Cover Picture:

Plasma edge localized instabilities called ELMs (long-black, short-orange) in ASDEX-Upgrade for shot 30411. The top frame shows the time evolution of the divertor current, being used for determining its temperature, and the bottom frame the energy lost during the ELMs.

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

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Association EURATOM-VR
# Annual Progress Report 2015

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Preface

On behalf of the Swedish Fusion Research Unit, we are pleased to present the Annual Progress Report for 2015. This document covers research carried out by Swedish groups in a broad range of fusion energy research. A large part of the work has been carried out under various international agreements of research coordination, such as the Contract of Association between the Swedish Research Council (VR) and the European Atomic Energy Community, EURATOM, the EUROfusion grant agreement under Horizon2020 and specific contracts for ITER work with Fusion for Energy.

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1 EXECUTIVE SUMMARY

1.1 Introduction - the international fusion framework

Controlled thermonuclear fusion offers the prospect of an intrinsically safe, virtually inexhaustible, essentially carbon-free 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.

Sweden is involved in the effort to develop fusion into a practical energy source since many decades. This involvement concerns fundamental research at the national level, at several Universities, technological research and developments involving also industry, participation on the international level both in the organizations governing the fusion research development and in the research itself.

At the international level, the proof-of-principal fusion experiment ITER has been under construction in Cadarache, France, since 2007. ITER is currently planned to start operations in the mid 2020’s and plays a key role in the development of fusion as an energy source. The mission of ITER is to:

- Demonstrate the capability of steady state fusion power production
- Optimise burning plasma confinement under reactor conditions
- Provide a facility with 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 to:

- Provide the contribution of EURATOM to the ITER International Organisation
- Provide the contribution of EURATOM to the Broader Approach (BA) activities with Japan for the rapid realization of fusion energy
- 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 technical ITER plasma is currently planned for the mid 2020’s and nuclear operations will commence a few years later.

5
The development of fusion power is a key action within the European research and development Framework Program structure. The research is coordinated and managed as a part of the EURATOM agreement under the practical leadership of the European Commission. The delivery of the European contribution to ITER is the responsibility of F4E. In parallel a substantial support effort is devoted to an accompanying European fusion research program. With the new 7-year Framework Program period starting in 2014, named Horizon 2020 (H2020), a new organizational platform for the coordinated European fusion research has been adopted. A consortium of 29 European partners, EUROfusion, has been formed to conduct the European fusion research activities on the request of EURATOM, which has awarded a substantial Joint Co-fund Action Grant to the consortium. A new Consortium Agreement regulated the internal work within EUROfusion and substitutes the fourteen year-old European Fusion Development Agreement (EFDA) as well as the 29 bilateral Association agreements between the Commission and the participating research institutions in the 27 countries. The Grant Agreement (EU contract) provides €424M in funding from the H2020 programme 2014-2018 and about the same amount from Member States, adding up to an overall budget of €850 million for 5 years. In addition, the main European fusion experimental facility, the Joint European Torus, JET, is operated as a common facility for researchers across Europe. For this purpose a €283M contract has been signed between the European Commission and the Culham Centre for Fusion Energy (CCFE, UK) to secure JET operation until 2018.

The work within EUROfusion is performed by national parties in the EU member states (and Switzerland). In Sweden, the Program Owner and Beneficiary within EUROfusion is the Swedish Research Council, VR, and the scientific/technical work is performed at a number of Swedish Universities. In order to regulate the rights and obligations of the partners a national Swedish Joint Research Unit, sanctioned by the Ministry of Education, has been formed between VR and the Universities involved in EUROFusion. At present the members of this consortium are Kungliga Tekniska Högskolan, Uppsala universitet and Chalmers Tekniska Höskola. The broader Swedish Research Unit (RU) in fusion also involves other actors with an interest or activity in fusion, for example towards F4E and ITER; at present, Studsvik Nuclear AB is the main such party.

The main aspects of the EUROfusion research program are:

- Co-ordinated activities in physics and emerging technology to prepare for ITER.
- The collective use of the JET facilities.
- Training and career development of researchers.
- European contributions to international collaborations.
- To maintain and develop the recently adopted “Roadmap for fusion energy” (see below) as the basis for the European research and development program in fusion.

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 but progress towards the realization of 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 cornerstone in the European fusion research program is the Roadmap for fusion energy: “Fusion Electricity - A roadmap to the realization of fusion energy”¹. The Roadmap proposes “an ambitious, yet realistic roadmap towards the demonstration of electricity production [from fusion] by 2050”.

1.2 The Swedish Research Unit in fusion

The Swedish fusion Research Unit (RU) in fusion encompasses a range of competencies that are important for the European fusion program and for the ITER project. The Swedish RU has as its basic goal to make important contributions to the development of fusion energy, in particular the ITER project, and to the long term goal of a prototype fusion reactor. The work is at present mostly channeled through the frameworks of EUROfusion and “Fusion for Energy”.

Swedish fusion research activities are currently carried out at three 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 within the Research Unit is focused on promoting and conducting Swedish activities in the field of coordinated fusion research and development, including, but nor exclusively devoted to, the EUROfusion and Fusion for Energy programs. The participating universities are: KTH Royal Institute of Technology (KTH) in Stockholm, Chalmers University of Technology (Chalmers) in Göteborg and Uppsala University (UU). These Universities, together with VR, also form the Joint Research Unit in fusion to coordinate activities within EUROfusion. A group at Studsvik Nuclear AB is also a part of the Research Unit with activities mostly focused towards F4E/ITER. In 2015, about 80 scientists, engineers, PhD students and support staff worked on projects within the scope of the RU, devoting an equivalent of about 50 full-time professional-years to the program.

The activity of the Joint Research Unit is coordinated by the Head of Research Unit (HRU) who is appointed by VR on a 6-year term; the HRU in 2015 was Professor Göran Ericsson, Uppsala University, who was appointed in July 2011. Two deputies to the HRU have been appointed; Docent Pär Strand, Chalmers, to assist in matters of international cooperation and Professor Jan Scheffel, KTH, to assist in matters of public relations, education and outreach.

Fusion research in the Swedish RU is mainly carried out at universities and is focused on fundamental research in areas such as transport of particles and energy, plasma stability (including active control of instabilities), plasma wall interaction, heating (mainly Ion Cyclotron Resonance Heating), energetic particle physics, and diagnostic development and implementations, in particular spectroscopy and neutron diagnostics. The research includes both experimental and theoretical work with a strong element of modeling and computer code development. Studsvik Nuclear AB has for many years been involved in fusion technology activities with a focus on work for ITER through contracts with Fusion for Energy.

The research and development projects within the Swedish RU are well integrated into the EURATOM fusion program both within EUROfusion and Fusion for Energy. The activity includes substantial participation in the joint JET experimental facility as well as collaboration with other Research Units. Through the participation of KTH, the RU also have access to

¹ https://www.euro-fusion.org/newsletter/getting-the-roadmap-rolling/
a domestic plasma device, the EXTRAP-T2R reversed field pinch experiment, which provides a rich source for research projects and a basis for training of students and staff in operations of complex plasma machines. The Swedish Fusion Research Unit is a dispersed, university-based organization of autonomous research groups. It involves a strong element of student participation and education, mainly at PhD student level but also for Master’s degree projects.

1.3 Overview of research activities, EUROfusion (H2020), EFDA (FP7) and Fusion for Energy (F4E) contracts

1.3.1 Overview of 2015 EUROfusion contracts

To conduct fusion research under Horizion2020 a new organization, EUROfusion, was prepared in 2013 and launched on January 1, 2014. EUROfusion is a consortium of fusion research organisations from 28 European countries and formed to respond to a directed Call from the European Commission. The EUROfusion work program for the period 2014-2018 is based on the “Roadmap for fusion” and structured around 33 Work Packages. Each Work Package has a well-defined Project Management Plan with tasks, deliverables and resources defined for the full period. Most work packages are led by a Project Leader, appointed by the EUROfusion General Assembly, and governed by a Project Board to assist the Project Leader and oversee the technical/scientific progress and budget. Exceptions are the “experimental” Work Packages, WPJET1 and WPMST1, which are led by a number of Task Force Leaders.

In 2015 work within EUROfusion was consolidated and Swedish participation, summarized in Table 1, continued on a level similar to but somewhat lower than in 2014. Some EUROfusion Work Packages launched their activities for the first time in 2015; for Sweden this mean a new activity within WPDC (Work Package Diagnostic and Control) concerning diagnostics for DEMO. On the other hand, participation in some WP:s was discontinued, as in WPMST2 and WPS2. In total, Swedish groups participated in 13 of the 33 Work Packages in 2015, the same as in 2014. The resources budgeted for this work amounted to 1384 kEUR, as shown in Table 1. The main part of the activity concerns Manpower costs, with smaller parts for Mission/travel and Hardware procurements.

As was also the case in 2014, for many Work Packages the actual spending, as reflected in the expected reimbursement, falls below the ceiling set in the EUROfusion budget. This can partly be explained by delays in certain activities, partly lower actual costs for performing the tasks. In three Work Packages (marked in red in Table 1), the Swedish participation used more resources than budgeted and the reimbursement is consequently capped by the budget ceiling. In the case of WPJET1 this is due to the shift of work and deliverables spilling over from 2014 into 2015. A discussion is ongoing with the Consortium to also sift the unused part of the 2014 WPJET1 budget to 2015.
### Table 1.3-1: Summary of budgeted and used resources for the Research Unit VR within the EUROfusion program 2015

Col 2 gives the estimated reimbursement based on the reported costs in the Internal Financial Statement (IFS), Col 3 gives the reimbursement allocated to VR in the EUROfusion budget for 2015, Col 5 gives any additional travel funds available, Col 6 gives the total reimbursement available to VR and, finally, Col 7 (light blue) gives the resources to be paid to VR at completion of all relevant program Deliverables.

<table>
<thead>
<tr>
<th>Work Package</th>
<th>Estimated VR reimbursement based on reported costs (IFS)</th>
<th>Sum of VR Budget (EUROfusion Budget Table)</th>
<th>VR - Min IFS/Budget</th>
<th>VR - additional amount to be made available for missions</th>
<th>VR Total Budget available</th>
<th>VR - Total to be paid after all deliverables achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>WP01 Jet Campaigns (WPJET1)</td>
<td>230.04</td>
<td>181.52</td>
<td>181.52</td>
<td>12.70</td>
<td>194.20</td>
<td>194.20</td>
</tr>
<tr>
<td>WP02 Investigation of Plasma- Facing Components for ITER (WPJET2)</td>
<td>192.23</td>
<td>191.88</td>
<td>191.88</td>
<td>23.11</td>
<td>214.98</td>
<td>192.23</td>
</tr>
<tr>
<td>WP03 Technological Exploitation of DT Operation for the ITER reparation (WPJET3)</td>
<td>35.54</td>
<td>39.18</td>
<td>35.54</td>
<td>0.00</td>
<td>39.18</td>
<td>35.54</td>
</tr>
<tr>
<td>WP04 JET Enhancements (WPJET4)</td>
<td>3.18</td>
<td>24.10</td>
<td>3.18</td>
<td>0.00</td>
<td>24.10</td>
<td>3.18</td>
</tr>
<tr>
<td>WP05 Medium-Size Tokamak Campaigns (WPMST1)</td>
<td>86.86</td>
<td>104.53</td>
<td>86.86</td>
<td>0.72</td>
<td>105.25</td>
<td>86.86</td>
</tr>
<tr>
<td>WP06 Preparation of Exploitation of Medium-Size Tokamals (WPMST2)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>WP07 Preparation of efficient PFC operation for ITER and DEMO (WPFC)</td>
<td>147.31</td>
<td>172.98</td>
<td>147.31</td>
<td>5.32</td>
<td>178.29</td>
<td>147.31</td>
</tr>
<tr>
<td>WP12 Stellarator Theory, Modelling, Eng. (WP52)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>WP13 Code Development for integrated Modelling (WP53)</td>
<td>110.51</td>
<td>113.91</td>
<td>110.51</td>
<td>9.05</td>
<td>122.95</td>
<td>110.51</td>
</tr>
<tr>
<td>WP23 Diagnostic &amp; Control</td>
<td>14.39</td>
<td>14.06</td>
<td>14.06</td>
<td>0.14</td>
<td>14.20</td>
<td>14.20</td>
</tr>
<tr>
<td>WP25 Materials (WPMA1)</td>
<td>61.89</td>
<td>80.88</td>
<td>61.89</td>
<td>1.07</td>
<td>81.85</td>
<td>61.89</td>
</tr>
<tr>
<td>WP30 Education (WPEDU)</td>
<td>367.70</td>
<td>240.74</td>
<td>240.74</td>
<td>0.00</td>
<td>240.74</td>
<td>240.74</td>
</tr>
<tr>
<td>WP31 Training (WPTRA)</td>
<td>9.50</td>
<td>26.88</td>
<td>9.50</td>
<td>0.00</td>
<td>26.88</td>
<td>9.50</td>
</tr>
<tr>
<td>WP32 Enabling Research (WPENR)</td>
<td>72.39</td>
<td>69.10</td>
<td>69.10</td>
<td>0.00</td>
<td>69.10</td>
<td>69.10</td>
</tr>
<tr>
<td>WP33 Program Mgm Unit (WPMMU) (int. travel)</td>
<td>0.70</td>
<td>38.6</td>
<td>0.70</td>
<td>0.95</td>
<td>39.55</td>
<td>0.70</td>
</tr>
<tr>
<td>WP33 Program Mgm Unit (WPMMU) Management</td>
<td>58.44</td>
<td>32.46</td>
<td>32.46</td>
<td>0.00</td>
<td>32.46</td>
<td>32.46</td>
</tr>
<tr>
<td><strong>Grand Total (kEUR)</strong></td>
<td><strong>1390.69</strong></td>
<td><strong>1330.81</strong></td>
<td><strong>1185.25</strong></td>
<td><strong>53.03</strong></td>
<td><strong>1383.84</strong></td>
<td><strong>1198.42</strong></td>
</tr>
</tbody>
</table>

