Uppsala University, Box 525, SE-751 20 Uppsala, Sweden

Edited by  
Jan Scheffel  
Deputy Head of the Swedish Research Unit  
Department of Fusion Plasma Physics  
School of Electrical Engineering  
KTH, SE-100 44 Stockholm, Sweden

Association EURATOM-VR
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Preface

On behalf of the Swedish Fusion Research Unit, we are pleased to present the Annual Progress Report for 2013 covering research carried out under the Contract of Association between the Swedish Research Council (VR) and the European Atomic Energy Community, EURATOM.

Göran Ericsson  
Head of the Swedish Fusion Research Unit

Edited by:  
Jan Scheffel  
Deputy Head of the Swedish Fusion Research Unit

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 fusion experiment ITER has been under construction in Cadarache, France, since 2007. ITER 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 2021 and first deuterium-tritium operation is scheduled for 2027.

Under the responsibility of the European Domestic Agency, the preparation of the ITER site at Cadarache is continuing. In January 2013, the new ITER Headquarters building was inaugurated in the presence of 200 guests, among them Günther H. Oettinger, EU Commissioner for Energy. Site construction activities continued at an increasing pace and good progress was made in the manufacturing of Tokamak components and supporting systems in all the ITER Members. As a test for future deliveries, in September 2013, a mock load weighing 800 tons was transported the 104 kilometres from Berre l'Etang near the
Mediterranean Sea to the ITER site. The ITER Council in November 2013 validated two important technical decisions for ITER: to immediately go to operations with a tungsten divertor and the inclusion of in-vessel coils into the ITER Baseline design. In December, concrete pouring began for the Tokamak Complex basemat - the actual floor of the three-building complex that will house the ITER fusion experiments.

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-coordinated 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 facility, 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:

(i) a test facility for materials, ultimately the International Fusion Materials Irradiation Facility, IFMIF, but possibly an Early Neutron Source for DEMO relevant studies;

(ii) continued exploration of fusion concept improvements that may, in the longer term, be attractive as a basis for a fusion power plant, e.g., stellarators;

(iii) continued development of technology required for a demonstration electricity-producing power plant (DEMO).

A new EU Research and Innovation Framework Programme for the period 2014-2020 (Horizon 2020) is in preparation. In view of the fact that both the Contracts of Association and the EFDA Agreement end in 2013, an intense period of discussions and planning of the future organization and program of EU fusion research, including the European stakeholders in fusion (European Commission, the Associations, member states etc.) culminated in 2013,
outlining the new organization and work plan of the coordinated European fusion research activity. An essential cornerstone in this program is the 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”. The implementation of the Roadmap will take the form of a Grant for a Joint CoFund Action. The organization that will implement the Action is the EUROfusion Consortium, formed by all the former Associations within the EURATOM fusion framework. The details of the Consortium organization and the work program for the H2020 period were worked out in an intense period of activity during 2013.

In parallel to the activities on the new fusion organization and program, the work within the Contract of Association and EFDA continued in 2013 according to the established plans. 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

Swedish fusion research activities are carried out at four universities and one industry, which together form the Swedish Research Unit (RU) in fusion under the auspices of the Swedish Research Council, VR. The work of this Research Unit is focused on promoting Swedish activities in the field of coordinated fusion research, including, but nor exclusively devoted to, the EFDA program. The establishment of a Swedish Fusion Association within the EURATOM framework is enabled by the Contract of Association between EURATOM and VR. 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 2013 included the members: Angelgiorgio Iorizzo (EU), Marc Cosyns (EU), Johan Holmberg (VR), Barbro Åsman (Stockholm University) and Goran Bogdanovic (Ministry of Education). The VR-SC met on November 15, 2013, 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 (expert, KTH), Per Karlsson (VR), Mikaela Laine (VR), Cecilia Mattsson (VR) and Duarte Borba (representing the 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

\(^1\) [https://www.euro-fusion.org/newsletter/getting-the-roadmap-rolling/](https://www.euro-fusion.org/newsletter/getting-the-roadmap-rolling/)
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 Association-VR. 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. The RU also operates its own plasma device, the EXTRAP-T2R reversed field pinch experiment at KTH, Stockholm, which provides a rich source for research projects and training of students and staff in operations of complex plasma machines. A further 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 and EFDA contracts

The Contract of Association and the EFDA Agreement provide the framework for the coordinated European fusion research activity under EURATOM. All EU member states with fusion research units participate in EFDA; in addition Switzerland is also a party. The EFDA leader during 2013 was Professor 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 stable at a level of about 50 full-time person-years (py) per year. This contribution has been divided between the major areas of the EFDA Work Programme:

- 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: 3 py
- Long term secondments: 2 py
- Other (central admin, Public info): 2.5 py

The total number of professionals involved in the RU program is about 80, of which more than 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 (not included in the CoA py).

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 for future a demonstration reactor (DEMO) is coordinated within the Power Plant Physics and Technology department and 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 2013 included tasks within most of the 11 Topical areas, for a total of 5.1 py Priority Support and additionally 1.6 py Baseline Support in named, specified contracts. The activity within the ITM-TF amounted to 1.57 py in Priority and 0.78 py in Baseline support contracts. The PPPT tasks summed up to 0.6 py Priority support contracts. In addition, two RU researchers were continuing their Fusion Researcher Fellowships into 2013, and an activity within the Goal Oriented Training program BeFirst involved about 0.8 py per year (tutor and student) has been initialized in 2013.

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 2013 the Swedish Association contributed about 470 person-days (about 2.1 py) for on-site ST Orders and Notification work as well as about 80 person-weeks (about 2.1 py) for work at the home institutes with preparations and analysis tasks connected to the JET experimental program (Notifications). In addition, Swedish researchers continued their work with increased activity in projects for JET Enhancements (“Upgrade of the Neutral Particle Analyzer”, “Vertical Neutron Spectrometer”) and in Fusion Technology tasks (“Material transport and erosion/deposition”, “Microbeam analysis and SEM/EDX analysis on cross section”, “Be-10 experiment”, “First test mirror at JET”, “Evaluation of integral JET plasma data”, “Upgrade of dust dynamic code”, “Assessment of TOFOR in view of a JET DT campaign”).

Summing up the RU involvement in named contracts within the European fusion program, a total of about 17 py are conducted under specific priority and baseline support tasks in 2012 (including JET Orders, Notifications and Fusion Fellowships). This corresponds to about 35% of the total amount of the py’s contributed by the Association-VR to the fusion program.

Fusion for Energy Grants are not formally part of the activities under the Contract of Association, but the status of such grants is provided here for information. They show that Sweden is taking an active part in the European fusion development regarding direct involvement with F4E procurement and design tasks for ITER. Most of the grants in this area are/have been held by the Studsvik Energy AB company. In 2013, Studsvik worked on four different F4E contracts in the area of corrosion and water chemistry; two were concluded and two continue into 2014. In addition, the Uppsala University Neutron Diagnostic group has continued work as a “third-party” contributor to a consortium awarded a F4E Framework Partnership Agreement 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

MHD stability and plasma control:
• Using an extended sensor array of 2x64 coils in EXTRAP T2R, the first generic and simultaneous measurement of the full resistive wall mode (RWM) dispersion relation in a reversed field pinch plasma is performed.
• The RWM growth rate spectrum obtained compares well with MHD model calculations.

Plasma wall interaction:
• Detailed studies of high-Z metals (tungsten and molybdenum) in the TEXTOR tokamak were performed using plasma spectroscopy and surface analyses methods.
• Evolution of carbon, beryllium and oxygen fluxes in the divertor during the JET-ILW operation was determined with spectroscopy.
• First Mirror Test in JET-ILW was performed. The optical performance (total reflectivity 400-1600 nm) of mirrors from the main chamber wall after long-term exposure was not degraded.

Physics of plasma heating and current drive:
• Experimentally observed turbulence suppression has been explained using gyro kinetic modelling in GENE (DIFFER) in the presence of ICRF fast ion population from SELFO (VR). It was shown that a detailed treatment of orbit effects was critical to account for the observed turbulence suppression.
• DEMO has been shown to only have four possible frequency bands for fast wave current drive. However, two of these may be subject to strong parasitic damping by impurities or alpha particles.

Plasma auxiliary systems

Neutron diagnostics:
• Development of a digital data acquisition system for TOFOR
• 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.
• Determination of the fuel ion ratio (n_d-n_t) using the MPRu spectrometer.
• Deuterium density profile determination at JET

Concept improvements
• Poloidal beta values up to 0.25 can be obtained in the reversed-field pinch by static current profile control (CPC), as found from nonlinear resistive MHD modelling.
• Energy confinement is enhanced by a factor three through static CPC.
• Beyond this regime, resistive pressure driven modes are limiting (in MHD modelling).

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 (PhD student), J. Weiland, M. Tendler

Introduction
This project is directed towards understanding the transport of particles, energy, and momentum in today’s fusion experiments and to find ways of improving the performance of a reactor. 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 2013 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 2013 the effect of finite plasma beta on the electron branch of the geodesic acoustic mode (el-GAM), driven by a background of Electron-Temperature-Gradient (ETG) modes, was investigated using a fluid model. The effect of finite plasma beta on the driving ETG eigenvalues was also investigated using fluid and gyrokinetic simulations using the GENE code. The fluid model, based on the Braginskii equations with non-adiabatic ions including impurities and finite beta-effects, was shown agree well with the gyrokinetic treatment. It was shown that the el-GAM may be stabilized by an increase in finite beta as well as by increased non-adiabaticity. In addition, the effects of higher order harmonics were self-consistently included in the derivation of the el-GAM. It was found that due to coupling to the $m=2$ mode the real frequency of the el-GAM may be significantly increased.
**Modelling**

Particle and impurity transport in Ion-Temperature-Gradient (ITG) and Trapped-Electron (TE) mode driven turbulence was studied using fluid and gyrokinetic models.\(^5\)\(^6\) Quasi-linear and nonlinear gyrokinetic simulations were performed using the code GENE, studying the sensitivity of mode stability and transport on the magnetic equilibrium model, sheared rotation, collisionality, finite beta, and the inclusion of a 2% C background for JET C wall plasmas.

It was shown that the impurity density gradient corresponding to zero impurity flux, the so called impurity peaking factor, was significantly lower in the shaped equilibrium compared to the simpler s-alpha model, while the qualitative trend of the scaling with Z was preserved. The effects of sheared rotation and roto-diffusion was included in the fluid description and found to agree well with the gyrokinetic results. A favourable reversal of the impurity pinch, from inward to outward, was observed for both low and high impurity charge fraction at a shearing rate $\gamma_{\text{E,B}} \approx 0.2$. For the considered JET discharges, however, the effect of sheared rotation was found to be weak.

Predictive simulations of JET L-mode and H-mode discharges was performed,\(^6\) including the self-consistent evolution of ion and electron temperature, electron density and one impurity species, while the toroidal rotation was treated interpretatively, using the coupling between the transport codes JETTO and SANCO. Both turbulent and neoclassical contributions to the transport were included. The predictive simulations resulted in density and impurity profiles that were consistent with the interpretative gyrokinetic results at mid radius. In the inner core region, the neoclassical effects dominated the impurity transport resulting in a significant increase in impurity peaking factor.

**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 centre 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 stochasticization 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.

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Toroidal rotation in the co-current direction generated by $J \times B$ force emerges primarily due to Stochastic Electrons. The cause is stochastic or braided magnetic fields and the closure by perpendicular currents driven by ions. The toroidal rotation in the stochastic layer is calculated from the balance of the $j \times B$ torque and the radial transport of toroidal momentum due to anomalous viscosity

$$j \times B = \sigma_{NDB} (E - E_{\text{NEO}}) B = -\frac{d}{dr} \left( \eta \frac{dU_T}{dr} \right)$$

Outside the stochastic layer the torque is equal to zero. There are plasmas in ITER in which the toroidal velocity is predominantly uniform in the inner regions with a pedestal that appears mostly at the edge.
Publications section 2.1.1

Peer reviewed journals

Presentations at international conferences and workshops

2.1.2 Particle and impurity transport

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

During 2013 we continued our studies on poloidal asymmetries and electromagnetic effects on transport, now focusing on trapped electron mode and micro-tearing turbulence. In collaboration with scientists at MIT and University of Maryland in the US we made significant progress in the topic of pedestal transport, not only analytically, but with the introduction of the numerical tool PERFECT. We also studied inclusion of magnetohydrodynamic drives into continuum gyrokinetic codes.

Impurity transport

We performed a gyrokinetic study of trapped electron mode turbulence, including the effect of a poloidally varying electrostatic potential. Its impact on radial transport of high-Z trace impurities close to the core was thoroughly investigated and the dependence of the zero-flux impurity density gradient on local plasma parameters was presented.

Based on a balanced neutral beam injection deuterium discharge from the DIII-D tokamak, we demonstrated that impurities alter the scaling of the transport on the charge and mass of the main species, and even more importantly, they can dramatically change the energy transport even in relatively small quantities.

A poloidally varying equilibrium electrostatic potential can lead to a strong reduction or sign change of the impurity peaking factor due to the combined effect of the in-out impurity density asymmetry and the $E\times B$ drift of impurities in the poloidal electric field. We presented an approximate expression for the impurity peaking factor and demonstrated that impurity peaking is not significantly affected by impurity self-collisions.
Neoclassical physics in an H-mode pedestal
We studied the effect of a finite radial electric field on ion orbits in a pedestal with subsonic main ion flow. We solved the kinetic equation in the banana and plateau regimes retaining the modifications due to finite $E\times B$ drift orbit departures from flux surfaces. We found that when the rapid radial variation of the poloidal ion flow coefficient and the electrostatic potential in the total energy are properly accounted for, previous banana and plateau regime evaluations of the ion flow, the bootstrap current, and the radial ion heat flux need to be corrected.

The new global $\delta f$ neoclassical solver, PERFECT, which is valid in large gradient regions such as the pedestal, has been validated against analytical formulae in the plateau regime of collisionality.

Particle and energy transport in micro tearing turbulence
The onset and characteristics of micro tearing modes (MTM) in the core of spherical and conventional tokamaks were studied through gyrokinetic simulations. For experimentally relevant core plasma parameters in the NSTX and ASDEX Upgrade tokamaks, in agreement with previous works, we found MTMs as the dominant linear instability. Also, for JET-like core parameters considered in our study an MTM is found as the most unstable mode. In all of these plasmas, finite collisionality is needed for MTMs to become unstable and the electron temperature gradient is found to be the fundamental drive.

MHD instabilities in gyrokinetic simulations
Using the new "low-flow" version of the gyrokinetic code GS2 developed for momentum transport studies, we modelled the effect of the induced parallel electric field on the electron distribution to study the destabilizing influence of current on stability. We identified high mode number kink modes in GS2 simulations and made comparisons to analytical theory in a sheared magnetic geometry.

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. 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. New simulations of the L-H transition in EAST started during 2013. 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. This model contains correlation length depending on flowshear and peeling ballooning modes (presentation in Princeton 2012). A new contribution has been a paper with C.S. Liu in Journal of Plasma Physics to the memory of its late editor Padma Shukla. This is a generalization of a previous work with Shukla on nonlinear equations for describing tokamak turbulence. This version also applies to the core and includes modes with odd parity (micro tearing modes).
Publications section 2.1.2

Peer reviewed journals


Presentations at international conferences and workshops


Licentiate theses

### 2.1.3 Integrated modelling

*P. Strand, D. Yadykin, L. Fazendeiro*

During 2013 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 mostly to the detailed verification and validation of the elements of the equilibrium-MHD stability chain. Activities were initialized for local deployment of the ITM frame in the Chalmers University of Technology. Following first verification results, more detailed studies were done using the codes integrated into the MHD equilibrium and stability chain: equilibrium refinement codes (CHEASE, HELENA,SPIDER, CAXE) and MHD stability codes (MARS, MARS-F, KINX). Equilibrium for the JET pulse #74221 (unstable for global kink mode) was used for the studies. Agreement between results of both equilibrium and stability codes is seen. Local deployment of the ITM platform is seen as an important further step of ITM framework evolution. Several European institutions including Chalmers University of Technology was chosen to be the ‘test bed’ for such deployment. First test were performed of the image of ITM platform at the Earth and Space Department. Further steps are planned taking into account the results of testing.

Work has progressed in IMP3 and IMP4 on providing transport models through the TCI (Transport Code Interface) module. This module is also utilized in JET as well. The range of models has been extended to supporting WEILAND; GLF23, RITM, MMM and EDWM models as well as 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

Presentations at international conferences and workshops


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.

**Confinement and pedestal characteristics in JET with CFC wall and ILW**

The baseline type I ELMy H-mode scenario has been re-established in JET with the new W MKII-HD divertor and Be-main wall (ITER-like wall, ILW).

A steady state H-mode profile database has been constructed from high quality Kinetic diagnostics. It contains plasmas with low (δ~0.2-0.25) and high (δ~0.38-0.42) triangularity with both the CFC wall and the ILW. For the CFC wall, the database contains both baseline ELMy H-mode plasmas $q_{95}=2.8-3.6$ as well as Hybrid H-mode plasmas with $q_{95}=3.5-4.2$ and plasma current in the range 1-3MA [1]. For the ILW plasmas, the database only contains baseline ELMy H-mode plasmas at $q_{95}=2.8-3.6$ and Ip in the range 2.0-2.5MA.

The applied heating systems are mainly NBI for all plasmas and some ICRH for the baseline plasmas ($P_{ICRH}/P_{NBI} < 0-10\%$).

During the steady state H-mode phase, the pedestal contribution to the total confinement is $W_{ped}/W_{tot} \sim 30\pm 5\%$ both in CFC wall and ILW. A strong coupling is found between the global normalized pressure $\beta$ and the pedestal $\beta$ in agreement with earlier CFC wall results.