### 1.3.2 Overview of legacy FP7/EFDA contracts

The EU’s 7th research Framework Program, FP7, officially ended by December 31, 2013. However, some of the contracts within the EFDA framework had their expiry dates set beyond this date. Some of these contracts were concluded in 2014, some were extended into 2015 and are reported here. All legacy FP7 contracts were concluded in 2015. Table 2 below gives an overview of these contracts.
### 1.3.3 Overview of Fusion for Energy contracts

The EU’s contribution to ITER is administered by the organisation “Fusion for Energy” (F4E), located in Barcelona, Spain. Participation in the ITER development activities is based on Partnership Agreements and Grants and in 2015 the Swedish Research Unit were involved in three such F4E “contracts”. One of these was held by Studsvik Nuclear AB and concerned erosion testing of materials. The other two were held by the Uppsala University neutron group and concerned neutron diagnostic developments. Thus the Uppsala group participated in a large consortium for the development of ITER’s Radial Neutron Camera system. A smaller diagnostic development concerned ITER’s High Resolution Neutron Spectrometry system. Table 3 below summarizes the RU’s involvement in F4E contracts in 2015.

#### Table 1.3-2: Overview of legacy FP7/EFDA contracts active in 2015.

<table>
<thead>
<tr>
<th>CoA Contract</th>
<th>Contract ends</th>
<th>Status / responsible</th>
</tr>
</thead>
</table>

#### Table 1.3-3: Summary of the Swedish RU’s involvement in F4E grants running in 2015.

<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-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>Concluding</td>
</tr>
<tr>
<td>F4E-FPA-327</td>
<td>Uppsala University – neutron group</td>
<td>Diagnostic Development and Design “Radial Neutron Camera and Radial Gamma-Ray Spectrometer”</td>
<td>Framework Partnership Agreement</td>
<td>170</td>
<td>Ongoing</td>
</tr>
<tr>
<td>F4E-GRT-403</td>
<td>Uppsala University – neutron group</td>
<td>Diagnostic Development and Design “High Resolution Neutron Spectrometer”</td>
<td>Grant</td>
<td>200</td>
<td>Ongoing</td>
</tr>
</tbody>
</table>

* The approximate value of the Swedish share in case of collaborative contracts.
1.4 Highlights of the research activity

In the field of “Energy and particle confinement and transport”:

- Using advanced neoclassical modeling tools we show that a change in plasma effective charge of order unity can affect the bootstrap current enough to cause a deviation in the divertor strike point locations on the W7-X.

In the field of “Neutron diagnostics”:

- For the first time, neutron and gamma-ray spectroscopy data, collected along two different sightlines, have been combined in order to obtain information about the distribution of MeV range deuterons in JET plasmas.
- Development of a first preliminary conceptual design and measurement requirements for a neutron diagnostic in DEMO for fusion power measurements.
- Further analysis of fast ion physics from neutron camera measurements on MAST was carried out resulting in the observation of fishbone-driven impurity transport from the edge to the core plasma, in the identification of the passing FI population in the core of the plasma as being susceptible to redistribution in the presence of fishbones, in the preliminary verification of TRANSP overestimation of the neutron production in MAST unreconcilable with experimental uncertainties, the identification of operating space in MAST optimized for q-profile control and non-inductive neutral beam current drive characterized by mitigated fast ions redistribution and losses.
- Design of different architectural options for the ITER radial neutron camera, development of its functional specifications and of the critical components test requirements, development, implementation and verification of neutron emissivity profile reconstruction within the ITER requirements based on a neural network approach.

In the field of “Plasma-Wall Interactions”:

- Plasma-facing components and erosion-deposition probes (EDP) retrieved from JET-ILW were studied in detail. The ratio of light impurities (Be, C, N, O) deposited on the divertor tiles was determined. Analysis of EDP such as quartz microbalance shield and test mirrors has resulted in the determination of Nitrogen-15 which was used as a tracer in nitrogen-cooled discharges. This opens ways to use $^{15}$N$_2$ for material migration studies in JET.
- Significant progress was achieved in studies of local deposition patterns of high-Z metal injected (MoF$_6$) in to TEXTOR on its last day of operation (December 2013). Spectroscopy and surface analysis data have been evaluated. This opens way to the determination of a material balance in high-Z migration experiments.
- For the first time comprehensive examination was performed for dust particles removed from JET. Four major categories of objects were identified: beryllium droplets, flaking Be co-deposits, tungsten flakes from W coatings and tungsten spheroids.

In the field of “Dust in tokamak plasmas”:

- First experiments on the interaction of the adhered metal dust with the transient heat loads have been carried out. A novel growth mechanism of wetting-induced coagulation has been identified, where cluster melting accompanied by droplet wetting leads to the formation of larger grains.
2 Support advancement of the ITER physics base

2.1 Energy and particle confinement and transport

2.1.1 Transport modelling

*J. Anderson, H. Nordman, M. Oberparleiter, P. Strand, D. Tegnered (PhD student)*

**Introduction**

This project is directed towards understanding the transport of particles, impurities, 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, which requires large scale computational modelling. The work is done in close collaboration with the experimental facilities.

**Modelling**

The transport work during 2015 included realistic large scale gyrokinetic turbulence simulations of JET experiments using the GENE code, comparing transport due to Ion-Temperature-Gradient and Trapped-Electron mode driven turbulence in the ITER-like Wall (ILW) experiment with similar Carbon wall (CW) experiments. It was found that the changes in core parameters between the CW and ILW discharges at similar normalized temperature gradients lead to larger normalized heat fluxes in the ILW cases. The result indicates that the core confinement in the ILW discharges was negatively affected by the degradation of the

**Figure 2.1-1:** Radial heat flux avalanche patterns in gyrokinetic simulations of ion temperature gradient turbulence. The presence of neoclassical transport (right) decreases the frequency and amplitude of events with high turbulent transport (M. Oberparleiter, 2015).
edge pedestal. While turbulence is responsible for most of the transport in a fusion plasma, collisions of the plasma particles and the curvature of the magnetic field also drive the usually weaker neoclassical transport. Our activity in this field focuses on studying the mechanisms of the interaction between turbulent and neoclassical phenomena, in particular, how the neoclassical radial electric field modifies the pattern of shear flows which regulates the level of turbulent transport. The presence of the neoclassical transport channel also changes the frequency and amplitude of turbulent transport bursts (avalanches, Figure 2.1-1).

**Publications section 2.1.1**

**Peer reviewed journals**


**Presentations at international conferences and workshops**


**2.1.2 Electric Fields in Tokamak Plasmas**

*M. Tendler*

The tokamak is the most advanced concept of toroidal confinement schemes. The self-consistent calculations of electric fields in tokamak plasmas are the basic key in obtaining regimes with improved confinement. Self-consistent electric fields in plasmas result from non-ambipolar drifts of ions versus electrons imposing the cancellation of plasma currents. However, the turbulence driven transport is primarily ambipolar because it is mainly driven by ExB fluctuations. Therefore, a much smaller transport driven by collisions (so called neoclassical transport) is crucial for understanding the mechanism causing the emergence of electric fields and resulting in improved confinement. Yet, the neoclassical theory must be revised in order to account for turbulence driven transport dominant in plasmas with low collisionality.

The radial electric field is determined by the momentum balance equations including both neoclassical and anomalous effects. There is a very strong need to find subtle and technologically viable methods to control electric fields beyond neoclassical values in a future fusion reactor. This requirement stems from the fact that even in the regime with improved confinement H – mode the phenomenon of intermittent loss of confinement reminiscent of
solar flares (by the way the Sun is the natural fusion reactor relying on gravity to obtain good confinement) termed Edge Localized Modes arises. Edge Localized Modes are repetitive bursts of the edge plasmas resulting in heat overloads of the surrounding structures of a fusion reactor, thereby preventing its operation. The novel method to overcome the detrimental impact of ELM’s depends crucially on the self-organized electric fields in plasma. In general, the ubiquitous phenomenon of filaments is observed frequently in plasmas and constitutes plasma entities emerging moving around and vanishing within a main plasma body. The great importance of filaments for plasma behaviour has been brought to light by Hannes Alfvén many years ago. Yet, the issue remains largely unaddressed. Recently, it was proposed to employ imposed externally magnetic field coils in order to modify electric fields in edge plasmas. External coils providing magnetic perturbations resonant with a tokamak magnetic field cause the emergence of the stochastic magnetic layer resulting from overlapping resonances. According to these ideas, ELM suppression occurs due to current closure of parallel electron currents occurring due to ambipolarity in case of a stochastic magnetic field.

The current closure is provided by perpendicular currents driven by ions (emerging due to off – diagonal terms neglected in the MHD models) and the well – known effect from biasing experiments (4). Radial electric field in a stochastic magnetic field is determined by the current closure \( j_r^e = -j_r^i \) where \( j_r^i \) is the ion radial current caused by the deviation of the radial electric field from the neoclassical value and the radial current of electrons \( j_r^e \) is a projection of a parallel current in a stochastic magnetic field emerging due to ambipolarity constraint.

The issue of electric fields in fusion plasmas emerged as the major milestone in fusion research. Control methods of the latter have been studied and addressed within the framework of tokamak research crucial for ITER project. Stochasticity of magnetic fields imposed by external magnetic coils has been brought to light as a powerful tool to affect electric fields and rotations in plasmas. The impact of filaments on plasma performance in a tokamak has been addressed. The progress made during many years of intensive studies justifies the future work in this area.

**Publications section 2.1.2**

**Peer reviewed journals**


**2.1.3 Particle and impurity transport**

*I. Pusztai, T. Fülöp, S. Newton, J. Omotani, A. Mollén (PhD student), S. Buller (PhD student)*

Impurity accumulation is a major issue for stellarators. During 2015, we continued studies of impurity transport, with a particular emphasis on non-axisymmetric configurations. We used the continuum neoclassical solver SFINCS, developed in collaboration with M Landreman at University of Maryland, that features a full linearized Fokker-Planck operator and is free of ad-hoc simplifying assumptions often used in neoclassical modeling for stellarators. We explained the 1/\( \nu \)-scaling of the inter-species radial transport coefficient at low collisionality,
which is not found with simplified collision models even when momentum correction is applied. We showed that a change in plasma effective charge $Z_{\text{eff}}$ of order unity can affect the bootstrap current enough to cause a deviation in the divertor strike point locations.

We have also studied the turbulent transport of an ICRH heated non-Maxwellian species in the three ion minority heating scheme and compare it to the transport of alpha particles. We found that the heated species tends to accumulate around the heating location, while alpha particles are diffusing outwards. The generation mechanism and the phase space dynamics play a crucial role in the turbulent transport of hot species.

Filaments play a crucial role in particle transport in the SOL. We have studied the effect of shape (ellipticity) and amplitude on the radial velocity of filaments, deriving analytical scaling relations from 2d numerical simulations. We have also contributed to numerical investigations of the effect of temperature on filaments in 3d and the experimental characterisation of SOL profiles in MAST, which provide evidence for the non-diffusive character of the particle transport, as would be expected from filaments.

**J. Weiland**

The publication of Ref. 5 - in its final form - occurred during 2015. This is our, so far, most complete work on the fluid closure. It starts from the coherent fluid picture of Mattor and Parker (PRL 79, 3419,1997) where it was shown that an integration along particle orbits can be replaced by one over wave phases, taking nonlinear frequency shifts into account. This was generalized to multi wave interaction, going into the turbulent limit in Ref. 5. This could be done since wave dynamics is considerably more tractable than particle dynamics in turbulent situations. Finally a Fokker-Planck equation for turbulent collisions could be derived. This leads to an asymptotic state completely without energy transfer between waves and resonant particles. This makes our closure exact for drift waves. Thus a simplified way to see our closure is just as the averaging out of the wave particle resonance by particle trapping.

The simulation of the L-H transition in the EAST tokamak (2014) depended strongly on the reactive fluid resonance in the energy equation, we now made a more direct test of that shown in Ref. 6. Of course this fluid resonance is due to the fluid closure as finally motivated in Ref 5. Our test was now the simulation of the nonlinear Dimits upshift found in the Cyclone work (Phys. Plasmas 7, 969 (2000)), Figure 2.1-2.

![Figure 2.1-2](attachment:image.jpg)

**Figure 2.1-2.** Simulation (full line) of the Dimits nonlinear upshift (triangles) for the Cyclone base case parameters (From Ref. 6).

Previous attempts to understand the width of it was as a decay of zonal flows due to higher order nonlinearities. However we obtained it quite accurately as due to the detuning of the
fluid resonance, which occurs at marginal linear stability, by the linear growth rate when we entered sufficiently far into the linearly unstable regime. A condition for this explanation is, of course, our reactive resonance and the fact that marginal linear stability occurs exactly at the fluid resonance in the energy equation. Thus, although kinetic models can obtain the exact result for the upshift, the interpretation in terms of the reactive fluid resonance is, of course, not available. Thus this is a very strong proof of our fluid closure! We simulated this by our predictive transport code by freezing all variables except the poloidal momentum which was driven nonlinearly by the Reynolds stress, including its temperature dependence (diamagnetic drift).

The active ingredient leading to our fluid closure is the nonlinear frequency shift. This was the case both in the coherent (Mattor Parker) limit and in the Fokker-Planck equation.

Our reactive fluid closure, in particular for the poloidal momentum, where the temperature dynamics is included in the Reynolds stress, has been the main reason for the successful simulations both for the spinup of poloidal momentum in ITB’s (AIP Conf. Proc. 1392 85 2011), the L-H transition on EAST (Phys. Plasmas 2014) and the Dimits shift, Ref. 6.

The Dimits upshift has later also been calculated analytically (Ref. 8) and the L-H transition has been verified also by the SWIP group using my code (Ref. 9). The SWIP work was done for their tokamak LH-2A which is the old ASDEX device on which the H-mode was discovered.

Finally we have also simulated the particle pinch on Tore Supra (Ref. 10). This was a follow up work on a work by the SWIP and Cadarache groups (PRL 111, 265001, 2013) using the code QuaLiKiz ((Phys. Plasmas 14, 112501, 2007). The agreement between the codes was fairly good. Here it is important to observe that the particle pinch is strongly dependent on the nonlinear frequency shift through the fluid closure. Thus purely quasilinear models do not give a particle pinch at typical modennumbers of ITG modes because of Landau damping. QuaLiKiz however, has a fixed frequency shift tuned to the nonlinear frequency shift of nonlinear gyrokinetics and thus has a particle pinch. In our model we also found that the particle pinch appeared when the ITG mode dominated due to strong ballooning. Thus this also verifies the eigenfunction solution in our code.

Further support of our approach was given in the book by M. Kikuchi, Frontiers in Fusion Research II, Springer 2015 where substantial parts from my books were included. I was also the main supervisor of Guanqiong Wang who had his dissertation at ASIPP in May 2015. I was also invited to write a paper in the issue of Plasma Physics Reports, to the memory of A. B. Mikhailovskii. This was published in May 2016 and is recommended for further information about the model.

Publications section 2.1.3

Peer reviewed journals


**Thesis**


### 2.1.4 Integrated modelling

**P. Strand, D. Yadykin, D. Tegnered (PhD student)**

The Integrated Modelling activity was reorganised on the European level under the EUROfusion structure. Swedish researchers maintain a high level of commitment and involvement with the activity. Swedish researchers have coordinating responsibilities for the European Transport simulator (ETS), a predictive transport code, the Heating and Current Drive activity (H&CD) and the MHD stability chain as well as taking part in the overall coordination of the Code Development Work Package (EUROfusion WP CD).

Work has continued developing transport physics (Chalmers) and the heating and current drive tools (KTH) in WP CD (ETS and H&CD) and tools have been starting to be deployed for exploitation at JET.
Participation in the verification activities of the RWM stability chain elements (including effects of external 3D structures), together with physical modules maintenance. Preparations for RWM stability chain validation on ASDEX Upgrade tokamak.

Publications section 2.1.4

Peer reviewed journals

Presentations at international conferences and workshops
2.1.5 Pedestal properties and confinement in JET plasma with carbon wall and ILW

L. Frassinetti, E. Stefanikova

Operations in JET have been resumed in autumn 2011 after the shutdown necessary to install the ITER-like wall (hereafter called ILW). Type I ELM My H-mode operation in JET with the ITER-like Be/W wall (JET-ILW) generally occurs at lower pedestal pressures compared to those with the full carbon wall (JET-C). In 2015, the study of the pedestal properties in JET with the new ILW has continued. The activity in this area has focused on investigating the role of collisionality and of the plasma current.

Role of collisionality on the confinement in JET-ILW

The baseline type I ELM My H-mode scenario with H=1 has been re-established in JET with the new tungsten divertor and beryllium main wall (JET-ILW) in 2011. Comparing carbon wall (JET-C) discharges in similar conditions, a degradation of the confinement has been observed in JET-ILW, with the reduction mainly driven by a lower pedestal pressure. The JET-ILW at low collisionality seems to reach a confinement comparable to the JET-C reaching \( H_{98} \approx 1.0 \), as shown in figure 1.

The present work has studied the confinement and the pedestal in a dimensionless collisionality scan in order to investigate the reason for the confinement improvement. The pedestal structure is significantly affected by the collisionality. Specifically, a reduction of the width with decreasing collisionality is observed. At low collisionality, the pedestal width is in good agreement with the expectations from the KBM prediction which expects \( w_{pe}=0.076(\beta_{ped})^{0.5} \).

The high stored energy at low collisionality is achieved by both the increased pedestal pressure (50%) and by the increased core pressure (75%). The pedestal stability show an improvement with decreasing collisionality. The reason is not clear yet and it will subject of further investigation in 2016.

It was not possible to find a perfect match between the present data set and JET-C, so a quantitative comparison cannot be done, but, qualitatively, JET-C and JET-ILW have similar trends with collisionality.

![Figure 2.1-3. Confinement factor versus \( \beta_N \) (a) and versus collisionality (b) in JET-ILW.](image)
Dependence of confinement and pedestal structure on plasma current in JET-ILW and comparison with JET-C

High plasma current and field are necessary to develop high performance scenarios with high thermal energy (Wth > 10 MJ) and temperature. During the 2014 campaign, JET-ILW has reached 4.0 MA in the baseline scenarios in quasi stationary conditions, avoiding W accumulation and controlling the divertor heat loads. The stored energy in JET-ILW tends to be lower than in JET-C. However, comparable Wth is obtained at 2.5 MA (but using different strike point positions).

This part of the work studies the role of the pedestal in the JET-ILW confinement of a current scan and discusses the differences with the JET-C.

An increase of the pedestal energy with Ip is observed in both JET-ILW and JET-C. In JET-ILW, the increase of the pedestal stored energy is related to the pedestal density, while the pedestal temperature does not scale significantly with Ip. In JET-C, both density and temperature increase with Ip. This difference could be related to the large gas fuelling in JET-ILW to control W accumulation. In the core, the low JET-ILW pedestal temperature (compared to JET-C plasmas obtained at similar current) produces low core temperature due to the profile stiffness. Moreover, the low density peaking due to the increased collisionality in JET-ILW reduces further the core contribution to stored energy.

The pedestal width analysis has been performed at each Ip level for the shots with the highest H98, both in JET-C and JET-ILW. Figure 2.1-4a) shows pedestal pe widths versus Ip. No clear trend with Ip is observed, but JET-C tends to have a lower pedestal width than JET-ILW. This might be related to the higher gas level used in JET-ILW [3]. Figure 2.1-4-b) shows the pedestal pe versus Ip and Figure 2.1-4 c) shows the correlation of the pedestal pressure gradient with Ip. A significant reduction, by a factor 2 or higher, for JET-ILW is observed.

Pedestal pe widths from the selected subset of shots do not follow any obvious trend with Ip. But JET-ILW reaches comparable or larger pedestal widths than JET-C. Also the pressure gradient at the pedestal is strongly reduced in JET-ILW with high Ip. This is in accordance with stability analysis from the MISHKA code which showed that at high Ip JET-ILW is far from the stability boundary.

ELM behaviour in AUG

The Type I ELM behaviour in ASDEX Upgrade with full W plasma facing components is studied in terms of time scales and energy losses for a large set of shots characterized by

![Diagram](image-url)
similar operational parameters but different nitrogen seeding rate and input power. ELMs with no nitrogen can have two typical behaviours, that can be classified depending on their duration, the long and the short ELMs.

The work shows that both short and long ELMs have a similar first phase, but the long ELMs are characterized by a second phase with further energy losses. This is shown in figure 3. The second phase disappears when nitrogen is seeded with a flux rate above \(10^{22}\) (e/s). The phenomenon is compatible with a threshold effect. The presence of the second phase is related to a high divertor/scrape-off layer (SOL) temperature and/or to a low pedestal temperature.

The ELM energy losses of the two phases are regulated by different mechanisms. The energy losses of the first phase increase with nitrogen which, in turn, produce the increase of the pedestal temperature. So the energy losses of the first phase are regulated by the pedestal top parameters and the increase with nitrogen is due to the decreasing pedestal collisionality. The energy losses of the second phase are related to the divertor/SOL conditions. The long ELMs energy losses increase with increasing divertor temperature and with the number of the expelled filaments.

In terms of the power lost by the plasma, the nitrogen seeding increases the power losses of the short ELMs. The long ELMs have a first phase with power losses comparable to the short ELMs losses. Assuming no major difference in the wetted area, these results suggest that (i) the nitrogen might increase the divertor heat fluxes during the short ELMs and that (ii) the long ELMs, despite the longer time scale, are not beneficial in terms of divertor heat loads.

**Figure 2.1-5.** ELM synchronized time traces of (a) divertor currents and (b) stored energy. (c) histogram of the ELM duration calculated has the FWHM of the divertor current from frame (a). The orange color corresponds to the ELMs with \(\tau_{\text{ELM}}<1.1\) ms and the black color to the ELMs with \(\tau_{\text{ELM}}>1.1\) ms. The continuous lines in frame (b) highlight the conditional average of the stored energy for short (orange) and long ELMs (black). Data correspond to a stationary phase between \(t=2-4\) s at \(P_{\text{NBI}}=5\) MW with no N seeding.

**Publications section 2.1.5**

**Peer reviewed journals**


12. M Romanelli and 470 co-authors “Overview of JET result” Nucl Fusion 55 104001 (2015)

13. H Zohm and 320 co-authors “Recent ASDEX Upgrade research in support of ITER and DEMO” Nucl Fusion 55 104010 (2015).

Conference proceedings


28. M Dunne, S Potzel, M Wischmeier, E Wolfrum, L. Frassinetti, F Reimond “Predictive modelling of the impact of a radiative divertor on pedestal confinement on ASDEX Upgrade” 57th Meeting of the APS Division of Plasma Physics, November 2015, Savannah, USA.