The electron density, temperature and pressure profile (Ne, Te and Pe) are studied for a wide range of collisionality ($0.1 \leq v_{\text{eff}} \leq 4$). In the parameters range in which ILW and CFC plasmas have similar collisionality ($v_{\text{eff}} \approx 1-2$, see figure 2.1.4-1), the wall seems not to drastically affect
the profile shape and the gradient length are relatively comparable \((R/L_{ne,tor}=0.6\sim1.5\) and \(R/L_{ne,tor}=0.6\sim7\) for both ILW and CFC). On a wider \(v_{\text{eff}}\) range, ILW plasmas have low Ne gradient length \((R/L_{ne,tor}=0.6\sim0-2)\), and high \(T_e\) peaking \((R/L_{Te,tor}=0.6\sim7-8)\). Consequently, the \(P_e\) peaking remains constant, \(R/L_{P_e,tor}=0.6\sim8-10\) for both CFC and ILW plasmas.

**ELM effect on the pedestal parameters and energy losses in ILW plasma**

The work compares the drop in electron temperature \((T_e)\) and density \((N_e)\) at the pedestal during ELMs in high triangularity \((\delta=0.38-0.42)\) baseline plasmas for CFC and ILW plasmas. The work also characterize the ELM time scales and the ELM energy losses. The analysis is focused on a set of shots characterized by type-I ELMs with \(I_p=2.5\text{MA}\) and \(P_{\text{NBI}}=15-18\text{MW}\). \(T_e\) measurements from ECE and \(N_e\) measurements from reflectometry are used. ELM energy losses are estimated from the volume integrated electron pressure before and after the ELMs.

The time scale of the \(T_e\) drop \((\Delta t_{T_e})\) is significantly different between non-seeded ILW and CFC plasmas, \(\Delta t_{T_e}=2.0\text{ms}\) and \(\Delta t_{T_e}=0.5\text{ms}\) respectively. The temperature drop at the pedestal is \(\approx40\%\) lower in the non-seeded ILW plasmas than in the CFC plasmas. For the \(N_e\) pedestal drop, no significant difference has been observed within the experimental uncertainty. The ELM energy losses are in the range \(\Delta W_{\text{ELM}}=0.1-0.25\text{MJ}\) for the non-seeded ILW plasmas and \(\Delta W_{\text{ELM}}=0.3-0.4\text{MJ}\) for the CFC plasmas. As a consequence, the power dissipated through the ELM, estimated as \((\Delta W_{\text{ELM}}/\Delta t_{T_e})\) is \(\approx0.1\text{GW}\) for the non-seeded ILW and up to \(\approx0.5\text{GW}\) for the CFC plasmas, see figure 1.

\(N_2\) seeded ILW plasmas can partially recover an ELM behaviour similar to the CFC plasmas, with respect to time scales and energy losses. The recovery of the CFC ELM behaviour seems correlated with the total stored energy.

**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, L. Frassinetti, E. Olofsson (PhD student), A. C. Setiadi (PhD student), and 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 research program at KTH on active MHD mode control is aimed at the development of methods applicable to both tokamak and reversed field pinch devices. 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. The work on active RWM stabilization is also carried out at the RFX-Mod reversed field pinch experiment. On a longer time-scale, the goal is to implement control algorithms for RWM control at the ASDEX Upgrade tokamak.

Figure 2.2.1-1. EXTRAP T2R device at Alfvén Laboratory KTH
Parameters of the EXTRAP T2R device are listed in Table 2.2.1-1 below.

**Table 2.2.1-1. EXTRAP T2R parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Notation</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<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</td>
<td>kA</td>
</tr>
<tr>
<td>Plasma electron temperature (typical)</td>
<td>$T_e$</td>
<td>300</td>
<td>eV</td>
</tr>
<tr>
<td>Plasma electron density (typical)</td>
<td>$n_e$</td>
<td>1x10$^{19}$</td>
<td>m$^{-3}$</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.

![Two-dimensional arrays of sensor flux loops and active saddle coils](image)

**Figure 2.2.1-2.** Two-dimensional arrays of sensor flux loops and active saddle coils installed at EXTRAP T2R.

The main features of the 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.
**Subspace identification analysis at RFX-Mod and EXTRAP T2R**

Subspace system identification methods (SIMs), introduced in the 1990s, have become widely spread in process control practice. A particularly attractive feature of SIMs is their ease-of-use for Multi-Input Multi-Output (MIMO) systems and the way non-linear and/or non-convex optimization is avoided by the usage of numerical linear algebra. The system identification literature suggests that SIMs perform well on generic discrete-time linear time invariant systems.

A subspace system identification analysis aiming to characterize the resistive wall mode response has been carried out at two reversed field pinch experiments: T2R and RFX-Mod [1]. The T2R system to be identified is obtained by analysing the 64 coil current inputs and the 64 sensor outputs signals, while the corresponding RFX-Mod analysis utilizes 192 inputs and 192 outputs. The RFP datasets, which are samples of the distributed magnetic field dynamics, are naturally divided into smaller batches due to the pulsed-plasma operation of the experiments. Using subspace system identification techniques and randomized cross-validation methods to minimize the generalisation error, state-space orders of the empirical systems are suggested. These system orders are compared to stabilization diagrams commonly used in experimental modal analysis practice. The relation of the cross-validation system order to the decay of the singular values from the subspace method is observed. Both stable vacuum diffusion and unstable plasma response datasets are analysed. Apparent simulation and prediction errors are quantified for both cases using a deviation-accounted-for index. These results are purely data-driven.

---

**Figure 2.2.1-3.** Output prediction (one-step and many-steps) for T2R and RFX response experiments. Left: The black solid line shows the measured output $y$. The green solid line is the many-step predicted output $y_{pf}$. The dashed blue line is the one-step predicted output $y_p$. The dashed-dotted red line is the one-step prediction residual $y-y_p$. The dotted cyan line is the many-steps prediction residual $y-y_{pf}$. Right: Decay of the deviation accounted for versus the horizon length $f$. Top panels (a) are RFX data, while bottom panels (b) are T2R data.
Differences and similarities between T2R and RFX-Mod are observed. It was noted that it is possible to obtain full “black-box” MIMO models with reasonable short-time predictive capabilities for both devices. T2R analysis has previously generated seemingly reliable and interpretable results, and T2R techniques and practical confidence has been developed over several years. RFX-Mod turns out to be more challenging to analyse so far. Possible explanations for this are (i) unfavourable time-scale ratio of flat-top to nominal long wall time, (ii) the possible errors-in-variables issues with the measured active coil current inputs. It may be possible to circumvent these problems by further developments of the estimation methods and by acquisition of more data.

SIM analysis of data from the full 2x64 sensor coil array at T2R
Considerable research effort has recently been devoted to the development of closed-loop system identification methods for analysis of EXTRAP T2R experimental data. Plausible detection of RWMs was made with a subspace system identification method (SIM) using data from a sensor array consisting of 2x32=64 coils. These previous data were suggestive of potential under-sampling, leading to aliasing of toroidal mode numbers.

![Figure 2.2.1-4. Left: Empirical RWM dispersion relation for T2R. Red colour indicates high model density (highly probable location of the plasma response eigenvalues) in the logarithmic scale. A stable pole is located in \( z<1 \), an unstable pole is located in \( z>1 \). The discrete-time normalisation is with respect to the control cycle rate \( \tau_c = 10 \text{ kHz} \). The continuous-time growth rate is given by \( \gamma = \tau_c \ln |z| \). Right: Resistive wall MHD eigenvalues for discrete toroidal wave numbers \( n \) transformed to discrete evolution on the T2R control cycle time scale. The symbols (a) to (e) corresponds to different RFP equilibria.](image)

Recently, sensor coil signals from the full 2x64=128 coil array has been analysed with the SIM code [2]. These sensors are connected to a separate data-acquisition system with its own clock signal. The real-time system input (the active coil currents) was accurately post-shot synchronized with the non-real-time high spatial resolution system output (the 2x64 radial field coil array time-integrated voltages), based on the common sensors shared with the real-time 2x32 array. A collection of 114 feedback-stabilized randomly perturbed T2R plasma discharges was processed. This collection corresponds to a sum-total of 3.8 seconds of steady-state slices of RFP data, each slice being of similar length. The used data is fully new and disjoint with the set used for previous analysis.

In this method the RFP plasma response is represented by a by a discrete-time linear time-invariant state-space system:

\[
\begin{align*}
x(t + \tau_c) &= A x(t) + B u(t) + K e(t) \\
y(t) &= C x(t) + e(t)
\end{align*}
\]
The system is evolved in steps of single control cycle times $\tau_s = 100 \mu s$. The vector $y$ represents the radial magnetic field sensor array signals and the vector $u$ represents the coil currents. The vector $x$ is the state vector. In this model the state vector does not have any simple physical interpretation. The vector $e$ is a residual that models the noisy part of the data, and $K$ is a filter gain. Finally, the system is represented by the constant matrices $A$, $B$, $C$, being determined in the system identification process. The state order selected was $\dim(x) = 600$.

With a 2x64 sensor array it was possible to avoid the aliasing problem. Using the extended sensor array of 2x64 coils, the method has provided the first generic and simultaneous measurement of the full RWM dispersion relation in reversed field pinch plasma. By generic it is meant that no assumption of the MHD model is built-in to the signal processing. Instead, the multivariate magnetic diagnostic data is regarded as a direct noisy time-domain eigenvalue problem. By simultaneous it is meant that all the RWMs are excited concurrently. The RWM growth rate spectrum obtained compares well to the MHD model calculation.

**Model Predictive Control in EXTRAP T2R**

A numerical study of fast Model Predictive Control (MPC) in EXTRAP T2R has been carried out [3]. A variant of predictive controller has been designed utilizing the system identification algorithm that has recently been implemented in T2R.

Predictive control, which belongs to a class of optimal control, is known to generally outperform a generic control such as Proportional-Integral-Derivative (PID) control. Furthermore, the predictive control treats Multiple-Input Multiple-Output (MIMO) system and actuation constraints explicitly. Numerical simulations of Model Predictive Control in T2R have been carried out, which assess the performance of the proposed predictive controller, in particular concerning the implementation feasibility of the controller for a system with fast time scale.

A discrete linear time-invariant system is considered. The aim of the MPC is to generate an optimal input that minimizes a cost function based on prediction of the system over some finite time horizon. If the optimization problem is unconstrained, then the optimal solution can be found analytically. If the optimization problem is constrained with linear constraints, then the MPC is a Quadratic-Program (QP). Furthermore, if the constraints are box input constraints, then the Fast Gradient method can be used. The proposed MPC is shown to be able to stabilize EXTRAP T2R with a reasonable computing time (latency) of about 0.1 ms.

![Outline of the proposed control scheme](image_url)

**Figure 2.2.1-5.** Outline of the proposed control scheme. Several components are needed for the simulation of the MPC controller. The first component is a model of EXTRAP T2R. In this work, the model is obtained with the system identification technique. The second component is the Observer which estimates the state from the noisy output data. A standard Kalman filter method is used. The last component is the Target Calculator, which is mainly an offline FFT analysis, to pre-compute the required state to reach the user defined output reference.
**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.

**Publications section 2.2.1**

**Peer reviewed journals**


**Conference contributions**


**2.2.2 External magnetic perturbation effects on plasma rotation**

**L. Frassinetti, E. Olofsson, P. Brunsell, J. R. Drake, S. Menmuir, W. Khan**

The work exploits 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.

**Estimation of the wall diffusion time for non-axisymmetric fields using rotating external fields**

A new method for the estimate of the wall diffusion time of non-axisymmetric fields has been developed. The method based on rotating external fields and on the measurement of the wall frequency response has been developed and tested in EXTRAP T2R. The method allows the experimental estimate of the wall diffusion time for each Fourier harmonic and the estimate of the wall diffusion toroidal asymmetries. The method intrinsically considers the effects of three-dimensional structures and of the shell gaps. Far from the gaps, experimental results are in good agreement with the diffusion time estimated with a simple cylindrical model that assumes a homogeneous wall. The method is also applied with non-standard configurations of the coil array, in order to mimic tokamak-relevant settings with a partial wall coverage and active coils of large toroidal extent. The comparison with the full coverage results shows a good agreement if the effects of the relevant sidebands are considered.
**Hysteresis in the TM locking-unlocking mechanism to an external field.**

The tearing mode (TM) locking and unlocking process due to an external resonant magnetic perturbation (RMP) is experimentally studied in EXTRAP T2R. The RMP produces a reduction of the natural TM velocity and ultimately the TM locking if a threshold in the RMP amplitude is exceeded. During the braking process the TM slows down via a mechanism composed of deceleration and acceleration phases. During the acceleration phases the TM can reach velocities higher than the natural velocity. Once the TM locking occurs, the RMP must be reduced to a small amplitude to obtain the TM unlocking showing that the unlocking threshold is significantly smaller than the locking threshold and that the process is characterized by hysteresis. Experimental results are in reasonable qualitative agreement with a model that describes the locking-unlocking process via the balance of the electromagnetic torque produced by the RMP that acts to brake the TM and the viscous torque that tends to re-establish the unperturbed velocity.
**Error field identification**

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. Stable and marginally stable external kink modes of toroidal mode number $n=10$ and $n=8$, respectively, were generated, and their rotation sustained, by means of rotating magnetic perturbations of the same $n$. Due to finite EFs, and in spite of the applied perturbations rotating uniformly and having constant amplitude, the kink modes were observed to rotate non-uniformly and be modulated in amplitude. This behaviour was used to precisely infer the amplitude and approximately estimate the toroidal phase of the EF. A subsequent scan permitted to optimize the toroidal phase. The technique was tested against deliberately applied as well as intrinsic EFs of $n=8$ and 10. Corrections equal and opposite to the estimated error fields were applied. The efficacy of the error compensation was indicated by the increased discharge duration and more uniform mode rotation in response to a uniformly rotating perturbation. The results are in good agreement with theory, and the extension to lower $n$, to tearing modes and to tokamaks, including ITER, is discussed.

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

**Publications section 2.2.2**

**Peer reviewed journals**


**Presentations at international conferences and workshops**


5. Frassinetti L., P.R. Brunsell, K.E.J. Olofsson, J.R. Drake, “Braking torque due to external perturbations in EXTRAP T2R”, Joint 19th ISHW and 16th IEA-RFP workshop, Sept 2013, Padova, Italy

6. Frassinetti L., Fridström R.,Menmuir S., Brunsell P.R., “TM locking and unlocking mechanism to an external resonant field”, 18th workshop on MHD stability control, November 2013, Santa Fe (NM), 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 instabilities in the core region of low-shear tokamaks and the influence of toroidal plasma flows on such instabilities. The activity during 2013 has dealt both with Kelvin-Helmholtz like instabilities in low-shear plasmas with strongly sheared toroidal plasma flow, and with resistive instabilities in hybrid-like tokamak equilibria.

An analytical modelling of a previously numerically studied Kelvin-Helmholtz like instability in tokamak plasmas with strongly sheared toroidal flows and low magnetic shear in the core region was completed during 2013 [1]. The analytical theory developed in [1] shows good agreement with the numerical results obtained with 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 explained by the analytical theory.

In [2] and [5], an analytic derivation of the dispersion relation for resistive instabilities in a low-shear tokamak configuration is presented. A previously developed (by Charlton et al.) resistive infernal mode model is generalized to include plasma diamagnetism, subsonic equilibrium toroidal flow shear and viscosity. An estimate of the transition point between the fast $S^{-3/13}$ infernal like and the slow $S^{-3/5}$ tearing like scaling is given. A novel $S^{-3/8}$ scaling is found close to the ideal ion-diamagnetic magnetohydrodynamic stability boundary. New moderately fast scalings in $S$ are also found when sheared toroidal $E \times B$ flow and viscosity are considered. An analytic treatment of the $m = n = 1$ quasi-interchange mode in presence of density gradients with flat temperature profiles is also presented.

Y. Liu, D. Yadykin

The research activity in 2013 covers analytic theory development; numerical code development together with extensive computer simulations; investigation of the 3D equilibrium for the JET tokamak, and stability limit studies at the ASDEX Upgrade tokamak.

The research work during 2013 (started in 2012) has been focusing on the development of the MARS-Q code, for studying the non-linear interaction between toroidal plasma flow and the macroscopic magnetic perturbations in the plasma. This is an important topic in view of (1) the often critical importance of flow and flow shear on various macro- and micro-instabilities in fusion plasmas; and (2) understanding of the penetration process of the resonant magnetic perturbations (RMP) that have recently been extensively applied for mitigation of large type-I ELMs in tokamaks.

In Ref. [3], we have developed a full toroidal, quasi-linear model, which is then used to study the penetration dynamics of the RMP field into the plasma. The model couples the linear, fluid plasma response to a toroidal momentum balance equation, which includes torques induced by both fluid electromagnetic force and by (kinetic) neoclassical toroidal viscous (NTV) force. The numerical results for a test toroidal equilibrium quantify the effects of various physical parameters on the field penetration and on the plasma rotation braking. The neoclassical toroidal viscous torque plays a dominant role in certain region of the plasma, for the RMP penetration problem considered in that work.
The MARS-Q model has also been used to investigate the non-linear interplay between the resistive wall mode (RWM) and the toroidal plasma flow [4]. In this case we simultaneously solve an initial value problem for the $n=1$ RWM and the $n=0$ toroidal force balance equation. Here $n$ is the toroidal mode number. Again the neoclassical toroidal viscous torque is identified as the major momentum sink that brakes the toroidal plasma flow during the non-linear evolution of the RWM. This holds for a mode that is initially either unstable or stable. We found that for an initially stable RWM, the braking of the flow, and hence the eventual growth of the mode, depends critically on the initial perturbation amplitude.

Investigations were continued of the 3D equilibrium for the JET tokamak. Activities were devoted to the investigation of the interaction between Error Field Correction Coils (EFCC) and plasma shape controller. The main reason of such interaction at JET is possible non-axisymmetric contribution via magnetic diagnostics to the plasma shape control. This could result in an additional unwanted axisymmetric part as response to non-axisymmetric perturbations. Studies are done of the several JET pulses when external perturbations in $n=2$ configurations are applied. Clear qualitative evidence of the EFCC/shape controller is observed. Further studies are planned to obtain quantitative characterization of the interaction.

Studies of the stability limit of the pressure driven global kink modes are performed at the ASDEX Upgrade tokamak. The characteristics of the kink mode appearing in improved H mode scenarios were studied both experimentally and using a numerical model. Agreement is seen between the eigenvalue observed in experiment and from the modelling.

Publications section 2.2.3

Peer reviewed journals


Presentations at international conferences and workshops

2.3 Power and particle exhaust, Plasma-wall interaction

2.3.1 Plasma-wall interaction

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

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.

Tungsten Migration Studies by Controlled Injection of Volatile Compounds

The use of tungsten PFC requires impurity seeding for improved edge radiation. The injection of neon (Ne), argon (Ar), or nitrogen (N₂) is performed for that purpose. Among many issues related to the injection is the in-vessel residence of gas by implantation, co-deposition or by compound formation with PFC materials. The latter may become important in the case of nitrogen-tungsten combination. To address W transport and the change of PFC surface morphology in the presence of nitrogen dedicated experiments were performed in the TEXTOR tokamak by injection of WF₆ and ¹⁵N₂. The aim was to assess: (a) material balance by qualitative and quantitative determination of a global and local deposition pattern of tungsten and local of nitrogen; (b) material mixing; (c) fluorine residence in PFC.
Two experiments with the localised WF$_6$ injection were performed at the TEXTOR tokamak prior to the major shutdowns (year 2008, 2011) connected with the retrieval of tiles for ex-situ analysis. They were done using a test limiter lock located at the bottom of the machine. Figure 2.3.1-1(a) shows the location of the lock with respect to the nearest blades of the toroidal belt pump limiter ALT-II (Advanced Limiter Test) which is the main PFC of TEXTOR defining the minor radius $a = 46$ cm. An assembly of the test limiter is shown in Figure 2.3.1-1(b): a roof-shaped block with a polished plate (both made of graphite) with a hole for WF$_6$ puffing. It was placed the scrape-off-layer (SOL). The first experiment (Exp. I) with the injection of $2 \times 10^{20}$ WF$_6$ molecules in 1.2 s long puffs during 7 shots was done, on purpose, 50 shots before the machine opening. The second (Exp. II) was performed on the last operation session when puffing of $1.93 \times 10^{20}$ W atoms in 13 shots heated neutral beam injection (NBI) was accompanied by puffing two other markers: Nitrogen-15 from the toroidal inlets ($3.46 \times 10^{21}$ at) and $^{13}$CH$_4$ ($1.75 \times 10^{21}$ C-13 at) from the upper test limiter. Major parameters for the two experiments are summarized in Table 2.3.1-1, whereas Figure 2.3.1-2 shows the timing of gas and neutral beam injection.

![Figure 2.3.1-1](image1.png)

**Figure 2.3.1-1**: Top view into the TEXTOR vacuum vessel showing the location of the test limiter with respect to ALT-II limiter blades with marked position of corner tiles (a); test limiter assembly with marked components of the set-up (b).

![Figure 2.3.1-2](image2.png)

**Figure 2.3.1-2**: Operation plan of the experiment: timing of NBI heating and injection of marker gases.
Table 2.3.1-1: Experimental conditions in tracer experiments with the WF$_6$ injection.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Experiment I</th>
<th>Experiment II</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALT-II (cm)</td>
<td>46</td>
<td>46</td>
</tr>
<tr>
<td>Test Limiter (cm)</td>
<td>47.5 (1.5 cm in SOL)</td>
<td>48 (2.0 cm in SOL)</td>
</tr>
<tr>
<td>$n_e$ ($10^{19}$ m$^{-3}$)</td>
<td>3.2</td>
<td>3.5</td>
</tr>
<tr>
<td>WF$_6$ (W atoms)</td>
<td>2x10$^{20}$ in 7 shots with 1-2 pulse breaks between injections</td>
<td>1.93x10$^{20}$ in 13 shots</td>
</tr>
<tr>
<td>$^{15}$N$_2$ ($^{15}$N atoms)</td>
<td>----</td>
<td>3.46x10$^{21}$ in 14 shots</td>
</tr>
<tr>
<td>$^{13}$CH$_4$ ($^{13}$C atoms)</td>
<td>----</td>
<td>1.75x10$^{21}$ in 14 shots</td>
</tr>
<tr>
<td>Probe retrieval</td>
<td>Directly after experiment</td>
<td>Directly after experiment</td>
</tr>
<tr>
<td>PFC retrieval</td>
<td>50 shots after last W injection</td>
<td>Directly after experiment</td>
</tr>
</tbody>
</table>

Local spectroscopy measurements were focused on the test limiter where NII (451.4 nm), WI (400.8) nm, CII (426.7 nm), FII (389.8 nm) and D (397.0 nm) lines were recorded. For the determination of the relative nitrogen fluxes (with respect to H$_2$) NII line 500.1 nm has been used. The fluxes at the SOL were estimated from the S/XB line ratio: nitrogen accounted for 5-10 % of the total flux. The W band at 5 nm and FVI line at 53.521 nm were recorded in core plasma. The exposures were followed by ion and electron beam analyses.

**Spectroscopy.** Temporal evolution of tungsten and fluorine fluxes at the test limiter is plotted in Figure 2.3.1-3 for the first and the last shot with WF$_6$ injection in Exp. II. The data are normalized with respect to the intensity of the D. line. The main message is that for a given species the shape and intensity of the signals are fairly similar. Some differences observed, as expected, at the beginning of the discharge level already after 0.7 s into the gas puff. Similar behaviour was also recorder during Exp.I both at the edge and core plasma. W and F fluxes where at background level when there was a one pulse break between discharges with injection. This weak “memory” effect may indicate that fluorine retention on the test limiter is not pronounced, i.e. species is effectively transported to other PFC or to pumps.

![Figure 2.3.1-3: Normalized spectroscopy signals of WI and FII lines for the first and the last discharge with the WF$_6$ injection.](image)

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Deposition profiles The injection of WF$_6$ lead to the formation of a co-deposit on the graphite plate in the vicinity of the gas inlet, as seen in the photo, Figure 2.3.1-1(b) taken after the limiter exposure to plasma in Exp. II. A similar deposition pattern was observed after the first experiment with WF$_6$ injection. The deposited layer, as identified with ToF HIERDA contains a mixture of light and heavy species: H, D, He, $^{10}$B, $^{11}$B, $^{12}$C, $^{13}$C, $^{14}$N, $^{15}$N, $^{16}$O, F and W accompanied by small quantities of Inconel components (Ni, Cr, Fe). The concentration varies, but the greatest amounts are found near the gas inlet: up to $1 \times 10^{18}$ W cm$^{-2}$, N-15 (3$\times$10$^{16}$ cm$^{-2}$), F (2$\times$10$^{16}$ cm$^{-2}$) and He (1$\times$10$^{17}$ cm$^{-2}$). These measurements reveal only a small quantity of fluorine in comparison to other species, especially to tungsten. They also prove and confirm nitrogen retention in deposits. Helium originating from regular glow discharge wall conditioning and He-beam diagnostics is identified again in deposit from TEXTOR. Its concentration is fairly high with respect to other gaseous elements in the analysed layer. On the molybdenum catcher plates attached to the test limiter base the quantities of W, $^{15}$N and F are below the detection limit.

![Figure 2.3.1-4: Deposition profiles of tungsten on the ALT-II toroidal limiter tiles detected: (a) 50 shots after the WF$_6$ injection, Exp. I; (b) and (c) after Exp. II in areas located at different positions with respect to the gas injector.](image)

In the examination of the ALT-II tiles the emphasis was on differences between tungsten deposition patterns on plasma-wetted areas (erosion zone) and in the deposition zone where the eroded species are eventually resting. The standard pattern for deuterium and impurity
atoms on ALT-II after entire campaigns has been shown previously: tiny amount of species in the erosion zone and a sharp increase (by orders of magnitude) in the deposition region. Figure 2.3.1-4(a) shows tungsten deposition profiles for two ALT-II tiles retrieved from TEXTOR 50 discharges after the last shot with WF$_6$: one tile located near the injection point and another 180° toroidally apart. Both profiles are fairly similar though there is a certain difference in the total amount of deposited tungsten; more is found closer to the injector. They correspond to the standard pattern on tiles after long-term operation. The profile in Figure 2.3.1-4(b) measured on tiles retrieved just after the experiment reveal irregular behaviour. There is an increase into the deposition zone and then sharp decrease. The graph in Figure 2.3.1-4(c) reflects the deposition in the area nearest to the injection point in Exp. II, corner Tile 28 marked in Figure 2.3.1-1(a) when ex-situ PFC studies were done directly after the WF$_6$ injection. The profile is wave-shaped with a concentration maximum at the in the central part of the tile, i.e. in the area known as the erosion zone on ALT-II. The same shape of the tungsten distribution has been found on the other corner plate (Tile 15) from the adjacent ALT-II blade, see Figure 2.3.1-1(a). W content on these two corner tiles is greater than measured on other plates from various toroidal locations.

This deposition pattern is a net result of global and local transport phenomena. It reflects the migration of tungsten from the net erosion area where it is originally deposited by plasma flux to areas where it rests: deposition – re-erosion – ionisation – re-deposition cycle. Erosion of tungsten occurs predominantly via physical sputtering. At the edge temperature $T_e$ of about 60 eV it is eroded mainly by plasma impurity ions (carbon, oxygen and boron), but the contribution of deuterium to the overall process is not excluded. The majority of sputtered species are neutrals with mean energy of 5-7 eV. At the edge density $n_e \sim 5 \times 10^{18}$ m$^{-3}$ their mean free path is 2-3 mm (normal to the limiter surface) before they get ionized. Species ionized close to the limiter surface may promptly be re-deposited within the first gyro orbit (Larmor radius is about 2.0 mm under the experimental conditions). The results of surface analysis explain gradual tungsten migration on ALT-II. They also clearly demonstrate the agreement with the model. The process leads to the “spill over” of tungsten on graphite until the equilibrium between the re-erosion and re-deposition is reached.

The other point is the micro-distribution of tungsten especially in the plasma-wetted area. In a backscattered electron image reflecting the contrast between low- and high-Z species dark fields corresponds to carbon and brighter spots related to the accumulation of high-Z elements were recorded. Tungsten was also present as identified with EDX. Metal resides in small pits acting as local shadowed regions. It explains why some tungsten is found in the erosion zone after long operation periods. This is in agreement with previous studies on micro-distribution of fuel and plasma impurities on PFC.

The reported tracer experiments, probably the most complex ever done in a tokamak, have resulted in several major contributions to material migration studies. The most important is the direct demonstration of tungsten erosion and its subsequent migration over long distances by re-erosion – ionization – re-deposition steps. To the authors’ knowledge, it is the first direct and so clear proof of the prompt re-deposition model predicted by Naujoks in the nineties, though there was an earlier indication following tests of a C & W twin limiter in TEXTOR. The transport is gradual (Figure 2.3.1-4) but very effective under experimental conditions, i.e. edge $T_e \sim 60$ eV. One may assume that such a significant W migration will be at least partly suppressed at low edge temperature and high divertor densities, as expected in ITER. However, this would not eliminate metal erosion followed by prompt re-deposition and local formation of modified mixed material layers.
Volatile WF\textsubscript{6} can be used as a high-Z transport marker without a major risk of leaving large quantities of fluorine sticking (co-deposited) to PFC and then released to plasma during subsequent pulses. The statement is justified by two facts: (i) the memory effect is not pronounced, as proven by spectroscopy and (ii) small quantities of F (maximum 2x10\textsuperscript{16} cm\textsuperscript{-2} versus 1x10\textsuperscript{18} cm\textsuperscript{-2}) are found even near the injection point. The application of the \textsuperscript{15}N tracer and a non-standard analysis method, i.e. HIERDA, has allowed for conclusive identification of nitrogen deposited on PCF. Though the exact material balance could not determined, the result shows effective co-deposition of toroidally puffed nitrogen. However, earlier experiments in TEXTOR and recent in ASDEX indicate the retention at the level of 30% of the injected amount. Also helium co-deposition and retention has been confirmed. It is associated with the He glow discharge. The level is quite significant (1x10\textsuperscript{17} cm\textsuperscript{-2}). Therefore, it can be recommended to study helium trapping following He-based ion cyclotron wall conditioning, i.e. a method considered for a reactor-class machine.

**Publications section 2.3.1**

**Peer reviewed journals**


**Presentations at international conferences and workshops**


### 2.3.2 Dust dynamics in SOL plasmas and microanalysis of dust particles

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

The production and dynamics of dust in the vacuum chamber of tokamaks are becoming an important aspect of tokamak performance, reliability and environmental safety.

The research carried out at KTH addresses both the experimental and modelling aspects of dust in fusion plasmas. While dust diagnostic techniques such as fast camera observations and particle collection – both in situ and post mortem – have been utilized, a major effort has been focused on the development of the numerical code MIGRAINe, as well as its validation against experimental data obtained during a dust injection campaign carried out in TEXTOR in 2012.

A TEXTOR campaign was also organized in 2013, during which, in addition to dust injection and collection similarly to the 2012 experiments, samples of pre-deposited dust were exposed to the plasma in order to study remobilization phenomena. Moreover, dust collection experiments have been carried out in the EXTRAP-T2R reversed-field pinch and their results have been used in MIGRAINe to investigate dust release processes.

The work was related to the following EFDA tasks:

- WP12-BS08-VR
- WP12-IPH-A03-2-18/BS/VR
- WP13-IPH-A03-P2-01/PS/VR
- JW13-FT-5.56
**Numerical modelling of dust migration with MIGRAINe**

MIGRAINe has been developed to simulate the dynamics of dust particles in order to investigate their migration and typical lifetime, as well as to estimate their contribution to the production of heavy impurities which can perturb or disrupt the discharge.

MIGRAINe relies on state-of-the-art models of the various physical processes involved in dust charging, heating and mass ablation. Moreover, it implements an analytical and physically transparent description of the collisions between particles and the vessel wall, accounting for the influence of particle size and velocity, as well as surface roughness effects. Simulations carried out to reproduce the 2012 TEXTOR dust injection experiment have shown that dust-wall collisions play a crucial role in dust migration, allowing the particles to travel long distances in a single discharge, as observed during the experimental campaign.

The results regarding the 2012 TEXTOR experiment and its modelling with MIGRAINe have been published in *Journal of Nuclear Materials* **438** S681 (2013) and *Nuclear Fusion** **53** 123002 (2013).

![Image](image.png)

**Figure 2.3.2-1:** Normal restitution coefficient $e_\perp$ (ratio of the dust velocity components normal to the wall surface after and before an impact) for a tungsten dust grain impinging on an INCONEL surface as a function of the initial normal velocity $v_\perp$ and the radius $R_d$ of the particle.

**Remobilization studies**

As the quantity of dust collected during the 2012 TEXTOR campaign and the comparison with MIGRAINe results implied that most of the particles had travelled in the device during several discharges – and hence were remobilized – a part of the 2013 campaign was devoted to a first investigation of remobilization.

Camera observations of pre-deposited dust samples immersed in the SOL of TEXTOR provided the first evidence that remobilization does indeed take place. This conclusion serves as a basis for new experiments in a more controlled plasma environment to investigate this phenomenon. Such experiments are planned in the linear plasma generator Pilot-PSI, where pre-deposited samples are to be exposed to plasmas covering a wide range of tokamak-relevant parameters.

**Investigation of dust release mechanisms in EXTRAP-T2R**

Dust particles resident in EXTRAP-T2R were collected using two different experimental setups. Mobile dust grains were captured in situ by silicon collectors, whereas immobile grains were sampled post mortem from the wall by adhesive tape. The simulation of collection asymmetries by MIGRAINe in combination with the experimental results has been employed to deduce some characteristics of the mechanism of intrinsic dust release. All
evidence suggests that remobilization is dominant with respect to dust production, further supporting the hypothesis that remobilization is a major aspect of dust dynamics.

The results have been submitted to Plasma Physics and Controlled Fusion.

**Microanalysis of dust grains**

A method has been developed to measure the fuel content of individual dust grains, in particular of grains that have been captured with velocity sensitive aerogel collectors. This is potentially valuable to determine which types of dust in a fusion device (size, composition, velocity, provenance) actually contain significant amounts of trapped fuel. The method has been applied to laser ablated dust ejected from TEXTOR limiter surfaces that were used for testing laser fuel removal methods.

The results have been submitted to Physica Scripta.

**Publications section 2.3.2**

**Peer-reviewed journals**


6. D. Alegre, H. Bergsäker, I. Bykov et al., *Study of correlation of deuterium content in a-C:D dust induced by laser irradiation from the co-deposited surface with the grain size and velocity*, Physica Scripta T161(2014) 014010


**Presentations at international conferences and workshops**

Seminars, reports and contributed lectures


Master theses


2.3.3 ICWC numerical studies for ITER

*V.E. Moiseenko, in collaboration with LPP ERM/KMS, Brussels and IPP NSC KhIPT, Ukraine*

For ICWC studies for ITER, the 1D single-ion species self-consistent model describing time evolution of the RF discharge is developed. Its distinctive feature is ability to make wave-field calculations in presence of the hybrid resonances.