2.2 MHD stability and plasma control

2.2.1 Active MHD mode control

P. Brunsell, L. Frassinetti, A. C. Setiadi (PhD student), R. Fridström (PhD student), and J. R. Drake

In collaboration with:
W. Suttrop, V. Igochine, Max-Planck-Institut für Plasmaphysik, Garching
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C. R. Rojas, H. Hjalmarsson, EES/Automatic Control, KTH

EXTRAP T2R device

A main feature of the EXTRAP T2R reversed field pinch device is a comprehensive system for development and test of methods for active MHD control. One aim of this research is to develop control methods for future RWM control experiments at the ASDEX Upgrade tokamak, which is turn is motivated by the desire to incorporate the possibility for active control in ITER and future tokamak reactor designs. Another distinguishing feature is an all metal (stainless steel/molybdenum) wall. The EXTRAP T2R device includes a number of plasma diagnostic systems, such as magnetics, interferometer, Thomson scattering, SXR detectors, visible and ultra-violet light spectrometers, bolometers, Langmuir and collection probes.

The main components of the MHD mode control system at EXTRAP T2R is an array of active control coils placed outside the conducting shell, and a corresponding array of sensor coils placed inside the shell, as shown in Figure 2.2-2.
Figure 2.2-2. Active MHD control system installed at EXTRAP T2R. Active control coils outside the shell in red, sensor coils inside the shell shown in blue, and the conducting shell itself depicted in orange colour.

The main features of system are:

- 128 magnetic flux loop sensors at 4 poloidal and 32 toroidal positions inside the shell.
- 128 active saddle coils at 4 poloidal and 32 toroidal positions outside the shell.
- Saddle coils and sensor flux loops pair-connected at each toroidal position to form 64 independent “m=1” coils and sensors.
- 64 “m=1” coil current transducers.
- 32 two-channel power amplifiers units providing at total of 64 independent channels.
- Integrated digital controller unit including CPU board, ADCs and DACs.
- Control algorithms implemented in software.

Audio amplifiers with output power of 800-1200 Watt are used for driving the active coils. Control algorithms are implemented in a Linux based PC equipped with a 3.0 GHz 6-core processor and 8 GB memory. The kernel of the Linux operating system has been modified so that all interrupts to the CPU are suspended during the shot. The kernel modification guarantees the availability of the CPU for the real-time feedback control algorithm. The integrated digital control system consists of several boards installed in a compact PCI crate. The data acquisition modules transfer data to a shared buffer in the host PC by Direct Memory Access. There are two data acquisition modules providing 16-bit analog-to-digital (ADC) for a total of 128 simultaneously sampled channels, and one digital-to-analog (DAC) module with 64 output channels. The setup of the data acquisition boards is facilitated by an additional Ethernet connection between the host PC and the boards. The minimum cycle time of the system with this channel configuration is of the order of 20 microseconds.

Feedback control algorithms are written in C++. Various types of controllers have been implemented, such as the conventional Proportional-Integrating-Derivative (PID) controller, as well as modern model based controller such as the Model Predictive Controller (MPC).
Improved Model Predictive Control by Error Field Estimator

The RWM response model obtained from system identification has been used as a base for a state-space controller of the Model Predictive Control (MPC) type. The MPC controller has been successfully implemented and tested on EXTRAP T2R. The MPC employs a predictive model to calculate the optimal control action. It is as an advanced control technique and one of its advantages is that the MPC is able to incorporate state and actuator constraints in the controller design.

Recently, the empirical model has been used to estimate the intrinsic machine error field. Two different error field estimation methods have been studied and compared. The error field estimator is then combined with the MPC to yield better radial field suppression at the wall. Figure 2.2.1-3 illustrates the basic idea: It is assumed that the error field is caused by an unknown input \( w \) acting on the plant \( P \). The Error Field (EF) Estimator provides an estimate of the error field \( \hat{w} \) used to perform compensation by negative feedback.

The first method is the Disturbance Observer (DOB). The main principles of the DOB are illustrated in Figure 2.2.1-4: The approximate inverse of the plant is found \( (P^{-1}) \) and used to reconstruct the input entering the plant. This reconstructed input is then compared to the actual input entering the plant, and the difference of the two is used as the estimate of the error field \( \hat{w} \). A filter \( (Q) \) is required for physical implementation of the DOB. Typically a low-pass filter is used, assuming a low-frequency, quasi-static error field.

The second method is the Unknown Input Observer (UIO), illustrated in Figure 2.2.1-5. Similar to the DOB, the UIO assumes that there are unknown inputs entering the system. The difference is that UIO provides state estimation along with disturbance estimation. The main idea for the UIO is that we need to update the dynamics of our system such that is incorporates the effects of the disturbance. The UIO requires some information regarding the dynamics of the disturbance. The most common assumption is a constant disturbance.
The main parameters of the error field that need to be estimated are for each Fourier mode number the amplitude and phase.

Figure 2.2-6. MPC w/o and with error field compensation. Time evolution of the radial magnetic field at the wall for difference toroidal Fourier modes, n=11, -8, -6, 4, 5, and 8.

The implementation of DOB and UIO to perform estimation and error field compensation alongside MPC feedback control is relatively simple. The experimental results are shown in Figure 2.2.1-6, comparing the radial field suppression for MPC w/o and with error field compensation, using DOB and UOI methods, respectively.

Publications section 2.2.1

Peer reviewed journals

Conference contributions
2.2.2 External magnetic perturbation effects on plasma rotation

L. Frassinetti, P. Brunsell, R. Fridström (PhD student), M. W. M. Khan (PhD student),
In collaboration with:
S. Munaretto, B. E. Chapman, University of Wisconsin-Madison, USA

External magnetic perturbations are an important tool in tokamaks to mitigate edge localized modes and/or to influence the neoclassical tearing mode island dynamics in order to optimize ECCD stabilization. On the other hand magnetic perturbations produce also undesired effects such as plasma flow braking. A clear study of the corresponding underlying physics is relatively complicated in tokamaks because of the limited number of active coils that inevitably produces a broad spectrum of side-band harmonics.

The EXTRAP T2R reversed-field pinch is equipped with a set active and sensor coils that can produce external magnetic perturbations (MPs) with a specific harmonic in a controlled fashion (i.e. with defined amplitude and phase). The feedback system of EXTRAP T2R has the capability of suppressing the entire RWM and error-field spectrum and simultaneously producing a clean external MP. EXTRAP T2R is therefore a useful machine to investigate the magnetic perturbation effect on the plasma dynamics. During 2015 a series of studies aimed at the understanding of the mechanisms that lead to the tearing mode locking-unlocking mechanism have been conducted. The work has been extended studying the a similar mechanisms in the MST experiment, located at University of Wisconsin-Madison.

2.2.3 Hysteresis in the locking – unlocking mechanism of a TM on an external resonant field in EXTRAP T2R

The RMP interaction with the tearing modes (TMs) can reduce the plasma rotation and eventually cause wall-locking. The wall-locking has been observed to produce disruptions in tokamaks and shot terminations in reversed-field pinches (RFPs). Clearly, rotation is desirable for achieving high confinement and disruption free fusion plasmas. Therefore, understanding of the physical mechanisms behind TM wall-locking and -unlocking is desirable.

The TM dynamics in the presence of an RMP have been theoretically studied in both tokamaks and RFPs. The TM locking and unlocking is characterized by a hysteresis behaviour, where the locking threshold (the RMP amplitude required to lock the mode) is significantly higher than the threshold for unlocking.

Theoretically, the hysteresis in the TM locking and unlocking process can be described by the magnetic island time evolution equations subject to an RMP. When an RMP is applied to a rotating plasma, it produces an electromagnetic (EM) torque that brakes the TM velocity. The velocity reduction spreads to rest of the plasma through the viscosity. The surrounding plasma produces a viscous torque that acts to restore the natural rotation and a lower plasma rotation is obtained. If the RMP is larger than the locking threshold, the TM goes through a transition to the wall-locked state. To unlock the TM, the EM torque must be reduced to a value lower than the viscous torque. However, soon after locking, the velocity reduction profile relaxes.
producing a sudden drop in the viscous torque. Therefore, to unlock the mode, the RMP must be reduced to a value significantly lower than the locking threshold. In addition, the theory predicts that the EM torque increases after the locking, due to the growth of the TM island. This should lower the unlocking threshold even more, in other words deepening the hysteresis.

The work in EXTRAP T2R has investigated from the experimental point of view the above described mechanisms. The results show that after TM locking to an external RMP, a relaxation of the velocity profile with a subsequent drop in the viscous torque and an increase of the TM island size is observed. The relaxation of the velocity profile is shown in Figure 2.2-7.

The drop in the viscous torque causes hysteresis in the RMP locking/unlocking threshold or in other words, to unlock the TM, the RMP amplitude needs to become significantly lower than the RMP amplitude required for locking the TM. The increased island size results in an increased EM torque and thereby a deepening of the hysteresis. The experimental results are in qualitative agreement with the theoretical model.

2.2.4 TM locking to an external field in the MST reversed-field pinch

Previous works in RFPs have mainly focused on the interaction between a single harmonic RMP and a TM of corresponding resonance. However in tokamaks, the number of RMP coils that can be placed outside the machine-wall is limited by other equipment, such as ports for neutral beam injection (NBI) and radio frequency (RF) heating. This leads to a broad spectrum of harmonics, which can potentially be resonant with more than one TM. For example, to describe the effect of magnetic perturbations on one TM island in ASDEX, the torques on all TM islands had to be included.

In addition to error field correction, the feedback system can be used to produce RMPs with a pre-set amplitude and poloidal mode number m. Due to the coils limited toroidal extent, they produce a broad spectrum in toroidal mode number n. MST has several TMs that are naturally rotating together with the plasma fluid. Hence, MST is a suitable device to study the simultaneous braking of several TMs, due to a multi-harmonic RMP. In this work, the RMP effect on the tearing mode dynamics is experimentally studied in MST.

With the application of a multi-harmonic RMP, the work has experimentally investigated the TM dynamics and locking threshold in MST. Observations showed that the locking threshold was increased with increasing plasma density. A model, describing the TM interaction with the wall and an external multi-harmonic RMP, showed qualitative agreement with the experimental data. It is shown that the EM torque acting on multiple resonant surfaces has to be modeled to describe the evolution of other TMs n > 6. Since the TM rotation is connected to the plasma rotation, the inclusion of multiple modes is also important to describe the viscous torque and estimate the kinematic viscosity.

Detailed studies of the kinetic viscosity will be performed in the future.
2.2.5 Non-disruptive techniques for the identification of resonant field errors in EXTRAP T2R

An error field (EF) detection technique using the amplitude modulation of a naturally rotating tearing mode (TM) is developed and validated in the EXTRAP T2R reversed field pinch. The technique was used to identify intrinsic EFs of \( m/n = 1/-12 \), where \( m \) and \( n \) are the poloidal and toroidal mode numbers. The effect of the EF and of a resonant magnetic perturbation (RMP) on the TM, in particular on amplitude modulation, is modeled with a first-order solution of the modified Rutherford equation. In the experiment, the TM amplitude is measured as a function of the toroidal angle as the TM rotates rapidly in the presence of an unknown EF and a known, deliberately applied RMP. The RMP amplitude is fixed while the toroidal phase is varied from one discharge to the other, completing a full toroidal scan. An example is shown in figure 2. Using three such scans with different RMP amplitudes, the EF amplitude and phase are inferred from the phases at which the TM amplitude maximizes. The estimated EF amplitude is consistent with other estimates (e.g., based on the best EF-cancelling RMP, resulting in the fastest TM rotation).