The model includes equations for the particle and energy balance and boundary conditions for Maxwell’s equations. The equation of charged particle balance takes into account the influx of particles due to ionization and their loss via diffusion and convection. The equation of electron energy balance takes into account the RF heating power source, as well as energy losses due to the excitation and electron impact ionization of gas atoms, energy exchange via Coulomb collisions, and plasma heat conduction. The deposited RF power is calculated by solving the boundary problem for Maxwell’s equations. When describing the dissipation of the energy of the RF field, collisional absorption and Landau damping are taken into account. At each time step, Maxwell’s equations are solved for the current profiles of the plasma density and plasma temperature. The plasma is assumed to be axisymmetric and homogeneous along the plasma column. A possibility to use the code at the frequencies higher than the ion cyclotron is implemented.

The calculations for the case of TEXTOR and ASDEX tokamaks with a new code are completed. The development of multi-ion species model is underway and is carried on in collaboration with LPP-Brussels.
Publications section 2.3.3

Peer reviewed journals


2.3.4 Theory of particle motion in magnetic fields

O. Ågren and V. E. Moiseenko

Non-axisymmetric fields (associated with field ripples, stellarator fields, quadrupolar fields or perturbations etc.) could destroy confinement. Confinement improve with existence of adiabatic invariants and, in particular, a radial constant of motion implying a bounded radial motion. The group has identified non-axisymmetric systems with a radial constant of motion. It is shown that a quasi-neutral electric potential improves radial confinement, and reduce radial excursions from the mean drift surfaces caused by magnetic drifts. In open geometries, the radial electric field can be controlled with biased potential plates.

Publications section 2.3.4

Peer reviewed journals

1. O. Ågren and V. E. Moiseenko "Radial constant of motion for particles in magnetic mirror fields" accepted for publication at Plasma Phys. Control. Fusion

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 [1,2] 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**

The group participated in the JET 2013 Work Programme though modelling of ICRF heating of experiments on sawtooth control and in the preparation for experiments on fast particle induced turbulence suppression in advanced scenarios. In the sawtooth program it was shown, from both from SELFO modelling and experiments, that when the cyclotron resonance was placed on the low field side of the resonance, the destabilising effect of the ICRF is less sensitive to the resonance position compared to high field side resonance [3]. This strengthens the case for ICRF control of the sawtooth in ITER.

![Figure 2.4.1: Comparison of nonlinear GENE simulations and experimental ion heat flux measurements for the five separate discharges at $\rho=0.33$. The importance of the fast ion contribution is underlined by the sensitivity studies carried out for discharges 66404 and 73224. The dashed lines connect the results of the nominal 66404 and 73224 simulations with results obtained at reduced $R/L_Ti$. Taken from Ref. [4].](image)

In addition numerical modelling the transport in discharges with large fast ion beta were analysed. Using fast ion profiles from SELFO along with the gyro-kinetic code GENE previously unexplained improvement of confinement has been explain through a non-linear mechanism involving the fast ion pressure gradient, see figure 2.4.2. The results extrapolate favourably for a reactor operating in an advance tokamak configuration [4].

**ICRH scenarios for DEMO and the SELFO-light code**

The SELFO-light code is a code suitable for routine analysis [1], although it is less advanced than SELFO and RFOF. 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 main difficulty when modelling wave propagation in plasmas is the spatial dispersive effects in plasmas. To take into account spatial dispersive effects new methods suitable to be included in FEM codes have been developed \cite{1}, see figure 2.4.1. A structure for an upgraded version of SELFO-light enabling coupling with a 2D-Fokker-Planck code has been devised \cite{C1}.

![Figure 2.4.1. Comparison of ICRF wave field in reactor size plasma (to the left) and the type of wave field common in today’s machines (to the right). The higher temperatures, densities and plasma dimension of a reactor plasma changes the character of the wave field from an ergodic field to a beam-like wave that is absorbed in the plasma centre. Taken from Ref. [1].](image)

Modelling has been performed to identify possible fast wave current drive scenarios in DEMO using the SELFO-light code \cite{2}. It was found that because of the strong damping by alpha particles only four scenarios could be found. The optimum toroidal mode number (critical for the design of the antenna) is determined by a phase velocity of about 1.2 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. Further studies of the three scenarios with the highest current drive efficiency of these four potential scenarios were done in order to access whether light impurities heated by RF could affect the power partition for the current drive scenarios. Self-consistent calculations with SELFO-light revealed that the presence of a low concentration of $^3$He ions e.g. produced by D-D reactions had a strong influence of the power partition reducing the current drive efficiency for the second scenario $\omega=3\omega_{d,\text{edge}}$ \cite{5}. The development of a tail on the tritium distribution function in the third scenario, $\omega=4\omega_{d,\text{edge}}$, reduced the current drive efficiency with about 10%.

**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 (previously lead by Torbjörn Hellsten). During 2013 the main contributions have been in the further development of the ITM infrastructure, in the integration of heating and current drive codes into the European Transport Solver (ETS), in the adaptation of heating codes to the ITM framework and the development of advanced Fokker-Planck models. The work has resulted in the publication \cite{6}.
**Improvement of Monte Carlo codes**

Monte Carlo codes enable the calculation of the distribution function in higher dimensions. However, accurate calculations require short time steps for convergence and a large number of particles for reducing the statistical fluctuations, which make Monte Carlo calculations time consuming. In particular, the presence of internal boundary layer in the phase space complicates the modelling and reduces the convergence. The possibility to develop faster and more accurate algorithms has been studied. A number of such methods are proposed [7-9].

**Coupling of waves**

One of the outstanding issues with RF-heating is designing the antenna and accurate predicting the coupling resistance and the radiated wave spectrum. In order to advance the understanding of this subject, the wave coupling in the presence of passive conductive structures near the antenna has been analysed. For scenarios with weak single pass damping it was found that the passive structures can have a strong effect on the radiated spectrum, and hence influence the efficiency for current drive scenarios, which in general have lower single pass damping than the heating scenarios [C2].

**Non-linear wave-particle interactions**

An algorithm has been developed to include non-linear wave-particle interactions suitable for including fast particle interaction with TAE modes in Monte Carlo methods. The algorithm has been tested for a 1D model, and found to reproduce formation of clumps and holes in the phase space [C3].

**Publications section 2.4**

**Peer reviewed journals**

3. Graves et al, to be published in Plasma Physics Controlled Fusion

**Presentations at international conferences and workshops**

2.4.1 Radio frequency heating and current drive

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 2013, 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.

Effect of impurities on ICRF heating of hydrogen plasmas with $^3$He minority ions

Hydrogen majority plasmas will be used in the initial non-activated phase of ITER operation. Optimizing ion cyclotron resonance heating (ICRH) in such scenarios will help in achieving H-mode in these plasmas. Past JET experiments with the carbon wall revealed a significant impact of intrinsic impurities on the ICRH performance in ($^3$He)–H plasmas relevant for the full-field initial ITER phase. High plasma contamination with carbon impurities resulted in the appearance of a supplementary mode conversion layer and significant reduction in the transition concentration of $^3$He minority ions, defined as the concentration at which the change from minority heating to the mode conversion regime occurs. In view of the installation of the new ITER-like wall at JET, it is important to evaluate the effect of Be and W impurities on ICRH scenarios in ($^3$He)–H plasmas. We derived an approximate analytical expression for the transition concentration of $^3$He minority ions that accounts for typical impurity species at JET. The analytical results are supported by 1D wave modelling. We suggest a potential experimental method to reduce the $^3$He level needed to achieve a specific heating regime by puffing a small amount of $^4$He ions additionally to ($^3$He)–H plasma.

Lower hybrid current drive on Tore Supra

We performed a comparative numerical modeling of lower hybrid current drive (LHCD) for the Fully Active Multijunction and the ITER-relevant Passive-Active Multijunction lower hybrid (LH) launcher setups. The interpretative modelling of LHCD uses several numerical codes and includes the calculation of the global discharge evolution, the spectrum at the antenna, the LH wave propagation, and the distribution function. The simulations are validated by systematic comparisons between hard X-ray measurements of fast electron bremsstrahlung emission and a reconstructed signal.

Publications section 2.4.1

Peer reviewed journals

1. Ye. O. Kazakov, T. Fülöp and D. Van Eester, Effect of impurities on the transition between minority ion and mode conversion ICRH heating in ($^3$He)–H tokamak plasmas, Nuclear Fusion 53 (2013) 053014.


2.5 Energetic particle physics

2.5.1 Physics of burning fusion plasmas

R. Nyqvist 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 capable of exciting wave instabilities whose presence in turn may lead to enhanced 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 linear excitation of MHD modes such as fishbone oscillations and toroidicity induced Alfvén eigenmodes (TAEs). However, a currently "hot" topic is the role of nonlinear wave-particle interaction and whether the fast particle transport results in a simple critical-gradient model or is convective in phase space due to frequency shifting nonlinear instabilities.

The research programme of the group focuses on the study of fast particle transport in magnetically confined fusion plasmas due to resonant wave-particle interaction. The research activity is based on close collaboration with JET-EFDA (Culham Science Centre, UK) and IFS at the University of Texas (Austin, USA).

Long Range Frequency Sweeping

In the presence of dissipative wave damping, a common feature of nonlinear wave-particle interaction is the formation of holes and clumps in the fast particle distribution function. Such scenarios correspond to a transformation from fast particle driven eigenmodes (e.g. TAEs) to beam-like, self-sustained energetic particle modes (EPMs) with time dependent frequencies, and experimental observations of frequency sweeping events are abundant, see e.g. Figure 2.5.1-1. Recently, emphasis has been put on asymmetric (Figure 2.5.1-1 a), transient and steady state long-range frequency shifts, and an efficient analysis tool has been developed to describe 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 of $n = 0$ modes on JET, showing up-down asymmetric sweeps. b) TAEs on MAST, whose frequency sweeping directivities evolve with the plasma equilibrium. These modes sweep over an extended frequency range.

Accounting for various long-range effects, the model accurately tracks nonlinear 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 predicts transitions from monotonic to transient sweeping. The connection to circular tokamak geometry was also developed in order to explain observations of time-evolving frequency sweeping directivities (Figure 2.5.1-1 b) in terms of inward/outward radial convection of holes and clumps.

Publications section 2.5.1

Peer reviewed journals

Presentations at EPS conferences

Presentations at international conferences and workshops

PhD thesis
2.5.2 Runaway electrons

T. Fülöp, G. Papp (PhD student), A. Stahl (PhD 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 2013, we performed experimental modelling of ITER-like wall JET experiments, we modelled the synchrotron emission of runaways and studied their interaction with whistler instabilities.

Interaction of electromagnetic waves and supra thermal electrons in the near-critical electric field limit

We investigated high-frequency electromagnetic waves destabilized by runaway electron beams when the electric field is close to its critical value. We calculated the linear instability growth rate of these waves and concluded that the obliquely propagating whistler waves are most unstable. We showed that the frequencies, wave numbers and propagation angles of the most unstable waves depend strongly on the magnetic field. Taking into account collisional and convective damping of the waves, we determined the number density of runaways that is required to destabilize the waves and showed its parametric dependences.

Synchrotron radiation of runaway electrons

The synchrotron radiation emitted by runaway electrons in a fusion plasma provides information regarding the particle momenta and pitch-angles of the runaway electron population, as well as the runaway density and its spatial distribution, through the strong dependence of the synchrotron spectrum on these parameters. We modelled the synchrotron radiation spectra for typical avalanching runaway electron distributions and contrasted it with previously used simplified models. We also examined the effects of magnetic field curvature and analysed the sensitivity of the resulting spectrum to perturbations to the runaway distribution. The calculations were compared to DIII-D data.

Publications section 2.5.2

Peer reviewed journals


Presentations at international conferences and workshops


**Master’s thesis**

3 Plasma auxiliary systems - diagnostics

3.1 Neutron diagnostics

3.1.1 Fuel ion density determination with neutron diagnostics

*Fuel ion ratio measurements in JET DT plasmas*


The fuel ion ratio \( \frac{n_i}{n_d} \) 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 core fuel ion ratio by comparing the thermonuclear and beam-target neutron emission intensities, measured by a high resolution neutron spectrometer, has been developed [1,2], as reported in the Annual Report for 2012. During 2013, this method has been extended to allow for the determination of \( \frac{n_i}{n_d} \) in plasmas with simultaneous neutral beam injection of both D and T, which is more complicated than the case with a single beam species. A paper describing the details of the method, and presenting results from MPR measurements of JET DT plasmas, has been submitted to the journal Nuclear Fusion [3]. The main results are summarized in Figure 3.1.1-1. The trend in the estimated \( \frac{n_i}{n_d} \)-values is consistent with Penning trap measurements at the edge of the plasma, but the MPR results are systematically higher. It is suggested to further validate this method by comparing it to the traditionally proposed method to estimate \( \frac{n_i}{n_d} \) from the ratio of the thermal DD and DT neutron emission components.

![Figure 3.1.1-1](image)

*Figure 3.1.1-1*. Fuel ion ratios derived from the MPR spectrometer for four JET discharges (points with error-bars). The error-bars represent the statistical uncertainty from the fit to the MPR data and the dashed lines are estimates of the systematical error due to uncertainties in auxiliary plasma parameters (e.g. electron density and plasma temperature) that are needed in the modeling. For comparison, the fuel ion ratio measured in the divertor by a Penning trap is shown in solid blue.

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2 Department of Physics, Universita degli Studi di Milano-Bicocca, Milano, Italy and EURATOM-CCFE Fusion Association, Culham Science Centre, Abingdon, UK.
**Deuterium density profile determination using the neutron camera and the TOFOR neutron spectrometer at JET**


In addition to the method for determining the core fuel ion ratio described in the preceding section, it has also been investigated whether it is possible to obtain fuel ion density profile information from neutron diagnostics, by combining measurements with a neutron camera and a high resolution neutron spectrometer. Since the neutron emission depends on the densities of the fuel ions, it is possible to set up a model of the neutron emissivity profile and the neutron energy spectrum, parameterized in terms of the fuel ion density profile. The density profile that best describes both the neutron camera and the spectrometer data can then be found in a fitting procedure. This method has been tested with synthetic data, and applied to neutron data from one recent JET D discharge [1]. The main result is shown in Figure 3.1.1-2. Future work will aim at applying the method to more D discharges at JET, as well as investigating the potential for determining the fuel ion ratio profile in DT plasmas.

**Figure 3.1.1-2.** (a) Neutron camera (black dots) and TOFOR (black triangle) data for JET discharge 82816. The TOFOR data point is the estimated ratio between the thermonuclear and beam-target neutron emission intensities, normalized to the number of counts in camera channel 15. The blue line is the calculated neutron emission corresponding to the best-fit \( n_D \)-profile (blue dots), shown in (b). The dashed lines are estimates of the systematical uncertainty due to uncertainties in auxiliary plasma parameters (e.g. electron density and plasma temperature) that are needed in the modeling. The measured \( n_D \)-profile (red line) is also shown for comparison.

**References**


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3 Department of Physics, Università degli Studi di Milano-Bicocca, Milano, Italy and EURATOM-CCFE Fusion Association, Culham Science Centre, Abingdon, UK.
3.1.2 Diagnostic developments for JET and ITER

A fully digital data acquisition system for TOFOR

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

The current data acquisition (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 to 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.

During 2013, a detailed analysis of model data was completed, in order to assess the performance of a fully upgraded DAQ system for TOFOR in DT campaigns. In particular, the ability of the forward modelling algorithms hitherto employed to analyse traditional TOFOR data to analyse data obtained using the DAQ upgrade, was investigated. The focus of the assessment was the determination of fuel ion ratios, given plasmas with varying concentrations of tritium. The results were compared to modelled scenarios where the kinematic background discrimination described above is not available (as would be the case with the original TOFOR DAQ system). The critical quantity to measure with TOFOR in order to determine the fuel ion ratio, is the fraction of neutrons originating from fusion between thermonuclear deuterium ions \( Q_{THN}^{DD} / Q_{Total}^{DD} \). The ability to correctly measure this quantity, given knowledge of its actual, true value in the modelled scenario, is visualised in Figure 3.1.2-1, where the measured value is plotted against the true value for a system with (red, upgraded DAQ) and without (blue, traditional DAQ) kinematic background discrimination capability, for various concentrations of tritium and a neutron count rate of 500 kHz in the primary detector array (S1). As can be seen, for the presented scenario the background discrimination method provides a significant accuracy in determination of \( Q_{THN}^{DD} / Q_{Total}^{DD} \) for various concentrations of tritium from 1 % to 50 %.
Figure 3.1.2-1: Comparison of the true and measured $Q_{THN}/Q_{Total}^{DD}$ for $RS1 = 500$ kHz with (red) and without (blue) kinematic background discrimination. The dashed line corresponds to the true values of $Q_{THN}/Q_{Total}^{DD}$, whereas the points represent estimations from synthetic data.

**Modelling the neutron and gamma fluences for the low energy Neutral Particle Analyzer at JET**

*N. Dzysiuk, S. Conroy, G. Ericsson*

The Neutral Particle Analyzer (NPA) at JET is designed to perform measurements of absolute fluxes of neutral particles emitted from the plasma. Also it has the ability to distinguish the hydrogen isotopes and hence to study the isotopic composition of the plasma. Within the framework of the Isotope Separator Upgrade Feasibility Study (ISU) project, Monte Carlo modelling was needed to help in the evaluation of an instrumental upgrade.

Neutron spectra for the JET KR2 diagnostic were simulated using MCNPX for typical JET DT and DD scenarios. Spectra were obtained for two KR2 locations, namely Octant 3 and Octant 8. All these calculations are based on already existing model of the JET Torus Hall, supplementing by detailed modelling of the KR2 diagnostic.