![Figure 2.2-8. Shown are the time-varying amplitude of the poloidal field (blue) and the phase of the TM (red) in the presence of a Br = 2 G RMP during rotation period. The vertical dashed line intersects the point where the poloidal field is maximized (blue point) and the TM phase at which this maxima occurs (red point). The solid horizontal line shows the phase of the applied RMP.](image)

Publications section 2.2.2-2.2.5

**Peer reviewed journals**

4. Puiatti, M; Dal Bello, s; Marrelli, L; Martin, P; Agostinetti, P; Agostini, M; Antoni, V; Auriemma, F; Barbisan, m; Barbui, t; Baruzzo, M; Battistella, M; Betti, R; Bigi, M; Bilel, R; Boldrin, M; Bolzonella, T; Bonfiglio, D; Brombin, M; Canton, A; Cappello, S; Carraro, L; Cavazzana, R; Cester, D; Chacon, L; Chapman, B; Chitarin, G; Ciaccio, G; Dalla Palma, M; Deambrosis, S; Delogu, R; De Lorenzi, A; De Masi, G; Dong, J; Escande, D; Esposito, B; fassina, a; Felli, F; Ferro, A; finotti, c; Franz, P; Frassinetti, L; Gaio, E; Ghezzi, F; Giudicotti, L; Gnesotto, F; Gobbin, M; Gonzalez, W; Hanson, J; Grando, L; Guo, S; Innocente, P; Jackson, G; Kiyama, S.; Komm, M; Laguardia, l; Lorenzini, R; Luce, T; maistrello, a; Manduchi, G; Mansfield, D; Luchetta, A; Marchiori, G; Marconato, N; M; Mazzitielli, G; Miorin, E; Momo, B; Okabayashi, M; Olofsson, K E J; Paccagnella, R; Patel, N; Pavei, m; Peruzzo, S; Pilan, N; Pigatto, L; Piovano, R; Piovesan, P; Piron, L; Piron, C; Predebon, I; Rea, C; Recchia, M; rizzolo, A;
Rostagni, G; Ruset, C; Ruzzon, A; Sajo-Bohus, L; Sakakita, H; Sarff, J; Sonato, P; Terranova, D; Xu, x; Yanovskiy, "Overview of the RFX-mod contribution to the international Fusion Science Program", Nucl Fusion 55 (2015) 104012.

Conference contributions
5. L. Frassinetti, R Fridström, P.R. Brunsell MWM Khan, CS Setiadi, “Experimental study on the physical mechanism related to the hysteresis of the TM locking-unlocking process to an external field in EXTRAP T2R.”, 17th IEA/RFP Workshop, 26-29 october 2015, Hefei, China.
8. R. Sweeney, Frassinetti L. Brunsell P.R., F. Volpe, “Non-disruptive techniques for the identification of resonant field errors in EXTRAP T2R” 20th workshop on MHD stability control, November 2015, Princeton (NJ), USA
2.2.6 MHD stability

Y. Liu, D. Yadykin

During 2015, we have been focusing on computational modelling of the plasma response to externally applied 3D magnetic field perturbations. Study of the plasma response to 3D fields is important in three key aspects: (i) for understanding the plasma MHD behaviour at high pressures, in particular when the plasma pressure approaches or even exceeds the so called no-wall Troyon limit; (ii) for identifying the best ways of controlling the large (type-I) edge localized modes (ELMs) in tokamaks, by applying 3D resonant magnetic perturbation (RMP) fields; and (iii) for further investigation of the toroidal flow damping of the plasma due to the presence of 3D fields. All these three aspects of modelling work have been pursued by our Group. In particular, we carried out the modelling for ASDEX Upgrade and JET, and compared the results with the experimental measurements. We also made predictive study of the flow damping due to the RMP fields in ITER, showing that the presently designed ELM control coils should not cause significant problem for the plasma core momentum confinement in ITER.

Reconstruction of the 3D plasma boundary shape based on the edge diagnostic measurements is important for understanding the ELM physics and the plasma response to the external magnetic fields including active feedback control and the plasma shape control. The work started in 2014 on JET tokamak is continued focusing on inclusion of the diagnostics taking measurements at different toroidal and poloidal positions, resulting in more accurate reconstruction of the plasma boundary. Plasma shape evolution is studied during application of the external magnetic fields. Effect of the interaction between Error Field Correction Coils and plasma shape control system on the plasma boundary is investigated.

Publications section 2.2.6

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, A. Garcia-Carrasco, P. Ström, A. Weckmann, Y. Zhou, A. Hallén, G. Possnert and D. Primetzhofer

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) International Atomic Energy Agency (IAEA), (iv) Implementing Agreements of International Energy Agency (IEA). It is demonstrated by the participation in:

- EUROfusion Work Programme:
  - Work package JET2: Analysis of Plasma-Facing Components from JET (M. Rubel from KTH is the Project Leader of that EUROfusion work package)
  - Work package PFC: Plasma-Facing Components for ITER
  - Work package MAT: Diagnostic Materials for DEMO
- ITPA, IAEA and IEA activities.

Experimental work is carried out at home laboratory, JET, ASDEX-Upgrade and Forschungszentrum Jülich. 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 including testing of high-Z metals.
- Development and testing of diagnostic components: first mirror test at JET for ITER
- Development of diagnostic methods for PWI studies.

Co-deposited layers in the divertor region of JET with ITER-Like Wall

The determination of fuel retention and material migration leading to the buildup of co-deposits – especially beryllium erosion and transport – belong to key research areas in operation of the JET tokamak with the ITER-Like Wall (JET-ILW). The analysis of PFC from a campaign which started in 2011 with clean tile surfaces has given a unique opportunity of looking for a material migration and deposition history. This also includes tracing of the plasma operation and the history of heating power increase throughout the campaign: starting from limiter plasmas and then followed by the divertor operation with a gradually increased heating. During the latter operation period impurity species (e.g. nitrogen) were seeded to cool the plasma edge. The retention of nitrogen is to be addressed. The focus of this work was on a correlation between the operation and the deposition accompanied by material mixing.

The study was carried out for the tungsten-coated carbon fibre composite (W-CFC) divertor plates and for erosion-deposition probes (EDP) retrieved from the JET vessel after the 2011-2012 campaigns which lasted totally for about 18.9 h including 13 h of X-point operation.
Specimens were obtained by coring the inner (Tile 1, 3 and 4) and the outer divertor (Tile 6, 7, 8) plates. In total nineteen samples have been examined. The study of wall probes was done for test mirrors made of polycrystalline molybdenum and for a stainless steel cover of the quartz microbalance (QMB); details about the structure and location of wall probes are in. It has already been known that the thickness of co-deposited layers in most positions does not exceed 1 µm. To study the impurity concentrations in these layers time-of-flight heavy ion elastic recoil detection analysis (ToF-HIERDA) was used. Its main advantages are: (a) high sensitivity, (b) good separation of light isotopes up to neon, (c) depth profiling with high resolution for about 0.5µm (i.e. information depth) from the sample surface and (d) quantitative measurements for different elements. Under normal conditions a sensitivity lower than 10^{-3} is normal. However, as both the impinging ion and the recoiled target ion are leaving the target at shallow angles the depth profiles are very sensitive to the sample roughness which consequently deteriorates depth resolution. For samples where the roughness is larger than the analyzed depth it is not possible to determine a quantitative depth profile. Instead the ratio of different elements in the analyzed layer were calculated. This feature was used in the examination of W-CFC cored samples from the divertor.

A representative HIERDA spectrum for a divertor target (Tile 4 in this case) is shown in Figure 2.3-1. Hydrogen, deuterium, beryllium, carbon, nitrogen and oxygen along with tungsten, steel or Inconel components are the main species detected in most locations. The mass resolution is not sufficient to resolve the different steel elements Fe, Ni, Cr accurately and they are therefore treated as a single element. In addition, molybdenum has been found in several locations. It originates both from the Mo-W marker layers on some tiles and the erosion of Inconel 625 parts of the radio frequency antenna. An important feature is a clear trace of nitrogen thus proving that gases for plasma edge cooling are efficiently retained in co-deposits on PFC. This confirms results of our works dedicated to the determination of nitrogen retention in TEXTOR and ASDEX-Upgrade.

Figure 2.3-1. Example of ToF-HIERDA spectrum from Tile 4.

An overview of the poloidal deposition pattern of Be, C, N and O is shown Figure 2.3-2. The divertor cross-section with the so-called S-coordinate is also shown. The data are given in the form of concentration ratios with respect to beryllium, deposited as a result of erosion from limiters in the main chamber: O/Be, N/Be and C/Be. In this notation low values correspond to points with high relative beryllium content. This particularly applies to the top part (apron) on Tile 1 where thick Be deposits were formed, as demonstrated in Figure 2.3-3, from which presents distribution and absolute Be and D contents along the tile. A clear maximum occurs on the flat apron. Except that Be-rich region, in the majority of other analyzed areas, a strong signal from the tungsten, or molybdenum for Tile 3 that has a special marker coating, substrate could be detected thus indicating that the entire deposited layer was probed. For a uniform layer of Be on top of W, under the current analysis conditions, a clear tungsten signal should be seen as long as the layer thickness was below 2x10^{19} Be cm^{-2}. For most of the
points the Be signal that was detected should correspond to less than 10% of this as the W signal is not strongly affected. For the high field side of Tile 4 the layer is possibly thicker but should be less than 50%. Also on the upper part of Tile 6 the W signal is affected but should be less than 25%. In the total amount of Be was found to be below $10^{18}$ at./cm$^2$ on Tile 4 and 6 with higher amounts found locally in valleys formed by the CFC structure, this indicates indeed that the estimates above is an upper limit.

![Figure 2.3-2](image)

**Figure 2.3-2.** Amount of light impurities related to the concentration of Be are given for different positions in the diveror. On top of the plot the corresponding tile numbers are given. Positions of the tiles are given in the insert. Note that the scale for N is different from the C and O scales.

![Figure 2.3-3](image)

**Figure 2.3-3.** Be and D concentration on Tile 1. Att: scales are different for different parts of the tile.

Using the data presented in Figs. 2.3-2 and 2.3-3 and the estimate above it is possible to estimate how much carbon, oxygen and nitrogen is found in the layer. From the histogram in Figure 2.3.1-2 one infers that the atomic concentration of nitrogen is between 3% on top of Tile 1 and 15% on Tile 3 in the inner divertor. However, when absolute numbers are considered, one perceives that the retention of nitrogen is the largest in the deposit on Tile 1. The same is true for oxygen and carbon. The obtained pattern is a result of the last period of operation with 151 pulses with the same position of strike points. Carbon migrates by erosion and re-deposition and it is transported also to Tile 4 where ratio changes from 0.49 on the sloping part to 0.93 in the corner under the protection plate of Tile 5. It is a result of a multi-step process, as determined earlier in marker experiments with $^{13}$C-labelled methane.
However, the most important point is that the absolute carbon concentrations are small reaching only a level $(10^{19} \text{ cm}^{-2})$, even in the thickest layers.

The chemical form of deposited species could not be studied. The formation of BeO by gettering of oxygen impurities can be assumed with high probability. Indeed, oxygen is the most common impurity but in most locations O/Be < 1. Therefore, the presence of other forms of Be in the divertor should be considered. While the formation of a certain amount of stoichiometric compounds, e.g. beryllium nitride (Be$_3$N$_2$) or carbide (Be$_2$C), under tokamak operation cannot be fully eliminated, the dynamic conditions of erosion and deposition suggest rather a mixture of compounds containing also chemically bound nitrogen. The formation of mixed oxides, nitrides, borides and carbides has been detected using X-ray methods on the very surface layer and in thicker films on components from TEXTOR and, also on test mirrors from JET.

On the divertor-inserted probes with smooth surfaces (quartz microbalance and test mirrors from the First Mirror Test) quantitative depth profiling could be accomplished. Plots in Figure 2.3-4 reveal the deposition history on a molybdenum mirror from the outer divertor. The total deposit thickness is around 180 nm. The lack of a sharp mirror-deposit interface could be a result of both material mixing and variations in the layer thickness, other effects such as the mirror roughness should be smaller. Beryllium is a dominant constituent in the deposited layer and its profile is nearly constant with O/Be, N/Be and C/Be are 0.3; 0.04 and 0.06, respectively. Only at the interface there is relative increase of the oxygen content attributed to: (a) unavoidable presence of the oxide (MoO$_2$, MoO$_3$) layer on the original mirror surface and (b) larger amount of oxygen impurities gettered by Be at the very beginning of the JET-ILW operation. Another increase of oxygen content at the very surface corresponds to the uptake of atmospheric oxygen. Carbon also has two regions of the increased content. They correspond to the initial phase of the ILW operation and exposure to air after the mirror retrieval from JET. In general, the C content is very low, on average 20 times less than Be, thus being in a very good agreement with spectroscopy measurements. There is also a clear feature of Inconel and steel components eroded from components such as the main chamber wall. The thickness of the layer where features of nitrogen and tungsten appear is smaller than for the elements described above. It reflects that fact of divertor operation started a few weeks after the initial ILW phase with limiter plasmas. The deposition of W is accompanied by the accumulation of nitrogen in the deposit. It is a strong indication that the nitrogen presence is directly related to the tokamak operation. Similar profiles have been also determined on the mirrors from the inner divertor where discrete structure of tungsten and Inconel deposition profiles could be traced.