Figure 3.1.2-2: Comparison between DD and DT neutron fluxes simulated at active Si layer
The comparison between calculated neutron fluxes at the Si layer for both DD and DT scenarios and locations is presented in Fig. 3.1.2-2. The current configuration of the shielding attenuates neutrons and could reduce neutron flux up to 10 times for DT neutrons and more than 20 times for the DD case. If placed in Octant 8, the neutron flux is going to be higher due to the more exposed position with respect to the torus vessel. Obviously the level of neutron flux in Octant 8 is higher which will cause more harsh conditions for Silicon detectors, and makes the position in Octant 3 more favorable for the reliable instrument’s operation.

A key element of KR2 is the Silicon detector array. That is why a special attention was paid to calculations the total energy deposition in these detectors in order to evaluate a level of possible background contribution to the total count rate. The total neutron and gamma energy deposition has been calculated for an active Silicon layer which is placed inside the NPA vacuum chamber (Fig. 3.1.2-3). The results of these calculations are presented in Fig. 3.1.2-4.

**Figure 3.1.2-3:** MCNPX model of the vacuum chamber. In order to show the position of silicon detector plane (diagonal dark band) the detector extension box was made transparent. The Silicon detector is placed in vacuum.

**Figure 3.1.2-4:** Total energy distribution in a 5 µm Silicon layer
**Design of a Backscatter 14 MeV Neutron Time-of-Flight Spectrometer for Experiments at ITER**

N. Dzysiuk, S. Conroy, G. Ericsson, C. Hellesen

A back-scatter time-of-flight neutron spectrometer (bTOF) for ITER is investigated that could potentially be integrated into one of the channels of the Radial Neutron Camera (RNC) to provide high resolution neutron spectrometry of 14 MeV neutrons. The main application of this spectrometer would be DT-experiments at ITER, it could, however, also operate in a low resolution mode which can be applied for measuring the minority flux of 14-MeV neutrons from deuterium plasmas to provide interesting information on tritium production, confinement and burn up. The instrument is based on two sets of scintillators, a first scatterer (deuterated scintillator) exposed to a collimated neutron beam and a second detector (plastic scintillator) set placed in the backward direction (see Fig. 3.1.2-5). As typically for a TOF approach the energy of the initial, incoming neutron can be determined based on geometry and time information ($t_{\text{tof}} = t_{\text{stop}} - t_{\text{start}}$). More details on this concept could be found in [1].

![Figure 3.1.2-5: Sketch of the spectrometer geometry.](image)

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 is characterized by rather compact size, low weight and reasonable cost (similar to the TOFOR spectrometer at JET). For the determination of the spectrometers performance specifications, a Monte Carlo simulation routine based on the MCNPX and Python codes has been developed. A design, working principle, details on the process of signal analysis as well as nature of background have been analysed thoroughly.

The maximum neutron flux over the D1 detector is dictated by condition to have 10 MHz in total as a maximum count rate acceptable for a normal D1 detector operation. It means that each D1 detector should be able to handle count rate of 1-2 MHz without degradation in the timing resolution. The capabilities of the scintillator detector are limited what is connected to electronics and PMT tube. The current Monte Carlo simulations shown that if the neutron flux equals to 108 (1/s) then in D1i CR = 3.81 MHz. This value could be reduced if to apply segmentation not only in vertical direction (stack layer structure) but also to do a spatial gridding (cubic structure, 15 cubes). When the neutron flux equals to 107 (1/s) then CR = 0.381 MHz and this value is suitable for a reliable spectrometer operation.

Different scattering “scenarios” have been studied. The D1 detector consists of three types of atoms correspondingly several types of scattering might took place and it was verified by the necessary modelling. Besides a single scattering of neutron on deuteron there are also a single and double (multiple) scattering on D, H or C. The contribution of these processes to the total...
background is illustrated in Fig. 3.1.2-6. Due to reason to analyze it the contribution of each scattering component was considered separately.

![Simulated time-of-flight spectra including different scattering components.](image)

**Figure 3.1.2-6.** Simulated time-of-flight spectra including different scattering components.

The blue line corresponds to the contribution of valid true coincidence events after kinematic cut (more details in Ref [1]). The red line shows a sum of accidental (random) and true coincidence events including certain type of scattering. In Fig.3.1.2-6 there are four cases of different scattering component: a) single scattering on D and no on C however multiple scattering on H is allowed; b) scattering on D including any type of scattering on C; c) single scattering on H only; d) all possible types of scattering. It is clearly visible that the contribution of hydrogen (H) is very small even could be negligible. This is explained by its small amount (5%). Meanwhile it is seen distinctly that mainly carbon (C) is a source of background on the left (high energy) side of the TOF peak (Fig. 3.1.2-6 b)). In addition some kind of structure is revealed what is caused by excitation of a carbon resonance. It could be seen that kinematic cut is a very efficient way to suppress the background because the components related to scattering on C or H do not survive after it.

The sensitivity to background is an important performance aspect closely related to the application. The background in the TOF spectrometer comes from random coincidences between the D1 and D2 detectors. That is why the signal to background ratio is connected directly to the neutron rate value. In contrary to background related to scattering on C or H the random component cannot be rejected completely. Current Monte Carlo model allows a possibility to distinguish virtually the true coincidences and random coincidences induced by interactions of two uncorrelated neutrons. In Fig. 3.1.2-7 there is a result of simulations of the time-of-flight spectra before and after random events filtering. The black line is a sum of all
events and the red line is result after a kinematic cut applying. The blue and magenta lines are pure random events before and after kinematic cut.

![Simulated TOF spectra before and after filtering of random events.](image)

Figure 3.1.2-7. Simulated TOF spectra before and after filtering of random events.

The main characteristic of any spectrometer is its response matrix. With the MCNPX model, the pure geometrical response of the instrument to incoming neutron fluxes of different energies over the range of interest could be simulated. Multiple interactions in the scintillators or the surrounding structural materials as well as scattering on carbon in the scintillators themselves were in this way taken into account for in addition to the single scattering events on deuterium in D1 and hydrogen in D2. The resulting time-of-flight distributions were used to create the geometrical neutron response matrix $R_n(E_n, t_{TOF})$. Due to need to verify the dynamic range of considered spectrometer the set of calculations was performed to construct the response matrix. Scanning of time-spectrum response in the energy range of 2-20 MeV with energy step of 0.05 MeV in the simulations is given in Fig 3.1.2-8.

![Energy-TOF matrix](image)

Figure 3.1.2-8. Response matrix $R_n$ for bTOF showing the $t_{TOF}$ as a function of simulated neutron energy $E_n$. 
The results obtained indicate that the bTOF spectrometer could deliver an energy resolution \( \text{d}E/E = 2.5\% \) (FWHM) combined with an efficiency of about 0.07\%. This was achieved with a geometrical configuration with a first scatterer (D1, “start”) of total thickness of 4.5 cm, divided into 5 layers of 0.9 cm, and a second detector (D2, “stop”) with a total thickness of 4 cm, segmented into 4 layers of 1 cm; the distance between D1 and D2 is 160 cm. It was shown that the segmentation is a straightforward approach to improve the energy resolution.

Reference


TPR – Preliminary detector performance tests

A. Hjalmarsson, S. Conroy, G. Ericsson

The Thin foil Proton Recoil (TPR) neutron spectrometer design is based on a thin hydrogen rich foil on which collimated neutrons impinge. A fraction of the incoming neutrons, with energy \( E_n \), will scatter elastically on hydrogen, creating recoil protons with energy \( E_p \), as:

\[
E_p = E_n \cos^2 \theta_{np} \tag{1}
\]

where \( \theta_{np} \) is the scattering angle between incoming neutron and produced recoil proton. At some distance behind the foil, an annular detector is positioned to detect recoil protons and record the deposited energy, resulting in a pulse height spectrum. From the obtained pulse height spectrum together with relation (1) the incoming neutron energy spectrum can be determined.

For the TPR, the first choice of an annular detector will be a silicon solid-state detector. Using this type of detector requires front-end electronics consisting of a pre-amplifier, which have to be tuned to used detector. In 2013, preliminary tests were performed on a silicon detector to investigate the energy resolution, \( \Delta E/E \), and linearity as function of proton energy. The experiments were performed with radioactive sources and proton beams at the Tandem Laboratory, Uppsala University. As part of the beam experiment, test of high speed digitizers in combination with silicon detector was also performed. The digitizer was used to record signal waveforms from the detector front-end electronic system. Figure 3.1.2-9 shows an example waveform induced by an 8 MeV proton with a sampling rate of 1GHz.

![Example waveform induced by a 8 MeV proton](image_url)

**Figure 3.1.2-9:** Example of a recorded waveform induced by a 8 MeV proton in a silicon detector and front-end electronic system.
By determining the maximum amplitude of the proton induced waveforms, the proton energy pulse height spectrum can be produced. From the resulting pulse height spectrum the energy resolution of the combined detector and front-end electronic can be determined. In Figure 3.1.2-10, a recorded pulse height spectrum for 8 MeV protons is shown resulting in a $\Delta E/E$ of 1.17 % FWHM. Also shown in the figure is the detector linearity as function of proton energy together with a linear fit to the data.

![Figure 3.1.2-10: Recorded pulse height spectrum (left) for 8 MeV protons and detector linearity as function of proton energy (right).](image)

In the beam experiment five proton energies, ranging from 4 to 8 MeV, were used and the result of $\Delta E/E$ as function of energy is shown in Table 3.1.2-1. The values of $\Delta E/E$ in the table are corrected for resolution broadening due to geometry effects in the experimental set-up.

<table>
<thead>
<tr>
<th>Ep (MeV)</th>
<th>$\Delta E/E$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>2.80 ± 0.04</td>
</tr>
<tr>
<td>5</td>
<td>1.70 ± 0.05</td>
</tr>
<tr>
<td>6</td>
<td>1.49 ± 0.05</td>
</tr>
<tr>
<td>7</td>
<td>1.13 ± 0.04</td>
</tr>
<tr>
<td>8</td>
<td>1.17 ± 0.05</td>
</tr>
</tbody>
</table>

With the results obtained from these preliminary tests one can conclude that the linearity of the detection system is good and that an energy resolution around 1 % could be achieved for the highest proton energies. The results of energy resolution obtained in this experiment indicate that the overall design goals for a TPR neutron spectrometer could be achieved by the use of a silicon detector system.

**Neutron emission spectroscopy using a NE213 liquid scintillator**

**F. Binda, G. Ericsson, J. Eriksson, C. Hellesen, S. Conroy, E. Andersson Sundén**

Neutron emission spectroscopy for fusion plasmas can provide information about various plasma parameters: ion temperature, ion densities, fast ions distributions etc. This has been done so far using big and complex neutron spectrometry systems that are optimized to provide spectra with very good resolution. However, they might not be suitable for future tokamaks such as ITER and DEMO, where the space allotted for diagnostics will be drastically reduced. Compact detectors such as NE213 liquid scintillators could be viable alternatives due to their
small dimensions. The drawbacks are the poor resolution, the sensitivity to gain variations, and the rather complex response function that make the analysis of the measured spectra a challenging task.

Previous attempts of spectroscopy with NE213s were mainly focused on using unfolding methods to extract the neutron spectrum from the experimental pulse height spectrum. Little or no information about the fusion plasma is gained in this way.

In this work we instead try to develop an analysis method from which parameters relevant for plasma physics can be obtained. In the so called forward fitting approach, modeling codes are used to calculate the contributions to the neutron spectrum from different plasma ion populations, such as thermal, beam heated, ICR heated ions etc. The resulting spectral components are then folded with the response function and compared with the experimental data. One can thus, for example, gain information about the intensities of such components, which are related to the density of the different ion populations and give information about the state of the fusion plasma.

A NE213 installed with the MPRu spectrometer at JET was used to measure the neutron emission during the experimental campaigns in 2013. The response function of the detector was obtained from MCNPX simulations, and it was fine-tuned using measurements from a gamma source and from JET ohmic pulses. The ratio between the intensities of the thermal and beam-thermal components was calculated for a selection of JET pulses with NBI heating. The obtained results were then compared with the results from the time of flight spectrometer TOFOR. The better statistics in the NE213 data partly compensates for the worse resolution of the instrument. Nevertheless, as expected, the uncertainties in the estimates based on the NE213 data are significantly higher than the ones made with TOFOR. Still the values obtained show a trend which is comparable to the one observed in the values obtained from the TOFOR data.

![TOFOR - NE213 comparison](image)

**Figure 3.1.2-11**: Comparison between the thermal fractions obtained from the TOFOR analysis and the NE213 analysis. The red solid line is the best linear fit, the blue dashed line is the ideal 1 to 1 relationship.
Monte Carlo simulations of a data acquisition chain for scintillation detectors


The performance of a scintillation detector can be strongly affected by the instrumentation used to acquire the data. The possibility of anticipating how the acquisition chain will affect the signal can help in finding the best solution among different set-ups.

In this work we developed a Monte Carlo code that aims to simulate the effect of the various components of a digital Data Acquisition system (DAQ) applied to scintillation detectors. The components included in the model are: the scintillator, the photomultiplier tube (PMT), the signal cable and the digitizer.

We benchmarked the code against real data acquired with a NE213 scintillator, comparing simulated and real signal pulses induced by gamma-ray interaction. Then we studied the dependence of the energy resolution of a pulse height spectrum (PHS) on the sampling frequency and the bit resolution of the digitizer. We found that exceeding some values of the sampling frequency and the bit resolution improves only marginally the performance of the system.

The method can be applied for the study of various detector systems relevant for nuclear techniques, such as in fusion diagnostics.

![Real and simulated signal comparison](image)

**Figure 3.1.2-12**: Comparison between an average gamma signal from a real NE213 scintillator (black dashed line) and an average gamma signal from the simulation code (red line).

3.1.3 Neutron Diagnostic at MAST and MAST Upgrade

Fast ion observations during the experimental campaign for 2013

M. Cecconello, I. Klimek, S. Sangaroon

The encouraging results obtained in the past years and the preliminary modelling provided the motivation and justification for carrying out a series of dedicated experiments during the 2013 MAST experimental campaign with the aim of measuring as accurately as possible, using the full set of fast ion diagnostics in a coordinate way and the interpretation codes, the fast ion losses and redistribution in many different operating scenarios, characterized by the presence of Alfvén eigenmodes, energetic particle modes such fishbones and long-lived modes, and sawteeth. These dedicated experiments were planned, coordinated and executed by the Fusion Neutron Diagnostic Group and involved collaborators from CCFE, PPPL and Florida.
International University: more than 100 dedicated pulses were carried out. In addition to dedicated experiments, the neutron camera directly supported experiments aimed at identifying operational regimes with low or no redistribution of fast ions, to the study of fast ions redistribution during ELM mitigation experiment with resonant magnetic perturbations. Some of the experimental observations obtained during the dedicated experiments are shown in figure 3.1.3-1. Panel (a) shows the signatures of bursting Alfvén modes, fishbones and long-lived mode on a Mirnov coil. Strong bursting fishbones have a large impact on the fast ion population as it can be seen in panel (b) where the neutron camera count rate profile before (red) and after (blue) after one of such burst is shown. Panel (c) show the typical time trace of the SXR emission for a sawtooth while panel (d) shows the dramatic effect of the sawtooth on the fast ion population as measured by the neutron camera.

Data analysis and modelling

TRANSP modelling continued in 2013 with a particular focus on the effect of small and large amplitude energetic particle modes on the neutron emission on MAST. Good agreement is obtained as shown in figure 3.1.3-2 by a combination of diffusive redistribution of fast ions well above the neo-classical level (so called anomalous diffusion) and fast ion losses. The effect of bursting fishbones on trapped and passing fast ions were modelled with NUBEAM.
resulting in identification of the regions in the energy-pitch angle of the fast ion distribution function that were most affected by this mode. The main question whether the trapped or fast

![Image](image1.png)

**Figure 3.1.3-2.** a) Fourier spectrogram of magnetic fluctuation picked up by a Mirnov coil showing the period of small and large fishbones evolving into a long lived mode, b) measured and modelled neutron yield using NUBEAM loss models c) Neutron count rate measured by the neutron camera for our channels whose radial position is characterized by impact parameter $p_1 = 0.79$ m and $p_2 = 0.59$ m

ions are mostly affected by the fishbones is still yet unresolved and more sophisticated modelling tools are required. An initial attempt in this direction is shown in figure 3.1.3-3, panel (a) where experimental neutron count rate profiles before and after a fishbones are modelled with the self-consistent nonlinear wave-particle interaction code HAGIS: agreement is achieved by an ad-hoc choice of the mode amplitude and frequency evolution.

![Image](image2.png)

**Figure 3.1.3-3.** Left panel: comparison between neutron camera profiles before and after a fishbone event compared with predictions using HAGIS. Right panel: measurements and TRANSP modelling of the neutron camera profiles in MAST plasmas with off-axis NBI. Right panel: radial profile of neutron camera signal for off-axis NBI heating (LSND plasma) obtained in 5 repeated discharges at 1.5 and 3 MW of NBI heating during a MHD quiescent period. TRANSP predictions with different levels of anomalous fast-ion diffusion.
Neutron camera upgrade for MAST upgrade

M. Cecconello, I. Klimek, S. Sangaroon, M. Weiszflog

At the end of 2013 MAST entered a long shut-down period for a major upgrade: operations on MAST Upgrade will resume in 2016. The upgrade concerns the central columns and the toroidal field coils, the position of the poloidal field coils and the divertor geometry (super-X). The number of the neutral beam injector heating system will increase step-wise from 2 to 4 resulting in the doubling of the neutron yield. In the first step of this upgrade (“core-scope”) the heating system will consists of one equatorial and of one off-axis NBI providing a great flexibility in the fast ion pressure profiles and current drive. The activities for the conceptual design of an neutron camera upgrade, able to measure in a single pulse the full radial profile in presence of off- and on-axis NBIs, initiated in 2012 has continued during 2013, when additional viewing geometries were explored. In addition to the 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, vertical and poloidal camera designs were investigated and their performances addressed. MCNP was used to determine the required neutron and gamma-shield, the ratio between direct and scattered neutrons, the collimator sizes and the expected direct fluxes at the detectors. These calculations were based on neutron emissivity profiles for MAST Upgrade predicted by TRANSP. The neutron shielding and collimation geometries for the equatorial views is shown in figure 3.1.3-4 while figure 3.1.3-5 shows the lines of sight investigated for a poloidal cross-sectional view of the plasma. Optimization of these designs is on-going: a final design for the upgraded neutron camera will be produced during 2014.
Collaborations
O. Jones, R. Akers, M. Turnyaskiy, D. Keeling, and the MAST team, Culham Centre for Science Fusion, UK
M. Gorelenkova, Plasma Physics Laboratory, Princeton University, Princeton, USA
W. Boeglin, R. Perez, Florida International University, Florida U

Participation to international conferences
S. Sangaroon, 40th EPS Conference & 16th Int. Congress on Plasma Physics, 2013, Helsinki
I. Wodniak, 40th EPS Conference & 16th Int. Congress on Plasma Physics, 2013, Helsinki
M. Cecconello, 17th International Spherical Torus Workshop, York, UK

List of publications

3.2 Neutron emission spectroscopy

O. Ågren, V.E. Moiseenko, A. Hagnostã, and K Noack in collaboration with ENEA (Milano/CNR) and Peking University

This work concerns development of interpretation models for the neutron emission spectra from present D plasmas of present and future tokamaks and present DT plasmas such as JET. It includes spectrometer instrumental development for D plasmas, present and future. Studies are also being done to explore the potential role for the role of neutron spectrometers in the monitoring of the DT plasmas of power reactors.

Interpretation model have been developed to handle the contribution in multi-step processes up to third order affecting the neutron emission in D and DT plasmas also with a 3He admixture added for RF heating purposes. This involved development of the neutron production description as well as development of estimation for missing reactions and scattering cross section data. This year we have published a comprehensive paper (number one below) that describes the contribution to the neutron emission down to the 10^-5 level relative to the fuel ion neutron production. The results show which energy regions, such as the tails that can be used for diagnostic purposes and under which principal conditions. These results also show which higher order terms are insignificant and can be ignored. An example of the latter is illustrated in the figure below which shows that in thermal DT plasma the alpha particle knock-on neutron (AKN) emission is dominating all other knock-on contributions in the neutron spectrum tail.
The work on interpretation code has also been exploited in the analysis of older neutron emission from JET DT campaign taken with the MPR spectrometer. This is represented by the result in paper nr. two.

The instrumental work was devoted to enhancing the design of the TOFOR type of time-of-flight spectrometer. Since its implementation at JET 2005, there has been further development in the electronics in allowing the digital waveforms (DWF) recording of all detector pulses. These provide both time and pulse height information while only the timing was available in TOFOR installed on JET. In order to take advantage of the new capabilities offered by DWF electronics the design of TOFOR has been revisited resulting in the idea to split the large detectors into two segments. This is referred to as the TOFOR II design. The two designs have been compared in detailed simulations. The results show that TOFOR II give significant cleaner spectra with a reduction in multiple scattering contributions and hence higher sensitivity in the measurements. It offers better time resolution for given efficiency. Moreover, with one more parameter (the segment ratio) it leaves more for optimizing the performance to the measurement conditions presented by the plasmas. The principles of the TOFOR II design is illustrated in the figure below.

![Figure 3.2.1-1. Example of calculated neutron emission for a thermal DT (50:50) plasma. Only the high energy tail of 14 MeV spectrum is shown.](image1)

![Figure 3.2.1-2. Principles of the time-of-flight neutron spectrometer (left) and the TOFOR II design.](image2)
task will be to record and interpret plasma evolution with accurate and high spectral sensitivity. TOFED will be the right instrument for this task. The JET experience has demonstrated that the TOFOR type can deliver required stability and reliability. Paper 4 was given the referee judgment: ‘This is a well-written paper containing remarkable idea on fusion neutron spectrometer based on leading-edge technologies. The proposed spectrometer will be able to contribute to physics experiments on beam ions in MCF.’

Neutron emission signal can be assumed to be essential for monitoring signal for the control of fusion power reactors and which, most likely, will include spectrometers, especially, in the start-up phase to reach steady-state full power operation. Not much is known about how this should be done, if at all possible. We have considered developing the MPR concept for the 14-MeV spectrometer and explore different adaptation possibilities which would be done under the name MPR II. As a first approach, we explored the new framework for neutron monitoring of a relatively simple plasma such as a mirror use as neutron source in fusion-fission hybrid reactor (reported in Jan Källne, Klaus Noack, Olov Ågren, Giuseppe Gorini. 'Neutron diagnostics for mirror hybrids' in Proceedings of the International Conference on 'Fusion for neutrons and subcritical nuclear fission (FUNFI)', (Editors J Källne et al), 1442 (2012) p. 291). The work is ongoing but no publishable results were obtained during 2013.

Publications section 3.2

Peer reviewed journals


3.3 Gamma emission spectroscopy

Jan Källne, and Massimo Nocente and Giuseppe Gorini of ENEA/CNR(Milano)

The code used for neutron emission spectroscopy has been adapted? gamma emission spectroscopy. This was done for purpose of being able to judge the characteristics of each diagnostic on the same footing at high accuracy level. No code for gammas was available earlier. Of special interest was to establish a basis for judging the diagnostic uses of these two nuclear processes whose detection methods are technically different. The plan is to go through different neutron and gamma production reactions, which in gamma case requires the ability to treat also results from unstable (broad) nuclear states. An initial issue has been to examine
to what extent relativistic effects play a role in the two cases. Preliminary results have been presented in paper one below.

**Publications section 3.3**

**Conference report**

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 and H. Nordman, Chalmers University of Technology

Our research within computational methods concerns stability and confinement of reversed-field pinch (RFP) plasma configurations as well as the development of new, time-spectral methods for solving systems of partial differential equations. In the first research area, resistive pressure-driven resistive instabilities have been studied, because of their detrimental effect on confinement in the RFP. The second research area concerns a new, general method for solving initial-value problems with strongly separated time scales.

Theoretical and numerical modelling of RFP confinement

A non-linear resistive MHD numerical study of confinement improvement in the RFP using a static model for current profile control (CPC) has been performed [1]. CPC has the aim of reducing current driven resistive (tearing) modes by flattening the current density profile in the centre of the plasma. It can be achieved by using RF techniques such as lower hybrid or electron Bernstein current drive. Our numerical models include the fully nonlinear resistive MHD code DEBSP as well as linear codes, including the effects of perpendicular and parallel heat conduction. By tailoring the parameters of the CPC model, an advanced mode of operation, characterized by up to a three-fold increase in energy confinement and a 30% increase in poloidal beta up to values of 0.27, is reached (Figs 1a and 1b). The edge heat flux is reduced to about a third of that in the conventional RFP case. The high-confinement phase may, however, be interrupted by a crash with a rapid decrease in confinement. The power going into the CPC during the high-confinement phase is non-negligible although not prohibitive; it causes 10–15% confinement time reduction in optimized scenarios.

![Figure 1](image1)

**Figure 1.** Poloidal beta (a) and energy confinement time (b) vs time (resistive time units) for aspect ratio $R/a = 4$ (red graphs) compared with reference (no CPC) and CPC cases (green graphs) with $R/a = 1.25$. 
Plasma fluctuations are substantially decreased by CPC; poloidal cross section Poincare’ plots show less stochastic flux surfaces. Magnetic power spectra show that essentially only two unstable modes remain in the high-confinement regime; these are the \((m, n) = (1,-2)\) and \((1,-8)\) modes. All \(m = 0\) modes are reduced to negligible levels. Contrary to the \((1,-2)\) mode, the \((1,-8)\) mode is resonant near the reversal region, where instability is shown to arise due to the combination of high pressure and a high pressure gradient.

The mode is analysed using both \(\Delta'\) theory and a linear full resistive MHD code based on the GWRM. It is found that the current profile is stable against tearing modes but that, using the traditional adiabatic energy equation, there is a significant growth of the linear \((1,-8)\) pressure-driven resistive g-mode prior to the crash. Pressure-driven instability is also found using a delta prime model with thermal effects included in the energy equation, above a Lundquist number threshold, and for all current Lundquist numbers in the GWRM model. Stability below a critical Lundquist number is consistent with our earlier results showing that, at higher Lundquist numbers, the heat conductivity causes linear growth rates to be only weakly dependent on the Lundquist number (Figure 2). Heat conduction effects, as applied to this model, thus do not inhibit resistive g-mode instability in reactor relevant (high Lundquist number) plasmas in the RFP; the unfavourable curvature effects are too strong. It remains to determine whether kinetic effects due to the relatively large Larmor radii in the RFP may quench the resistive g-modes in this regime.

The crash obtained in the DEBSP simulations subsequently establishes a lower beta and a weaker global pressure gradient. A similar behaviour is obtained for simulations at high aspect ratios. Further studies are required to establish whether stable plasma behaviour can be obtained in the high-confinement regime using static current profile control. The required practical implementation of RF techniques such as lower hybrid and electron Bernstein current drive need also be assessed.

![Figure 2. Growth rate \((\gamma)\) of the \(m = 1, n = -8\) mode versus resistivity for \(t = 0.54\), obtained by the \(\Delta'\) model.](image)

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

Numerical solution of systems of partial differential equations for fusion plasma modelling, as for DEBSP described above, is extremely time-demanding. Employing traditional methods, some \(10^5-10^7\) time steps are required for simultaneous resolution of the basic MHD, resistive as well as conductive time scales. Work has thus continued on the Generalised Weighted Residual Method (GWRM), a generalisation of weighted residual methods to the time and parameter domains. The novelty, as compared to standard (explicit or implicit) finite
difference methods, is that the time domain is treated spectrally, thus avoiding the limitations on time step length caused by CFL-like conditions. A semi-analytical finite Chebyshev polynomial ansatz is employed, and the numerical problem reduces to determination the coefficients of the ansatz from linear or nonlinear algebraic systems of equations. In order to avoid large memory storage and computational cost, the temporal and spatial domains are divided into subdomains. Methods and examples to show how this can be achieved are now published. Efficient spatial subdomain methods will be a major research topic for 2014.

The work during 2013 was aimed to extend application of the GWRM to solution of 2D two-fluid initial-value equations, modelling drift wave turbulence. This work is carried out in collaboration with prof. H. Nordman at Chalmers University of Technology. Presently, the basis for a 2D GWRM code is being developed to determine the temporal evolution of nonlinear ITG and TE modes. For benchmarking, all linear terms have so far been implemented, using the parameters of the standard Cyclone base case and a 2D box, the sides of which are 50 ion Larmor radii. Preliminary results indicate very good agreement between theoretical and GWRM linear growth rates.

In summary, we have to this date applied the GWRM to a number of linear and nonlinear initial value problems in the forms of ordinary and partial differential equations. Accuracy and efficiency have been studied by comparisons with exact solutions. Improved performance by using temporal and spatial subdomains is shown. Comparisons with standard explicit and implicit finite difference methods display very positive results relating to computational efficiency.

**Publications section 4.1**

**Peer reviewed journals**

**Presentations at international conferences and workshops**

**4.2 Stellarator plasmas with localized neutron production**

*V.E. Moiseenko, O. Ågren, S.V. Chernitskiy (PhD student), A. Hagnestål, J. Källne in collaboration with IPP NSC KhIPT, Ukraine*

For a stellarator concept with localized neutron production, calculations of the magnetic field had been carried out to determine magnetic surfaces in the Uragan-2M stellarator (Kharkiv, Ukraine). One toroidal magnetic field coil is switched off, which results in a local magnetic mirror where neutrons can be produced by sloshing D-T ions. The calculation predicts existence of magnetic surfaces for such a case. This is also confirmed by measurements made in the device by the method of luminescent rod.

Neutral beam injection (NBI) into the stellarator-mirror is computed to model fast ion confinement using a two-dimensional kinetic code. The code accounts for Coulomb collisions between the hot ions and the background plasma. Along with the kinetic calculations, the neutron production intensity in a D-T plasma is computed.
Publications section 4.2

Peer reviewed journals


4.3 System studies (based on concept transfer from fusion-fission hybrid research)

O. Ågren, V.E. Moiseenko, A. Hagnestål, S.V. Chernitskiy (PhD student), J. Källne in collaboration with IPP NSC KhIPT, Ukraine

In a magnetic fusion device utilizing a metallic coolant, it is necessary to pump the coolant across a magnetic field. This could require a large pumping power to overcome the retarding Lorentz force in case the inner surfaces of the coolant pipes are conducting. Dielectric coatings of the pipes may reduce the power requirements by eliminating short-circuited currents in the pipes, but the coatings need to withstand wear and chemical aggression. To study this, a proposal for experimental tests on power demands, wear and material analysis, of coatings for a liquid metallic coolant flowing across a magnetic field has been suggested.

It is necessary to achieve a tritium breeding ratio (TBR) above unity in any a stand-alone fusion reactor. This is a challenging task and as a complement to the standard TBM development it has been suggested this could be achieved through the introduction of fissile material. Valuable experience could then be gained from studies of hybrid reactors, where a combination of fusion and fission reactor segments could enable a high TBR. Monte Carlo simulations by our group predict a high TBR (around 1.8) in certain hybrid reactor schemes. These studies have been accompanied by design of superconducting coils and geometrical arrangements for equipment needed for heating, diagnostics and other issues.

A difficulty encountered in the coil design is the need to produce magnetic field gradients of sufficient strength to achieve a moderately high mirror ratio, combined with a need to leave sufficient space for reactor parts in the region interior to the coils. Several methods were tested with inadequate results for the mirror ratio and precision of the field design. A final attempt with 3D superconducting coil arrangements resulted in a compact design (coil radii 6m) and quite high precision towards the aimed field. The field errors associated with the designs could still lead to radial loss due to magnetic drifts. However, it is shown theoretically that such loss could be cured by sectioned biased endplates to produce a radial electric field. This results in a slow drift motion around the magnetic axis and, in a collision free approximation, the particle motion is predicted to be radially bounded for an infinite time.
Publications section 4.1.2

Peer reviewed journals


5 Emerging technology

5.1 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 previously 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. A KMC model that can be used to simulate the evolution of the material under both thermal and irradiation conditions has been developed. This model is based on pair interactions which have been shown to not be ideal for describing the processes involving interstitial oxygen atoms. Notably, the strong anisotropic effects that are predicted from DFT for the oxygen-oxygen interactions is difficult to take properly into account. We have thus in collaboration with the group of Matthias Posselt at HZDR, Germany implemented a pair+triplet interaction model for the KMC code. This model provides a reliable way to implement the DFT predictions into a KMC framework and its implementation into the LAKIMOCA code allows for simulations of cluster nucleation and irradiation stability. The many-body interaction model is written as

$$E = \sum_{i} \frac{1}{2} \sum_{j,k} m(i,j;k) \varepsilon(i,j;k) + \sum_{i} \frac{1}{2} \sum_{j,k} \sum_{J,k} n(i,j;J,k;kl) \delta(i,j;J,k;kl)$$

With this model implemented, we can now see the formation mechanisms for three dimensional clusters, see for example figure 1. The crucial role of vacancies is highlighted and without them, as previously determined, the clusters would nucleate in planar shapes.
Figure 1. A three dimensional cluster nucleated with 8 vacancies, 8 oxygen atoms and 5 yttrium atoms. Cr atoms are loosely attached to the cluster surface.

**Publications section 5.1**

**Peer reviewed journals**


6 Participation in the EFDA Program 2013

The EFDA Work Programme for 2013 includes:

• Activity at JET, under Art 6.3 of the EFDA Agreement and also specified in the Contract of Association under Art 8.1a (Baseline support for Notifications), Art 8.2c (Additional Support in connection with Science and Technology (S/T) work) and Art 8.2g (Close Support Unit (CSU) Secondments).

• Non-JET activity specified in the Contract of Association under Art 8.1a (Baseline support) as well as Art 8.2a, Art 8.2b and Art 8.2e (Additional Support).

The annual EFDA Work Programme is prepared by the EFDA leadership and endorsed by the EFDA Steering Committee and the Consultative Committee EURATOM - Fusion (CCE-Fu). The EFDA leader for 2013 was F.Romanelli.

The EFDA JET activity is structured under the JET Department (Dept head L.Horton) and is mainly structured in Task Forces (TF): the experimental task forces TF-E1 and TF-E2 organize and elaborate the scientific exploitation of the JET device and the task force Fusion Technology (TF-FT) coordinates a number of fusion technology projects at JET. In addition, several Enhancement Projects (EP) are conducted to upgrade old or add new instrumentation to the JET facility. On-site participation in Task Force or Enhancement work is covered by Orders while Notifications (and Mobility) are issued for on-site work outside Campaigns as well as at the home lab.

The Non-JET EFDA Work Programme is structured under the Departments for ITER Physics (Dept head R.Neu) and the Department for Power Plant Physics and Technology (PPPT, Dept head G.Federici).