Depth profiles in Figure 2.3-4(b) have been recorded for a cover of QMB located in the outer divertor. The features of beryllium, carbon and oxygen are as those on the mirror. The amount of Be on the cover is even more pronounced: O/Be, N/Be and C/Be ratios equal to 0.1; 0.03 and 0.01, respectively. The profile of steel components is different than that of Inconel on the mirrors because on the QMB there is combination of deposition of Ni+Cr+Fe from plasma and also mixing of those elements at the cover-deposit interface due to roughness and possibly local erosion re-deposition. Small traces of W were found but are not shown in the Figure 2.3-4. The nitrogen isotopes have different sources: $^{14}$N used during the entire divertor operation for a long period and, a rare isotope $^{15}$N (natural abundance 0.37%) used as a marker puffed locally from a single gas inlet module (GIM 14) in the divertor floor between Tiles 6 and has only been found on the QMB cover so far. This was done only during four pulses which were followed by two-weeks operation period (151 pulses) before shut-down. The detection of $^{15}$N in the deposits leaves no doubts regarding the origin of nitrogen in all studied deposits. It also shows great value of HIERDA in studies of plasma-facing materials.
In summary, both on the mirror and the QMB cover the amount of impurities is much lower compared to PFC surfaces of the divertor. It shows only limited transport of species to the shadowed areas. Even in the case of carbon only small quantities are measured on the probes. However, there are some differences between the probes. For instance, the cover has 30 times less deposition when compared to the louvre clip exposed for the same time in the outer divertor: $5 \times 10^{16}$ cm$^{-2}$ on the cover versus $170 \times 10^{16}$ cm$^{-2}$ on the clip, but this amount is nevertheless two orders of magnitude smaller found in flaking layers after the JET-C operation.

**Concluding remarks:** The work has brought two important results to the better understanding and description of material migration processes in JET-ILW: (a) significant residence of nitrogen used for edge cooling and (b) transport of metals to the remote areas. On all surfaces some nitrogen was found although generally in lower concentrations that those of carbon and oxygen. There is no doubt that a fraction of the injected nitrogen is retained. The sticking mechanisms and the identification of a chemical form of nitrogen-containing compounds deserves further studies taking into account that the injected small amount of 15N was not desorbed or isotopically exchanged despite over 100 plasma pulses before the end of campaign. All types metals (Be, W, Inconel components) eroded from PFC are transported to locations with no plasma line-of-sight. This poses questions regarding their transfer mechanism whether this simple transport of neutrals sputtered from the target plates or chemical transport. While BeD$_x$ compounds can be responsible for the beryllium transport, the chemical transfer of tungsten would require oxides. The presence of W oxides on PFC surfaces has been detected on several occasions. A conclusive answer regarding the transport could probably be determined a dedicated marker experiment with the 18O2 rare isotope.

**Publications section 2.3.1**

**Peer reviewed journals**


http://dx.doi.org/10.1016/j.jnucmat.2014.11.074


Presentations at international conferences and workshops


2.3.2 Characterization of metallic dust remobilization and vaporization

*S. Ratynskaia, P. Tolias, L. Vignitchouk*

The investigations, carried under PFC.SP7.5, aimed to explore and quantify the underlying physics of two ITER-relevant dust aspects that cannot be treated adequately within current dust dynamics codes:

- Dust dynamics in the nearest vicinity of the PFCs, where the processes of remobilization and gap accumulation take place.
- Dust-plasma interaction in the near SOL, where local impurity generation due to enhanced heating and vaporization can pose an operational risk.

Remobilization is one of the most prominent unresolved fusion dust issues, strongly related to the lifetime of dust on plasma facing surfaces, dust accumulation site formation and the specification of realistic initial conditions for dust dynamics codes. Therefore, a systematic cross-machine study has been initiated to investigate W dust remobilization from W surfaces. A newly developed technique based on controlled pre-adhesion by gas dynamics methods that mimics sticking as it naturally occurs in tokamaks has been utilized in several devices (DIII-D, TEXTOR, COMPASS, Pilot-PSI, EXTRAP-T2R) and has provided new insights on remobilization under steady-state and transient conditions.

The data are theoretically interpreted with the aid of macroscopic contact mechanics and heat conduction simulations. Under steady-state conditions, generic remobilization conditions – direct lift-up, sliding, rolling – have been formulated. The dominant role of adhesive forces has been assessed by a comparison with the plasma forces acting on the grain.

A consistent picture emerged from the exposures under transient heat fluxes: dust grains can melt under much lower heat loads than bulk materials, especially as clusters or multi-layers, due to poor heat conduction through the small contact area. We support this interpretation by heat transfer simulations. A novel growth mechanism of wetting-induced coagulation has been identified, where cluster melting accompanied by droplet wetting leads to the formation of larger grains, see Figure 2.3-5.

![Figure 2.3-5. Frozen capillary waves at the bottom of a non-spherical W grain formed by wetting-induced coagulation. Notice the contrast between size of the newly formed grain to that of original particles.](image-url)
Particle-in-cell simulations of dust-plasma interaction have been carried out by means of the CPIC code, developed by G. L. Delzanno at the Los Alamos National Laboratory. As they rely only on first principles, these simulations reproduce dust charging and heating effects that are not accounted for by the OML theory implemented in dust codes, such as the formation of electrostatic potential wells in the vicinity of strongly emitting dust grains and the return currents due to the Larmor gyration of the emitted electrons. Preliminary simulations of Pilot-PSI plasmas demonstrate a significant reduction of the heat flux absorbed by the dust compared to OML predictions.

Publications section 2.3.2

Peer-reviewed journals

Conference contributions
6. L. Vignitchouk et al, “Dust vaporization and accumulation sites formation”, EUROfusion joint working session on integrated plasma-wall interaction modelling, Tervaniemi, Finland 2015.
2.4 Heating and current drive

2.4.1 Radio frequency heating and current drive

T. Johnson and T. Hellsten

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 EUROfusion program through participation in the WPCD and the exploitation of the JET facility.

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

Exploitation of JET

Analysis has been performed of experiments on “Fusion Product Studies” were conducted under the scientific coordination of Sergei Sharapov (CCFE) and Torbjörn Hellsten (VR). In these experiments third harmonic ICRF were used to accelerate deuterons to MeV energies, which strongly enhanced the D-D fusion yield and also produced unusually high intensities of several other reactions that is of interest for diagnosing a high performance D-T plasma. The experiments were very successful. They provided e.g. a test of recent upgrades to the neutron camera detector system and the new gamma detectors. In addition, the FLR cut-off in the ICRF accelerated fast deuteron population was measured with high precision by the TOFOR neutron spectrometer, which enabled detailed benchmarking with ICRF modelling. These experiments have resulted in a number of publications [1-4].

Figure 2.4-1. Comparison of measurements using TOFOR and BGO and numerical results using SPOT/RFOF and ASCOT/RFOF.
During 2015 experiments were performed on the optimization of ICRF heating in JET with the ITER-like wall. Considerable improvement in the coupled power was achieved by optimizing the gas puffing near the antenna. The results were published in [5].

In addition, the KTH group has participated in the work on JET experiments M15-24 on “Target discharge for TAEs in DTE2 and fast particle physics in all scenarios” and M15-27 on “ICRH scearios for DT”, as well as in the modelling activities “T15-01” on “DT scenario extrapolation”. In each of these projects, significant efforts have been made modelling several discharges and presenting the results during internal JET meeting.

**Contributions to the MST1 Work Programme**

During 2015 experiments have been performed at AUG, under MST1, on the effect of ECRH on the stability of ICRF driven TAE modes. The results have shown that a dramatic change in the TAE stability is obtained when ECRH is switched on. The KTH group has performed extensive ICRF modelling of these discharges and the next step is to use the ICRF results in an analysis of the TAE stability.

MST1 experiments were also performed on the 3rd harmonics ICRF acceleration of deuterium beam ions at AUG. Similar experiments have already been performed at JET, but never before at AUG. During the experiments a clear acceleration of deuterium beam ions were observed using the NPA. Modelling has been performed of these experiments using both PION and SELFO and the results have been published in [6].

**EUROfusion-WPCD**

The group participates in integrated modelling within EUROfusion, where Thomas Johnson is Task Coordinator for the Heating and Current Drive activities. During 2015 the main contributions have been to work on the installation of the ITM infrastructure at JET, within the ETS4JET project, including the development and testing of new ITM standard to ensure platform independence and to enable public releases of Kepler-actors based on physics codes. In addition, a new implementation of the NBISIM code has been developed to facilitate a simplified transition to IMAS. Also ICRF wave codes have been benchmarked using the WPCD infrastructure. This work has resulted in the publications [7].

**Non-linear wave-particle interactions**

The 1D code for studying the interactions between Alfven eigenmodes and fast ions that was developed during 2014 has been extended to include a quasilinear model. The new code has been used to study the validity of the quasilinear approximation for bump-on-tail systems with phase decorrelation [8]. In addition, a new code, FOXTAIL, for the interactions of fast ions and MHD modes in full tokamak geometry has been developed. The novelty of this code is the use of canonical angles from an action-angle coordinate system of the unperturbed motion. In this system the time stepping for modelling MHD interactions is limited only be the time-scale of the toroidal precession. The first paper published on the code [9] focusses on the mathematical formulation and the numerical algorithms employed.
Bounce

Figure 2.4-2. Bounce and precession frequencies in ITER for particles with the magnetic moment 100 keV/T, as calculated using the new FOXTAIL code.

**Iterative approach to spatial dispersion**

The wave equation for ICRF waves include spatial dispersion that in general should be modelled by an integral equation. To reduce the computational effort, while retaining the complete integral operator, an iterative method has been developed in which an elliptic differential equation is solved multiple times. To separate the different wave length within the the wave field a wave-let transform is used. Such localised spectral representations could provide a significant speed up of the evaluation of the dielectric tensor and is particularly well suited when a quasi-homogeneous approach to spatially dispersive responses are applicable. The work will be published in [10].

Figure 2.4-3. Wavelet spectrum of solution wave equation in a dispersive media, where the dispersion is treated iteratively.
Publications section 2.4.1

Peer reviewed journals
4. M. Schneider et al, Nuclear Fusion 56 (2016) 112022
2.5 Energetic particle physics

2.5.1 Physics of burning fusion plasmas

Energetic particle physics

R. Nyqvist and F. Eriksson (PhD student)

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. In fact, energetic particles constitute the only heating alternative beyond the Ohmic regime, but are also known to play a decisive role for plasma stability. E.g., fast particles are prone to excite wave instabilities in the Alfvénic frequency range, which may subsequently lead to severely degraded alpha particle confinement and heating. Within this field, our research activity focuses on theory development and modeling of nonlinear wave-particle interaction, which is motivated by the need to assess the implications of Alfvénic activity on burning plasma scenarios and may further provide opportunities to extract information on the plasma core via comparison with diagnostic measurements.

Publications section 2.5.1

Peer reviewed journals

Presentations at international conferences and workshops

2.5.2 Runaway electrons

T. Fülöp, I Pusztai, E. Hirvijoki, S. Newton, A. Stahl (PhD student), O. Embréus (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 2015, we investigated factors that influence the effective critical electric field for runaway-electron generation in plasmas. We presented numerical solutions of the kinetic equation and discussed the implications for the threshold electric field. We showed that the effective electric field necessary for significant runaway-electron formation often is higher than previously calculated due to both (1) extremely strong dependence of primary generation on temperature, and (2) synchrotron radiation losses.

We found that under certain conditions, due to radiative momentum losses, a non-monotonic feature – a ‘bump’ – can form in the runaway electron tail, creating a potential for bump-on-tail-type instabilities to arise. We studied the conditions for the existence of the bump. We derived an analytical threshold condition for bump appearance and gave an approximate
expression for the minimum energy at which the bump can appear. Numerical calculations were performed to support the analytical derivations.

The transport of energetic electrons is sensitive to magnetic perturbations. By using three-dimensional numerical simulation of test particle drift orbits we showed that the transport of untrapped electrons through an open region with magnetic perturbations cannot be described by a diffusive process. Based on our test particle simulations, we proposed a model that leads to an exponential loss of particles.

Finally, we developed a numerical solver of the 2D non-relativistic linearized Fokker-Planck equation for ions and used it to consider conditions for runaway ion acceleration in tokamaks. Typical time scales and electric fields required for ion acceleration were determined for various plasma compositions, ion species, and temperatures, and the potential for excitation of toroidal Alfvén eigenmodes during tokamak disruptions was considered.

**Publications section 2.5.2**

**Peer reviewed journals**


**Presentations at international conferences and workshops**


**Thesis**
3 Plasma auxiliary systems - diagnostics

3.1 Neutron diagnostics

3.1.1 Diagnostic developments for JET and ITER

Neutron emission spectroscopy using a NE213 liquid scintillator

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

NE213 liquid scintillators are compact neutron detectors that have the capability of providing neutron spectroscopy information. This capability has been investigated using a detector installed with the MPRu neutron spectrometer at JET.

The analysis of the data from the 3rd harmonic RF heating experiment at JET, started in 2014, has been finalized. A simple model of the ion velocity distribution has been used to calculate the neutron emission. The model showed good agreement with the data (Figure 1). The results have been included in 2 papers [1,2], where the NE213 measurements are compared to measurements done with the TOFOR spectrometer and with a diamond detector.

Figure 3.1-1. NE213 spectra measured during the 3rd harmonic RF heating experiment at JET for discharge 86459 (left) and corresponding neutron energy distribution (right).

Calculation of the profile-dependent neutron scattered component for the JET neutron camera

F. Binda, G. Ericsson, S. Conroy, E. Andersson Sundén

The energy spectrum of the neutrons that strike a detector includes a contribution that comes from neutrons scattered on the tokamak and on the structures surrounding the detector. The intensity and energy distribution of this contribution can depend on the neutron emissivity profile.
The investigation on such dependence was started by building a matrix from a MCNP model which allows to go from a given neutron emissivity distribution to the scattered neutron spectrum at a certain detector position.

Figure 2 shows the weights of the distribution of the weights for the matrix calculated for the central channel of the horizontal neutron camera at JET.

![Figure 2](image)

**Figure 3.1-2.** Spatial distribution of the weights of the scattered neutron matrix for channel 5 of the neutron camera at JET. A brightest colour indicates that the region gives a higher contribution to the scattered component. The red line indicates the line of sight of the detector.

**Neutronics calculations supporting WPJET3 and WPJET4**

*S. Conroy, J. Eriksson*

The upcoming DT campaign at JET is planned to include a phase with a high nT/nD ratio. This will mean significant neutron production from the Tritium-Tritium (TT) reaction. In order to assist with planning, the spectra and fluxes of these neutrons at various locations inside the vacuum vessel are required. Unfortunately the sources in MCNP are not sufficient to model this well, so software was made to model the production of neutrons from this reaction. The DRESS code was modified to include this reaction and produce an energy and pitch angle resolved neutron map.

Calculations were also carried out relating to the DT upgrade of the JET gamma camera. Using a JET model neutrons were transported from the plasma to the surface of the KN3 camera using MCNP. In a second step, those neutrons were then transported into the camera and thermalized, generating gamma rays. The interaction of those gamma rays with the proposed upgraded detectors was then estimated. Comparisons with the existing CsI detectors were also carried out and found to be in fair agreement with experimental observations.
3.1.2 Neutron Diagnostic at MAST and MAST Upgrade

**Modelling of the absolute neutron emission on MAST**  
*M. Cecconello, I. Klimek, S. Conroy*

A detailed study of the comparison between the neutron emissivity predicted by TRANSP on MAST and the one measured by the neutron camera was carried out on a series of different plasma scenarios with and without the presence of fast ion redistribution and losses and non-resonant MHD perturbations. In all analysed cases, TRANSP overestimated the measured neutron emissivity by a factor of approximately 1.6 independently of the plasma scenarios. Preliminary comparisons with an independent experimental measurement of the DD fusion rates via the charged fusion product detector array confirms the neutron camera measurements. A systematic study of the effect of the uncertainty in the experimental measurements used as inputs to TRANSP and NUBEAM modelling indicated that the relative error in the predicted neutron emissivity is at worst approximately no larger than 20% and therefore unable to explain the observed discrepancy. The source of this overestimate is not clear and the subject of ongoing study.

![Figure 3.1-3](image)

**Figure 3.1-3.** Neutron count rates predicted by TRANSP/NUBEAM (in red) and measured experimentally (black curve) without (left) and with (right) the scaling factor for pulse 29738.

**Fast Particle Physics with the MAST neutron camera**  
*M. Cecconello, I. Klimek*

Interpretation of the neutron emission in MAST plasmas in the presence of resonant MHD perturbation using TRANSP, NUBEAM and FIDASIM codes integrating observations from other fast particle diagnostics such as FIDA and the charged fusion product detector with stability, modelling and predictive codes to provide a consistent description of the fast ion behaviour in MAST was continued and extended in 2015. The work carried out expanded upon the previous study by providing:

- a rigorous quantitative assessment of the degree to which the reduction in FI confinement is correlated with TAEs and fishbones;
• direct experimental confirmation of the fact that these MHD modes cause losses of FIs from the plasma;
• an improved implementation of the fishbone loss model in TRANSP, including fast-ion deuterium alpha (FIDA) data as a constraint for the first time;
• a demonstration that simultaneous analysis of data from multiple FI diagnostics allows transport models to be confronted and validated, or to have their shortcomings revealed.

Figure 3.1-4. Comparisons between measured and NUBEAM-modelled FI diagnostic time traces and radial profiles in the presence of chirping TAEs and fishbones. Panel (a) shows the global neutron rate measured in shot #29210 (black) compared to that modelled with (red) and without (blue) spatially-uniform anomalous FI diffusion in TRANSP. The forward-modelled NC and FIDA profiles are compared to the measured profiles in panels (b) and (c) for t = 0.165 s and in panels (d) and (e) for t = 0.240 s. The vertical dashed and dotted lines in panels (b)–(e) indicate the approximate radial positions of the magnetic axis and minimum-q surfaces.

The main findings are the confirmation that anomalous transport and losses of FIs accompany both chirping TAEs and fishbones; the demonstration that multiple diagnostic signals may in some cases be modelled consistently using anomalous FI diffusion in a global transport model; and the identification of the passing FI population in the core of the plasma as being susceptible to redistribution in the presence of fishbones. Four main conclusions are supported by the results obtained:

• Drops in both FIDA and NC signals are correlated with chirping TAE and fishbones at a statistically significant level, indicating a reduction in the confined FI density.
• Chirping TAEs and fishbones cause enhanced losses of FIs from the plasma.
• The profiles of NC and FIDA signals averaged over individual bursts of MHD activity are well modelled by applying anomalous diffusion to the FIs in NUBEAM.
• Fishbones strongly affect the high-energy, passing FI population in a manner which may be reproduced with some success using the fishbone model in NUBEAM.
In MAST, bursting TAEs and fishbones are observed to give rise in some cases to an asymmetric perturbation to the soft x-ray (SXR) emission close to the magnetic axis which grows and decays on the time scale of the fishbone evolution. As the fishbone nears its maximum amplitude, the SXR emission starts to increase (decrease) at radial positions smaller (larger) than the radial position of the magnetic axis. This trend in the SXR emission persists for a few milliseconds, until the fishbone starts to decay in amplitude and the slower overall trend of the SXR emission once again becomes dominant. A preliminary analysis suggests that the change in the SXR emission is due to the localized accumulation of high-Z impurities, sustained against parallel transport by the effects of fishbones on the fast ion population. One effect of the fishbones on the background plasma in MAST, giving rise to the observed SXR emission behaviour, is the poloidal redistribution of heavy impurities from the low- to the high-field side of the plasma. The novelty of the observations here reported is the apparent direct link between bursting energetic particle modes and the inboard accumulation of high-Z impurities. Since ITER will be characterized by a substantial population of super-Alfvenic fast particles, these observations open the possibility that a similar effect might occur in ITER thus affecting impurity transport and ultimately the energy confinement. This effect is particularly crucial for ITER due to the tungsten divertor.

The phenomenon of the redistribution of neutral beam fast ions due to MHD activity in plasma has a focus of research on MAST in order to address their impact on the q-profile control and non-inductive neutral beam current drive. Theoretical work on fishbone modes states that the fast-ion distribution acts as the source of free energy driving the modes that cause the redistribution. In 2013 a series of experiments were carried out on MAST to
investigate a range of plasma densities at two neutral-beam power levels to determine the region within this parameter space in which fishbone activity and consequent fast-ion redistribution is suppressed. The fusion diagnostic group contributed to the analysis of these experiments which showed complete suppression of fishbone activity at high densities with increasing activity and fast-ion redistribution at lower densities and higher neutral-beam power. The results indicated the existence of correlations between gradients in the modelled fast-ion distribution function, the amplitude and growth rate of the fishbone modes, and the magnitude of the redistribution effect.

Figure 3.1-6. FI distribution function gradient $\frac{\partial f}{\partial \psi_{pp,N}}$ (plotted with arbitrary units) averaged over POI; black: one-beam shots, red: two-beam shots. Also shown for comparison are the one- and two-beam shots carried out in previous experiments. The indicated ‘Critical’ level is the level above which FB modes should be expected to cause FI redistribution. Mode growth rate $\frac{dB_{pert}}{dt}$ versus line-averaged density for black: one-beam shots, red: two-beam shots, blue: one- and two-beam shots carried out in previous experiments.

These findings were then used to optimize the geometry of NBI injection in MAST-Upgrade in order to mitigate the effect of fishbone-driven fast ion redistribution and losses.

3.1.3 Neutron Diagnostics for the JET Physics program

Dual sightline measurements of MeV range deuterons

J. Eriksson, C. Hellesen, F. Binda, G. Ericsson

A JET experiment (M13-45) accelerating deuterons to the MeV range by third harmonic ICRH coupled into a deuterium beam were analyzed during 2015 [1]. Measurements based on a set of advanced neutron and gamma-ray spectrometers, observing the plasma simultaneously along vertical and oblique lines of sight, were combined to infer the shape of the fast deuteron energy distribution. An example is shown in the left panel of Figure 3.1-X. The distributions were estimated from the data within a uniform analysis framework for neutron and gamma-ray spectroscopy based on a one-dimensional model of the fast ion distribution.

Furthermore, a framework to calculate neutron and gamma-ray emission from a spatially resolved, two-dimensional deuteron distribution specified by energy and pitch was also
developed and used for a first comparison with predictions from the ASCOT/RFOF code, which provides a more sophisticated model of ICRH at multiple harmonics. This comparison is shown in the right panel of Figure 3.1-X.

The results of this analysis are of relevance for the development of advanced diagnostic techniques for MeV range ions in high performance fusion plasmas, with applications to the experimental validation of RF modelling codes and, more generally, to studies of the energy distribution of ions in the MeV range in high performance deuterium and deuterium-tritium plasmas.

**Figure 3.1-7.** Left: Fast deuterium distribution functions estimated from the TOFOR (blue) and NE213 (red) neutron spectrometers. For details, see [ref]. Right: Comparison between the measured TOFOR spectrum (points with error bars) and the neutron spectrum obtained from modelling with the ASCOT/RFOF code.

**TOFOR measurements of the RF induced neutron emission in JET hybrid experiments**

**J. Eriksson**

The hybrid scenario is an operational tokamak plasma regime designed to achieve long pulse operation with a combination of inductive and non-inductive current drive. It has been suggested for ITER to allow operation at a high fusion power over 1000s at a lower plasma current than for the inductive reference scenario. In recent JET experiments (M13-33) with the new ITER-like wall, high-performance hybrid discharges have been achieved with combined NBI and ICRH. The ICRH was tuned to the fundamental cyclotron frequency of
minority H ions which coincides with the 2nd harmonic cyclotron frequency of D ions in the plasma centre.

The TOFOR spectrometer was used to measure the neutron spectrum from these discharges. From the measurements it was possible to estimate the fraction of the neutron emission that was due to RF accelerated D ions reacting with the thermal background plasma. The TOFOR estimates could be compared with the corresponding fraction obtained from modelling with the ICRH code PION and the results were found to be in overall agreement, as exemplified in Figure 3.1-Y. More details are given in [2]. This is an important validation of the ICRH modelling and lends confidence in extrapolations to hybrid plasmas with DT fuel.

![Figure 3.1-Y](image.png)

Figure 3.1-Y. RF neutron fraction estimated from TOFOR measurements (points with error bars) compared with the corresponding quantity obtained from PION modelling (blue line).