The ITER Physics work is organised into one Task Force: Integrated Tokamak Modelling (ITM-TF) and eleven cross-cutting Topical Areas A1-A11. The EFDA Task Force for Plasma Wall Interaction (PWI) and the Topical Groups for Heating and Current Drive (HCD), Diagnostics (D), Magneto-HydroDynamics (MHD), Fusion Materials (FM) and Transport (T) are at present not used in implementing the program. The ITER Physics department also handles issues of common computing resources and the collaboration with Japan on the development of the JT60-SA tokamak under the Broader Approach agreement. There is a very high level of collaboration between the research groups of the RU and these entities of the EFDA program organization.

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).

An overview of the participation of the Swedish Fusion Research Unit in this activity is presented below.
6.1 Participation in EFDA JET Coordinated Activities

6.1.1 JET Work Programme Task Agreements

Involvement of the RU in the EFDA JET Task Agreements is summarized in Table 6.1. This includes the Task Agreements covering the JET experimental campaigns, the work in Enhancement projects and in Fusion Technology tasks.

<table>
<thead>
<tr>
<th>EFDA Task Agreement reference</th>
<th>Title</th>
<th>Person, group / subject</th>
<th>Comment/ Further Info</th>
</tr>
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<tr>
<td>JW12-TA-EXP-06B</td>
<td>JET Campaigns C31-C34</td>
<td>KTH, Chalmers, UU, LU Amendment</td>
<td>Table 6.3 Ongoing</td>
</tr>
<tr>
<td>JW12-TA-FT-JET JW12-OFT-VR-37</td>
<td>JET Fusion Technology</td>
<td>KTH – Alfvénlab Uppsala University</td>
<td>Table 6.2 Ongoing</td>
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<tr>
<td>JW12-TA-EDT-VNS-01</td>
<td>Vertical Neutron Spectrometer</td>
<td>Uppsala University, Neutron diagnostic group: Development of data analysis tools</td>
<td>Table 6.2 Started</td>
</tr>
<tr>
<td>JW13-TA-EDT-ISU2</td>
<td>Isotope Separator Upgrade Feasibility Study (NPA) - continuation</td>
<td>Uppsala University, Neutron diagnostic group: “Modeling of neutron flux at KR2 detector position”</td>
<td>Table 6.2 Starting in 2014</td>
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<td>JW13-TA-FT-JET JW13-OFT-VR-41</td>
<td>JET Fusion Technology</td>
<td>KTH – Alfvénlab Uppsala University</td>
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6.1.2 Overview of Orders and Notifications within the JET Enhancement and Fusion Technology Activities

Table 6.2 provides information on the Orders and Notifications for the activity within JET Enhancements and Fusion Technology, i.e., not including the JET campaigns.

As can be seen in Table 6.2, the Swedish Association is involved in a large number of activities in the JET Task Force Fusion Technology (TF-FT) an within two projects in the JET Enhancement Programme (EP) for future DT operations (presently planned for 2017). Some of the projects initialized in the Work Programme 2012 are still active.

The work in the Enhancement Programme concerns participation in the project for the “Neutral Particle Analyzer upgrade” and the “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”, “Be-10 experiment”, “First test mirror at JET”, “Evaluation of integral JET plasma data”, “Update of the dust dynamic code”, “Assessment of the TOFOR spectrometer” and “Fuel ion ratio determination”.

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Table 6.2 Swedish participation in JET EP2, Fusion Technology and Orders other than campaign related activity.

<table>
<thead>
<tr>
<th>EFDA reference</th>
<th>Key persons / Groups</th>
<th>Title / subject</th>
<th>Period (remaining cost)</th>
</tr>
</thead>
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<tr>
<td>JW12-NEP-VR-44</td>
<td>UU-ND (Ericsson)</td>
<td>VNS: Analysis tools for Vertical Neutron Spectrometer</td>
<td>2015 - ongoing (160 ppd)</td>
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<td>JW12-FT-3.74</td>
<td>KTH (Bergsäker)</td>
<td>Plasma facing components. Microbeam analysis and SEM/EDX analysis on cross section</td>
<td>2013 - ongoing (102 ppd, 10 k€)</td>
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<tr>
<td>JW12-FT-3.75</td>
<td>KTH (Bergsäker)</td>
<td>Plasma facing components. Be-10 experiment</td>
<td>2013 - ongoing (105 ppd, 10 k€)</td>
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<tr>
<td>JW12-FT-4.24</td>
<td>KTH (Rubel)</td>
<td>Engineering: First mirror tests JET</td>
<td>2013 - ongoing (100 ppd, 15 k€)</td>
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<tr>
<td>JW12-FT-5.44</td>
<td>UU (Ericsson)</td>
<td>Neutronics and Safety: Fuel ion ratio determination</td>
<td>2013 - ongoing (213 ppd)</td>
</tr>
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<td>JW13-OEP-VR-38</td>
<td>UU-ND (Ericsson)</td>
<td>ISU2: Modeling of neutron flux at KR2 detector position; work at JET</td>
<td>2014 - starting (Orders 10 k€)</td>
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<tr>
<td>JW13-NEP-VR-43</td>
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<td>ISU2: Modeling of neutron flux at KR2 detector position; work at UU</td>
<td>2014 - starting (20 ppd)</td>
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<td>JW13-FT-3.77</td>
<td>KTH – PWI (Bergsäker)</td>
<td>Marker experiments with 10-Be in JET ITER_like wall; AMS measurements and modelling</td>
<td>2013 – ongoing (Orders 1 k€) (Notif 23 k€)</td>
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<td>JW13-FT-3.78</td>
<td>KTH – PWI (Rubel)</td>
<td>Analysis of mirrors exposed in JET ITER-like wall …</td>
<td>2013 – ongoing (Orders 14 k€) (Notif 5 k€)</td>
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<td>JW13-FT-3.79</td>
<td>KTH – PWI (Rubel)</td>
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<td>JW13-FT-4.34</td>
<td>UU – ND (Ericsson)</td>
<td>Assessment of the TOFOR time-of-flight n spectrum. in view of …</td>
<td>2013 – ongoing (Notif 15 k€)</td>
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</table>
6.1.3 Overview of Orders and Notifications for JET Campaigns

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-C30, JET went into shutdown in the end of July 2012. The JET machine was ready for pump-down in May 2013 and after a 2-month restart period, experimental campaign C31 started on July 8, 2013. C31 lasted until Sept 27 and was immediately followed by C32, running from Sept 30 and pre-maturely ended in October due to several technical problems. JET operations are presently suspended, and will commence in 2014. Campaigns C33 and C34 will follow in 2014.

Work in C31-C32 has been focused on continued exploitation of the ITER-like wall, expanding the operational range by, for example, moving into operations with higher heating power. Researchers and groups from VR participate in a number of active, parasitic and back-up experiments as well as in the newly formed “Tasks”, cross-cutting collaborations of JET participants. VR scientists also act as Scientific Coordinators, Diagnostic Coordinators and control room experts for various diagnostic systems. The VR commitment to the C31-C32 experimental campaigns in 2013 amounts to about 470 person days (preliminary number of ST Order and on-site Notification days). In addition, VR scientists conducted work in support of the JET campaigns under Notifications at their home institutes for about the same number of days. The experimental activities under these contracts continued into 2014.

Table 6.3 gives information on VR Orders and Notifications associated with JET campaigns.

<table>
<thead>
<tr>
<th>EFDA reference</th>
<th>Key persons / Groups</th>
<th>Title / subject</th>
<th>Period (total secondment days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JW12-O-VR-40</td>
<td>KTH, UU, Chalmers, LU</td>
<td>S/T Order for experimental campaigns C31-C33</td>
<td>Superseded by …-40A</td>
</tr>
<tr>
<td>JW12-O-VR-40A</td>
<td>KTH, UU, Chalmers, LU</td>
<td>S/T Order for experimental campaigns C31-C34</td>
<td>Superseded by …-40B ST Orders: 430 p-days Notif at JET 40 p-days</td>
</tr>
<tr>
<td>JW12-O-VR-40B</td>
<td>KTH, UU, Chalmers, LU</td>
<td>S/T Order for experimental campaigns C31-C34</td>
<td>Continues into 2014 ST Orders: 430 p-days Notif at JET 40 p-days</td>
</tr>
<tr>
<td>JW12-N-VR-45A</td>
<td>KTH, UU, Chalmers, LU</td>
<td>Notifications for experimental campaigns C31-C34</td>
<td>Finished Superseded by …-45B</td>
</tr>
</tbody>
</table>

6.1.4 Additional Participation in EFDA JET Activity

In addition, VR provides personnel to the EFDA JET activity through secondments to the JOC effort (for information only):

- Neutron group - Sean Conroy
- Spectroscopy group - Sheena Menmuir
VR also provides expert personnel such as Scientific Coordinators, Diagnostic Coordinators and Control Room Experts in neutron diagnostics, spectroscopy and other diagnostics, as well as in plasma theory and modelling.

### 6.2 Participation in EFDA Coordinated Activities on ITER Physics

The non-JET activities of EFDA are structured within the Departments for “ITER Physics” (IPH) and “Power Plant Physics and Technology” (PPPT). Within the EFDA Coordinated Activities in ITER Physics there is at present one Task Force with specified activity in the Work Programme: the Integrated Tokamak Modelling Task Force (ITM-TF). The rest of the activities are structured into 11 cross-cutting topical research areas, which each involve several of the old Task Forces and Topical Groups. The activities in PPPT are structured under six different Project Areas. Some activities of smaller scope, like joint activities in the area of “broader approach”, i.e., JT-60SA Physics, are also included here.

VR participates in many of these activities with tasks in TF-ITM, in 5 of the Topical research areas, in 3 projects within PPPT and with a small activity for JT60SA. 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 Yadykin (Chalmers) and the Deputy TF-PWI Leader is Marek Rubel (KTH). Marek Rubel has also acted as Area coordinator for ITER Physics Research Area A3 - Fuel Retention and Removal.

The topical research areas are given in Table 6.4, which also includes the VR contact person for each area.

<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 Formation Marek Rubel (KTH)</td>
<td>A7</td>
<td>Disruptions, prediction, avoidance, mitigation and consequences Tünde Fülöp (Chalmers)</td>
</tr>
<tr>
<td>A2</td>
<td>Shaping and controlling performance limiting instabilities Per Brunsell (KTH)</td>
<td>A8</td>
<td>Physics of the Pedestal and H-mode Tünde Fülöp (Chalmers)</td>
</tr>
<tr>
<td>A3</td>
<td>Fuel Retention and Removal Marek Rubel (KTH)</td>
<td>A9</td>
<td>Fast Particles Vacant</td>
</tr>
<tr>
<td>A4</td>
<td>Plasma rotation Thomas Johnson (KTH)</td>
<td>A10</td>
<td>Particle transport, fuelling and Inner Fuel Cycle modelling Hans Nordman (Chalmers)</td>
</tr>
<tr>
<td>A5</td>
<td>Core electron heat transport and multi-scale physics Pär Strand (Chalmers)</td>
<td>A11</td>
<td>Operation with metallic plasma facing components including High Power ICRH Yevgen Kazakov (Chalmers)</td>
</tr>
<tr>
<td>A6</td>
<td>Pedestal instabilities (ELMs), Mitigation and Heat loads Lorenzo Frassinetti (KTH)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 6.5 gives an overview of the activity in the area of JT-60SA Physics in 2013.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Description</th>
<th>Commitment (in PY)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WP13-JTA-RWP</td>
<td>M. Rubel, KTH</td>
<td>0.1 baseline</td>
</tr>
</tbody>
</table>

Table 6.6 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>WP13-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>WP13-ITM-EDRG</td>
<td>ACT3-01 Synthetic diagnostics (neut)</td>
<td>0.10 baseline</td>
</tr>
<tr>
<td>WP13-ITM-IMP12 MHD Equilibrium, stability and disruptions</td>
<td>ACT1-01 CarMa code .. (Chalm RoG) ACT1-02 Contr workflow (Chalm RoG)</td>
<td>0.15 priority 0.10 priority</td>
</tr>
<tr>
<td>WP13-ITM-IMP3</td>
<td>ACT1-01 Maint . core comp (Chalmrs)</td>
<td>0.20 priority</td>
</tr>
<tr>
<td>WP13-ITM-IMP4 Transport proc. and Micro.</td>
<td>ACT3-01 Linear/non-linear (Chalmrs) ACT4-01 Maint. &amp; standards (Chalmrs)</td>
<td>0.08 priority 0.08 baseline</td>
</tr>
<tr>
<td>WP13-ITM-IMP5 Heating, Current Drive, Fast Particles</td>
<td>ACT1 Benchmarking (UU) ACT2 Integr. of modules (KTH) ACT3 Dev &amp; integr. (KTH)</td>
<td>0.05 priority 0.15 priority 0.10 priority</td>
</tr>
<tr>
<td></td>
<td>ACT4 Fast particle codes</td>
<td>0.10 baseline</td>
</tr>
<tr>
<td>WP13-ITM-ISIP ITER Scenario Modelling</td>
<td>ACT3 Infrastructure and code integr. (Chalmers RoG)</td>
<td>0.16 priority</td>
</tr>
<tr>
<td>WP13-ITM-ISM ITER Scenario Modelling</td>
<td>ACT1 Support validation (Chalmers)</td>
<td>0.08 priority</td>
</tr>
<tr>
<td>TOTAL 2013</td>
<td></td>
<td>1.57 PY priority 0.78 PY baseline</td>
</tr>
</tbody>
</table>
Table 6.7 gives an overview of the activity in the EFDA ITER Physics topical areas:

<table>
<thead>
<tr>
<th>Activity</th>
<th>Description</th>
<th>Commitment (PY) (k€ for hardware)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WP13-IPH-A01-P1</td>
<td>Material migration ... (KTH/UU)</td>
<td>0.90 priority 20 k€ hardw. priority</td>
</tr>
<tr>
<td>WP13-IPH-A01-P2</td>
<td>Formation and re-erosion.. (KTH)</td>
<td>0.65 priority 16 k€ hardw. priority</td>
</tr>
<tr>
<td>WP13-IPH-A02-P2</td>
<td>Shape and control .. (KTH-MHD)</td>
<td>1.60 baseline 0.90 priority</td>
</tr>
<tr>
<td>WP13-IPH-A03-P2</td>
<td>Fuel removal methods ..(KTH)</td>
<td>0.4 priority</td>
</tr>
<tr>
<td>WP13-IPH-A03-P3</td>
<td>Ion Cyclotron conditioning for fuel removal… (KTH-PWI)</td>
<td>0.6 priority 16 k€ hardw. priority</td>
</tr>
<tr>
<td>WP13-IPH-A08-P2</td>
<td>Multi device research … (KTH)</td>
<td>0.3 priority</td>
</tr>
<tr>
<td>WP13-IPH-A09-P1</td>
<td>Alpha-driven modes - Neutron camera MAST (UU-ND)</td>
<td>0.7 priority 10 k€ hardw. priority</td>
</tr>
<tr>
<td>WP13-IPH-A09-P2</td>
<td>Diagnosing fast ions in ITER (UU-ND)</td>
<td>0.4 priority</td>
</tr>
<tr>
<td>WP13-IPH-APL-01</td>
<td>Task Force Deputy Leader PWI – M.Rubel (KTH)</td>
<td>0.25 priority</td>
</tr>
<tr>
<td><strong>TOTAL 2013</strong></td>
<td></td>
<td>1.60 PY baseline 5.10 PY priority 62 k€ hardware priority</td>
</tr>
</tbody>
</table>

6.3 Participation in EFDA Coordinated Activities in Power Plant Physics and Technology

The PPPT work is structured 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 2013 in the Areas MAT, PEX and DAS.

Table 6.8 gives an overview of activity in the EFDA Coordinated Activities in PPPT.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Description</th>
<th>Commitment (PY)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WP13-MAT-IREMEV-01-01</td>
<td>Phase Stability and Bonding (KTH, Reactor physics)</td>
<td>0.20 priority</td>
</tr>
<tr>
<td>WP13-MAT-IREMEV-02-01</td>
<td>Evolution of microstructure (KTH, Reactor physics)</td>
<td>0.20 priority</td>
</tr>
<tr>
<td>WP13-PEX-03a</td>
<td>Erosion behaviour of W-coating steels. (KTH-PWI)</td>
<td>0.10 priority</td>
</tr>
<tr>
<td>WP13-DAS-03-HCD</td>
<td>Ion Cyclotron Heating and Current Drive for DEMO (KTH – Alfvenlab)</td>
<td>0.10 priority</td>
</tr>
<tr>
<td><strong>TOTAL 2013</strong></td>
<td></td>
<td>0.60 priority</td>
</tr>
</tbody>
</table>
6.4 Participation in Goal Oriented Training (GOT)

Table 6.9 gives a summary of VR participation in the EFDA Goal Oriented Training program as included in the WP12-GOT-BeFirst task agreement, 25 July, 2012. The level of activity in 2013 is about 0.78 ppy, including both tutoring and time spent by the student in the program.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Description</th>
<th>Commitment (in ppy, total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WP12-GOT-BeFirst</td>
<td>Goal oriented training in PWI, Beryllium First Wall Ongoing</td>
<td>2 ppy student 0.33 py tutoring EC contr. 96.4 kEUR</td>
</tr>
<tr>
<td>FU07-CT-2012-00068</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL 2012 - 2015</td>
<td></td>
<td>2.33 (0.78 py/yr)</td>
</tr>
</tbody>
</table>

6.5 Participation in Programme for Fusion Researcher Fellowships

Table 7.10 gives an overview of VR participation in Fusion Researcher Fellowships in 2013. The fellowship WP11-FRF-VR (S.Moradi, Chalmers) was concluded in June 2013. The Fellowship WP12-FRF-VR for D.Yadikin (Chalmers) had a nominal extension into 2014, but was prematurely terminated.

<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.</td>
<td>Transport study of intrinsic and seeded impurities through scenario modelling – Concluded, reported</td>
<td>0.5 ppy (131 kEUR total)</td>
</tr>
<tr>
<td>Fusion Researcher Fellowship July 2011 – June 2013</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WP12-FRF-VR/Kazakov, Y.</td>
<td>Efficient heating and decontamination: mutual effect of ICRH and impurities in tokamaks Early termination, reported</td>
<td>0.33 ppy (~75 kEUR total)</td>
</tr>
<tr>
<td>Fusion Researcher Fellowship April 2012 – April 2013</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL in 2013</td>
<td></td>
<td>0.83 py</td>
</tr>
</tbody>
</table>

6.6 Summary of VR Activity in EFDA Work Programme

Table 6.11. Summary of Swedish RU involvement in EFDA JET, ITER Physics and PPPT specific actions, Task Forces and Topical Groups for 2013.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Art 8.1 baseline PY</th>
<th>Art 8.2a priority PY</th>
<th>Art 8.2b priority (k€ hardware)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITER Physics</td>
<td>1.60</td>
<td>5.10</td>
<td>62 k€</td>
</tr>
<tr>
<td>TF ITM</td>
<td>0.78</td>
<td>1.57</td>
<td></td>
</tr>
<tr>
<td>Power Plant Physics &amp; Techn.</td>
<td>-</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td>TOTAL 2013</td>
<td>2.38</td>
<td>7.27</td>
<td>62 k€</td>
</tr>
<tr>
<td>JET TF- E1,E2 (Notif./Orders)</td>
<td>~2</td>
<td>~2.0</td>
<td></td>
</tr>
<tr>
<td>JET TF-FT</td>
<td>~1</td>
<td>~0.3</td>
<td></td>
</tr>
<tr>
<td>JET Enhancements</td>
<td>~0.2</td>
<td>~0.1</td>
<td></td>
</tr>
<tr>
<td>Fusion Researcher Fellowship</td>
<td>-</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>GOTiT</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PY in Specified activities</td>
<td>~6.1</td>
<td>~11.2</td>
<td>62 k€</td>
</tr>
</tbody>
</table>
The estimated total RU involvement within the EFDA work program 2013 is about 47 ppy. Activities for a total of about 9.65 person-years have been included in specific EFDA Calls for participation in ITER Physics, ITM and PPPT, as detailed in Table 6.11. In addition, the activities in support of the JET programme, in connection with the campaigns within the E1 and E2 task forces, in the fusion technology programme (TF-FT), in the JET Enhancement programme as well as the participation in the Fusion Researcher Fellowship program, have constituted another 7.7 person-years. Thus, in 2013 about 38% of the contributions of VR to the EFDA programme have been in specific activities; this is a slight reduction compared to previous years. On the other hand, about 24% of the activities have been deemed essential for the programme (here including Orders and Fellowships) and received Priority Support; this is on par with the previous year.

6.7 Projects with additional support

Priority Support for Active in-vessel coils and conducting wall for MHD stabilisation in ASDEX Upgrade (Stage 1).

The ASDEX Upgrade project "Conducting Wall and Active Coils (CWAC)" is led by Max-Planck-Institut für Plasmaphysik (Assoziation IPP-EURATOM) in collaboration with Forschungszentrum Jülich (Assoziation FZJ-EURATOM), Consorzio RFX (Associazione EURATOM-ENEA) and KTH Royal Institute of Technology (Association EURATOM-VR). The involvement of KTH is in the development of the Local Control System for active stabilization of resistive wall modes.

6.8 Fusion Technology at JET

6.8.1 First Mirror Test

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

Windows and so-called first mirrors are essential plasma-facing components (PFC) in all optical spectroscopy and imaging systems used for plasma diagnosis. The installation of more than eighty metallic first mirrors is planned in ITER. Detailed knowledge of their performance is crucial for reliable controlling of plasma operation thus having ultimate impact on the reactor safety, economy and the quality of scientific work. To recognize the extent of changes in the mirror performance a thorough First Mirror Test (FMT) has been carried out at the JET tokamak which 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. 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. The first phase, in JET with carbon walls (JET-C), was completed and described in detail: all divertor mirrors lost reflectivity, while only minor reflectivity degradation occurred to mirrors facing plasma at a big solid angle in the main chamber. The test has been continued in JET with the ITER-Like Wall (JET-ILW) and the first step of the program was finished. The aim of this paper is to overview recent results and, to provide a brief comparison between the two phases of the JET operation.
The exposure in JET-ILW was performed during the entire experimental campaign with twenty polycrystalline molybdenum (Mo-poly) mirrors of which four specimens were coated with a 1 µm thick layer of rhodium (Rh). Mirrors were placed in cassettes located in the divertor (outer, base, inner) and on the main chamber wall; technical details can be found in. The exposure lasted in total 19.1 h with 13.1 h of X-point operation. For comparison, in JET-C, some specimens were exposed during two campaigns for 80 h. Before and after exposure mirrors underwent detailed surface analysis using optical methods (to determine reflectivity), ion and electron beam techniques. Total reflectivity was determined in the range 400-1400 nm using equipment specially designed for handling materials contaminated by Be and tritium. For mirrors from the main chamber wall also specular reflectivity was measured. The essential results for JET-ILW are summarized by several points.

**Mirrors in the divertor** Reflectivity of all test mirrors in the divertor has been significantly degraded. The reflectivity loss by 50-85% was caused by the formation of deposits. Plots in Figure 6.1.1-1 show the initial and post-exposure reflectivity of mirrors exposed in the divertor base (a) and the inner divertor (b). The greatest loss has been determined for the short wavelength range 400-600 nm.

![Figure 6.1.1-1: Total reflectivity of mirrors from: (a) the divertor base and (b) the inner divertor.](image)

The deposit thickness on the divertor mirrors was in the range 60 – 600 nm. It is significantly less than during the JET-C operation when carbon-rich layers exceeding 20 micrometers were formed on the inner divertor mirrors. Beryllium is the main component of co-deposits on divertor mirrors. The layers contain also hydrogen isotopes, carbon, nitrogen, oxygen and inconel components traces of tungsten, but depth profiles of respective elements are different, as shown by the depth profiles recorded with heavy ion elastic recoil detection, Figure 6.1.1-2. While the Be content is high and fairly uniform, the oxygen feature has two maxima: at the surface and at the interface what is most probably associated with its adsorption on the exposed surface and on the original mirror when it was installed in JET. Carbon is found predominantly at the mirror-to-deposit interface, thus corresponding to the initial period of the JET-ILW operation. At the smaller depth the content decreased by a factor of about seven what agrees with spectroscopy measurements of C impurity species. The concentration of nitrogen increases towards the deposit surface thus reflecting the history of the H-mode operation associated with N2 impurity seeding predominantly done during the second half of the operational campaign. The most striking feature is the presence of tungsten. Its content is low but rising with a sharp increase at the surface of the deposit corresponding to the increase of heating power in JET operation. From the ITER diagnostic perspective tungsten deposition on mirror surfaces is probably the most important fact because it would be very hard to remove by cleaning techniques. It points to the need of looking for alternative solutions for optical components in ITER divertor diagnostics.
Main chamber wall. The majority of Mo mirrors (7 out of 8) from the main chamber wall retained high total reflectivity, i.e. the decrease from the initial value was not exceeding 5%. This situation is much different from the observation in JET-C where only mirrors close to the channel mouth (0 or 1.5 cm) retained high reflectivity, while the performance of others was degraded because of the deposition. In some cases in JET-ILW, optical performance has even been increased what might be associated with the removal of the molybdenum oxide during the exposure to plasma. Only one mirror located close to the molten Be outer poloidal limiter got a 60 nm thick beryllium deposit. The surface region (15-30 nm) of wall mirrors in JET-ILW contains light impurities. There are small quantities of metals such as Ni, Fe, W and Cu. Although the layer does not resemble co-deposits, such as found in the divertor, its morphology is a net result of erosion and deposition processes, where deposited light species were efficiently removed by the incoming flux of neutral particles. It is important to state that only traces of tungsten and no nitrogen have been detected on any specimen thus indicating that these impurities are confined in the divertor.

In summary, the results obtained so far for the main chamber mirrors allow some optimism regarding the reliability of diagnostics in ITER. To ensure the best possible predictions the First Mirror Test will be continued in JET-ILW with the increased heating power. There is no doubt, however, that in ITER long-term exposure and off-normal events may change surface properties of the mirrors. A practical solution for maintaining high mirrors’ performance in the main chamber diagnostics can be based on a periodic evaporation of a fresh molybdenum layer on the mirror surface. This approach, limited to mirror surfaces without flaking layers, can be applied in-situ and its implementation and application is more realistic than photonic cleaning, application of protective filters, local plasma or gas puff or other methods critically assessed in earlier works. To implement an evaporator is challenging but it would be less complex that the installation of a mirror exchanger.
**Figure 6.2.1-3:** Total reflectivity of mirrors from two cassettes on the main chamber wall.

**Publications section 6.2.1**

**Peer reviewed journals**


**Presentations at international conferences and workshops**


7 ITPA and IEA activities

7.1 Overview of ITPA/IEA 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 and more recently on topics related to the fusion demonstration reactor that will follow ITER (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.

The KTH EXTRAP T2R group (P.Brunsell, L.Frassinetti, et al.) participated in the IEA Implementing Agreement for Research on RFPs, for example by contributing talks at the 16th IEA/RFP Workshop, 16-20 September 2013, in Padova, Italy.

The KTH PWI group (M.Rubel, P.Petersson, D.Ivanova, A.Garcia-Carrasco) participated in the work of both the ITPA on “Divertor and SOL Physics” and in Diagnostics. The ITPA on Divertor and SOL met in Hefei in (January 2013) and the KTH group presented material on fuel retention and tungsten migration and contributed to presentations on material migration in JET-ILW. In diagnostics the work is related to “first mirrors”. Reports and updates were
submitted to the leaders of the Working Group on First Mirrors but no meetings were attended in 2013.

In the IEA Implementing Agreement on Fusion Nuclear Reactor Technology M. Rubel (KTH) is a task leader on "Plasma Surface Interactions and Tritium Removal". Presentations are given annually at the Ex-Co meetings. In 2013 M. Rubel presented the report at the meeting held in Barcelona during the ISFNT-11.

M. Rubel also participated in an IAEA Coordinated Research Project on Dust in tokamaks at a meeting in Nov. 2011. A final report was issued in 2013.

Gergely Papp (Chalmers) participated in the 13th IAEA Technical Meeting on Energetic Particles in Magnetic Confinement Systems, 17-20 September 2013, Beijing, China. He gave an invited presentation with the title “The effect of magnetic perturbations on runaway dynamics”.

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

7.2 Other international activities

By appointment of the Swedish Ministry for Research, James Drake (Prof Emeritus, Alfvénlab, KTH) has been a member of the Governing Board of the European Joint Undertaking for ITER and the Development of Fusion Energy (Fusion for Energy, F4E). Professor Drake has also been a member of the Euratom Scientific and Technical Committee.
8 Other activities

8.1 Training and education

PhD training
The physics programme of the Swedish Fusion Research Unit is university based. There are PhD programmes at Chalmers University of Technology, KTH Royal Institute of Technology, Stockholm and Uppsala University. During 2013 there were 23 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.

Swedish PhD and Master courses, related to fusion, are now coordinated nationally (http://www.fysikersamfundet.se/pf/doktorandkurser.html) so that all students can obtain the best training possible.

8.2 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 has been J. Scheffel at the Division of Fusion Plasma Physics, KTH in Stockholm.

J. Scheffel also co-chaired 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. The group met in October 2013 in Culham to discuss future steps to be taken.

The Swedish PIN activities include 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 sofar in practice not supported fusion research.

A substantial contact with the public was held in 2013. 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 ITER in Cadarache, France in May 2013 to discuss common strategies with respect to fusion information and lobbying.

J. Scheffel participated (as sole non socio-economic researcher!) in the Satellite Event of the ISFNT - International Symposium on Fusion Nuclear Technologies in Barcelona, 19 September 2013, regarding Socio-Economic Research on Fusion.

**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**

Events like lectures for the public, contact with media and participation in energy debates occurred frequently in 2013. Some activities (primarily carried out by the PIN representative as well as by prof. E. Rachlew, prof T. Fülöp and associate prof T. Johnsson) are

- Physics colloquium at Chalmers: "Fusion energy, stellarators and the Wendelstein 7-X project" (March)
- Seminar with title "Fusion: current status and future outlook" at Sustainable Nuclear Energy Center, Chalmers (April)
- Workshop, Royal Swedish Academy of Sciences, Intermittency in electricity generation in Sweden and in Germany (May)
- Workshop, Royal Swedish Academy of Sciences, Nuclear Power 2050 (May)
- Seminars "Energidagarna" (The Energy Days) for students aged 13 and 17, arranged by the Observatory Museum, Stockholm (May)
- Workshop in Greifswald - Future of nuclear power (fusion, fission, questions, April)
- Inspiration days for teachers, talk on Fusion research and fusion energy, Gävle, May)
- Seminar in Almedalen, Discussion on future energy systems (July)
- Workshop, Royal Swedish Academy of Sciences, Renewables, storage, systems (Sept)
- Seminar given at KTH Teknik och Motor Klubb for researchers and engineers from KTH (October)
- Open lecture on fusion at KTH, attracting more than 250 attendants (November)
- Talk at a symposium organized by the Swedish national committee for mathematics for Mathematics of Planet Earth 2013" (November)
- Speaker at Nobel Week Dialogue; theme Exploring the future of Energy (December)

- Leadership of the energy group of the Royal Swedish Academy of Sciences. Meetings, studies, articles in newspapers debating the energy system in Sweden
- Leadership of (with Lennart Bengtsson, Reading) the project within EASAC on “Breakthroughs of low carbon energy supply and consumption by 2050 and beyond”
- 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 students 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 KTH summer course on energy includes lectures on fusion by J. Scheffel.
- 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 contributions to the Research Units 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 programme must have a programme where preparations for ITER have the highest priority. Therefore information of the Association VR activity for F4E is provided here for information.

In 2013, four different F4E contracts were active within the Swedish Fusion Research Unit, three held by the group at Studsvik Nuclear AB, and one held by the Neutron Diagnostic group at Uppsala University, as shown in Table I.1. Two of the grants held by Studsvik AB were concluded during this year. The third contract held by Studsvik (F4E-GRT-515) as well as the activity by Uppsala University were on-going, continuing into 2014. The involvement of the UU Neutron Diagnostics group was as a third party contributor to a 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 I.1. Summary of Swedish involvement in F4E grants running in 2013.

<table>
<thead>
<tr>
<th>Contract No.</th>
<th>VR Group</th>
<th>Title</th>
<th>Type</th>
<th>Amount k€</th>
<th>Comments</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>338</td>
<td>Finished</td>
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<tr>
<td>F4E-GRT-268</td>
<td>Studsvik</td>
<td>Assessment of Erosion Corrosion Parameters</td>
<td>Grant</td>
<td>236</td>
<td>Finished</td>
</tr>
<tr>
<td>F4E-GRT-515</td>
<td>Studsvik</td>
<td>Assessment of erosion corrosion parameters of CuCrZr &amp; CuCrZr/316L(N)-IG</td>
<td>Partial Grant</td>
<td>318</td>
<td>Ongoing</td>
</tr>
</tbody>
</table>
Appendix II: Contact Information

**European Commission**

Lars-Göran Eriksson  
lars-goran.eriksson@ec.europa.eu

European Commission  
DG Research & Innovation - CDMA 05/023  
B-1049 Brussels, Belgium  
Tel: +32 229-81611

**Swedish Research Council (VR)**

Per Karlsson  
per.karlsson@vr.se  
Tel: +46 8 456 44 177

Johan Holmberg  
johan.holmberg@vr.se

Research Infrastructures  
Swedish Research Council (VR)  
SE-103 78 Stockholm, Sweden

**Ministry of Education**

Goran Bogdanovic  
goran.bogdanovic@regeringskansliet.se  
Tel: +46 8 405 42 47

**Royal Institute of Technology**

* Per Brunsell  
per.brunsell@ee.kth.se  
Tel: +46 8 790 6246

* Jan Scheffel  
jan.scheffel@ee.kth.se  
Tel: +46 8 790 8939

* Marek Rubel  
marek.rubel@ee.kth.se  
Tel: +46 8 790 6093

* Alfvén Laboratory  
Department of Fusion Plasma Physics  
School of Electrical Engineering  
KTH, SE-100 44 Stockholm, Sweden

**Chalmers University of Technology**

* Hans Nordman  
hans.nordman@chalmers.se  
Tel: +46 31 772 15 64

** Tünde Fülöp  
tunde@chalmers.se,  
Tel: +46 31 772 3180

* Department for Earth and Space Sciences  
CTH, SE-412 96 Göteborg, Sweden

** Department of Applied Physics  
CTH, SE-412 96 Göteborg, Sweden
Uppsala University

Göran Ericsson  
goran.ericsson@fysast.uu.se,  
Tel: +46 18 471 3446
Marco Cecconello  
marco.cecconello@fysast.uu.se,  
Tel: +46 18 471 3043
Christer Wahlberg  
christer.wahlberg@fysast.uu.se,  
Tel: +46 18 471 3104

Department of Physics and Astronomy
Ångström Laboratory
Uppsala University, Box 525, SE-751 20 Uppsala, Sweden

Lund University

Christer Jupén  
christer.jupen@fysik.lu.se,  
Tel: +46 46 222 7735

Department of Astronomy
Lund University, Box 117, SE-221 00 Lund, Sweden

Studsvik

Johan Öijerholm  
johan.oijerholm@studsvik.se,  
Tel.: +46 155 22 15 23

Studsvik Nuclear, SE-611 82 Nyköping, Sweden