**Publications section 3.1**

6. Giacomelli, L. et al. (incl. S. Conroy), High rate measurements of the neutron camera and broadband neutron spectrometer at JET. Physics Procedia. - 2015 62, s. 124-8

3.2 Neutron emission spectroscopy

Neutron spectrum calculations for arbitrary reactant distributions

J. Eriksson, S. Conroy, C. Hellesen

A code to perform Monte-Carlo calculations of neutron energy spectra from arbitrary reactant distributions, using fully relativistic kinematics, has been developed [1]. The code is called the Directional Relativistic Spectrum Simulator (DRESS) and is set up to calculate energy spectra from neutrons and alpha particles produced in the D(d,n)3He and T(d,n)4He fusion reactions (furthermore, any two-body reaction could be simulated by including the corresponding cross section). The code has been thoroughly tested. The kinematics calculations have been benchmarked against the kinematics module of the ROOT Data Analysis Framework. Calculated neutron energy spectra have been validated against tabulated fusion reactivities and against an exact analytical expression for the thermonuclear fusion neutron spectrum, with good agreement.

An example calculation of the neutron spectra from a NBI heated JET-like plasma is shown in Figure 3.2-1. The DRESS code will be used as the core of a detailed synthetic diagnostic framework for neutron measurements at the JET and MAST tokamaks.

Figure 3.2-1. Left: An example of a D distribution of the type commonly found in NBI heated JET plasmas. Right: beam–thermal (BT) and beam–beam (BB) neutron spectra calculated with the DRESS code, for an emission direction perpendicular to the plasma magnetic field.
Fast ion weight functions for neutron spectrometry

J. Eriksson, G. Ericsson

By computing neutron energy spectra for a large number of fast ion energies and pitch angles, it is possible to make a mapping between a given neutron energy interval and the region in the fast ion phase space that can give rise to neutrons in this energy interval. The resulting “maps” are commonly called weight functions, and have previously been derived for several fast ion measurement techniques, such as FIDA and collective Thomson scattering. In [2], velocity-space weight functions were derived for neutron spectrometry and neutron yield measurements. An example is shown in Figure 3.2-2.

The overall aim of the weight function project is to combine measurements from different fast ion diagnostics, with their respective weight functions, and infer the underlying fast ion distribution by means of tomographic inversion techniques. This investigation is ongoing.

Figure 3.2-2. Fast ion weight function for neutrons with energies En = 2.73 0.015 MeV. Only fast ions with non-zero weights can give rise to neutrons in the given energy range.

Publications section 3.2

4 Concept improvements

4.1 Computational methods and operational limits

J. Scheffel and K. Lindvall (PhD student)

In light of the need for efficient multiple time and spatial scale simulations in physics, it is surprising that time-spectral methods for partial differential equations have not yet been studied and explored systematically. For example, turbulence in fusion plasmas at high Reynolds or Lundquist numbers are presently addressed by gyrokinetic codes that are allocated millions of CPU hours for parallel processing on supercomputers. If there exists a new avenue that may alleviate the requirements on computer power for these crucial problems, it is certainly of great importance to explore it.

The aim of this project is to develop novel time-spectral methods for solving systems of partial differential equations related to current advanced problems in fusion plasma physics. This new type of numerical tool has an efficiency potential far exceeding that of traditional explicit and implicit time-differencing methods, but is still in the developing phase. Nevertheless, linear and nonlinear problems in resistive MHD and 2D transport theory have been successfully solved. As a next step, the physics of nonlinear two-fluid drift-wave turbulence in the tokamak is approached. Future research areas include linear and nonlinear resistive g-mode stability in the reversed-field pinch (RFP). A brief report on progress during 2015 follows.

4.1.1 The Generalized weighted residual method (GWRM)

In the time-spectral method also the time domain is treated spectrally, thus avoiding the limitations on time step length caused by CFL-like conditions. This is quite different to standard (explicit or implicit) finite difference methods. A semi-analytical finite Chebyshev polynomial solution ansatz is employed, and the numerical problem reduces to determination of the coefficients of the ansatz from linear or nonlinear algebraic systems of equations. Being a generalisation of weighted residual methods to the time and parameter domains, the method is termed the Generalised Weighted Residual Method; GWRM.

In order to avoid large memory storage and computational cost, the temporal and spatial domains are divided into subdomains. Until recently we had published only basic algorithms for carrying out this. By “basic” is meant that, although the spatial subdomains were divided into subdomains, the corresponding coefficient matrix equations to be solved were not significantly less than those for a single global domain. The latter case is not practical, since for sufficient resolution a huge number of Chebyshev modes would be required for the single, global domain; the computational time scales as the cube of the total number of modes (memory requirements scale quadratically).

During 2015 we have found a method to drastically reduce the number of computational operations and the memory requirements when solving the algebraic equations for the Chebyshev coefficients that represent the linear or nonlinear system of partial differential equations relevant to the problem at hand. For guaranteed convergence, the GWRM requires simultaneous information from all spatial domains of the computational domain. A primitive algorithm would then simultaneously involve all the Chebyshev coefficient equations of all
the subdomains when the corresponding Jacobian is inverted in each iteration. This would be costly; say that the number of Chebyshev modes in total is $N$ – then memory requirements scale as $N^2$ and computational complexity scales as $N^3$, which would be prohibitive for advanced problems. In the new method, all physics equations are solved locally in each spatial subdomain for each iteration, whereas only the boundary condition equations, linking the domains, are solved globally. This procedure not only drastically reduces the number of global equations to be solved; it enables parallelization of the computations of each subdomain and reduces the algebraic complexity of the equations, with a strong reduction in required memory space and even more dramatic reduction in computational operations. In 2015 we also found that sparse matrix methods have strong potential for further reduction of the matrix operations.

4.1.2 Modelling of drift wave turbulence in tokamaks

J. Scheffel and H. Nordman

Drift wave turbulence is driven by density or temperature gradients. This universal phenomenon is inherently limiting performance in the tokamak. It can be studied in a host of models, reaching from two-fluid to advanced, nonlinear gyrokinetic models. Turbulence driven by pure ITG modes in 2D geometry, neglecting trapped electrons, is to be studied using the present GWRM model and compared to results obtained with the fluid turbulence code developed at Chalmers University. Particular emphasis will be on accuracy and efficiency and subsequent development of more advanced turbulence models within the GWRM. As a next step, extension to kinetic drift wave turbulence will be attempted.

The main instabilities that drive the turbulent transport in the core of tokamaks are Ion-Temperature Gradient (ITG) modes, driven by the ion temperature gradient, and Trapped Electron (TE) modes, driven by electron temperature and density gradients. As a starting point, the turbulence driven by pure ITG turbulence in 2D geometry, neglecting trapped electrons, will be studied in this project, and compared to the results obtained with the fluid turbulence code developed at Chalmers. Pure 2D ITG turbulence is governed by two complex nonlinear and coupled time-dependent pde's. Results for this basic turbulence model should first be obtained. Subsequently additional physics will be included in the form of 3D effects, trapped electrons, multiple ion species, and finite beta electromagnetic effects, corresponding to the level of realism included in the latest version of the Chalmers transport model as implemented in the JETTO transport code. This will allow more realistic studies with coupled ITG/TE mode turbulence. The relevance of the method for more advanced gyrofluid and gyrokinetic models will also be investigated. If the GWRM offers substantial efficiency gains, the next step would be to integrate a fast turbulence code with a transport code to go beyond the quasilinear approximations used in present transport codes.

The Chalmers ITG turbulence model has been coded into a 2D GWRM code, employing both spatial and temporal subdomains. Employing three spatial domains in each of the $x$- and $y$-directions, $4^{th}$ order spatial Chebyshev polynomials and $6^{th}$ order temporal resolution, the full nonlinear problem for the toroidal $\eta_i$ mode (Cyclone base case) was solved on a table-top computer, using about 1 GB of memory for approximately 10 minutes. The corresponding linear problem was more efficiently for a number of physical and numerical parameters.

Subsequent development of what is termed “Common BC” algorithm, and use of sparse matrix methods have now significantly diminished these numbers. The COMMON BC algorithm allows parallelisation of the solutions of the physical equations of each spatial subdomain, solving only the equations that couple the subdomains globally.
5  EUROfusion, EFDA and F4E Work

5.1 Participation in EUROfusion Work Packages

5.1.1 EUROfusion Work Package JET3 (Technology Developments)

Sub-project NCAL: Characterization of neutron field, activation and dose

Henrik Sjöstrand, Sean Conroy

This sub-project had started with making an inventory of current JET models and numerical tools, moving on to agreeing on the numerical tools and cross-sections to be used. Necessary modifications to the MCNP model were made to incorporate the planned experiments from WPJET3. The neutron field at requested positions was then evaluated. Quantities of interest included DD/DT neutron/γ fluxes, nuclear heating, DPA (a measure of predicted radiation damage) and activation of Indium targets at the KN2 irradiation station. A typical set of neutron spectra are shown in Figure 5.2-1.

One special study was the effective cross-section of the 115In(n,n')115mIn reaction and its uncertainty. This is an important reaction for determining the 2.5 MeV neutron yield at JET by means of activation foils. The reaction and its uncertainty are determined by using the Total Monte Carlo (TMC) method. The results are compared to what has been found in Ref. [1]. An uncertainty of 7% was obtained using the TMC method which is larger than what was previously calculated. One possible explanation is that there are stronger correlations in the model based TMC method than what is available in the IRDFF co-variance files used in [1].

During 2015 the Total Monte Carlo method was used to study the effect of transport nuclear data uncertainty of the JET structural materials. The nuclear data uncertainty have been propagated to uncertainties for the neutron and photon flux around the JET KN2 irradiation ends and uncertainties for the reaction rates in KN2 for the two reactions 93Nb(n,2n)92mNb and 115In(n,n')115mIn. The work was performed for both DD and DT plasmas.

![Figure 5.1-1. Neutron spectra at a number of places around the JET machine calculated using MCNP within the JET NCAL Technology project.](image-url)
5.1.2 EUROfusion Work Package PPPT-WPDC

EFDA published “Fusion Electricity – A roadmap to the realisation of fusion energy” [1] in November 2012 that sets out a strategic vision to demonstrate the generation of electrical power by a Demonstration Fusion Power Plant (DEMO) by 2050. The roadmap elaborates 8 strategic missions to tackle the main challenges in achieving this overall goal. The need for the Diagnostic & Control Project is derived from the following statement within the Roadmap: “The design of ITER diagnostics has progressed a number of issues, and it is intended to take advantage from results on ITER diagnostic development as much as possible.

However, it is expected that many of the diagnostics used in ITER will either not be available for DEMO or diagnostic components will have to be mounted in a much more remote position in order to be compatible with the harsh environment on DEMO, leading to a significantly reduced diagnostic capability. Details of the diagnostic implementation on DEMO have to be clarified along with the overall DEMO design work, in order to allow for developing an integrated design with minimum impact on the TBR. New control concepts will have to be developed in order to cope with the reduced set of diagnostics and on the same time with the enhanced requirements for control reliability.”

The work package for Diagnostic and Control (WPDC) within the EUROfusion work program for Power Plant Physics and Technology (PPPT) was set up to address these issues and the primary objective of the project WPDC is to “deliver a feasible, integrated concept design of the DEMO diagnostics and control systems that, with an acceptable confidence level, can be shown to meet the control requirements of the device. The concept design shall be substantiated and verified to an appropriate level for a plant-level Conceptual Design Review.”. The Swedish Research Unit responded to the call for participation through Uppsala University at a level of 0.3 ppy/year for the period 2015 – 2018 in the sub-task “Diagnostic R&D: Studies on the feasibility, lifetime and performance of components and subsystems”.

Initial conceptual studies on neutron / gamma diagnostics

M. Cecconello, S. Conroy, A. Hjalmarsson

The project was carried out in four major steps: 1) the review of applicable documents (in addition to the reference documents provided as part of the call and their ranking in term of relevance); 2) the clarification of the requirements and specifications for the neutron diagnostic (clarification of the separation between control and diagnostic requirements); 3) software development for the integration of DEMO scenarios in the framework of software tools available at Uppsala University and 4) the development of a preliminary conceptual design of the diagnostic (estimation of the stray magnetic fields, possible viewing geometries and associated expected count rates, footprint on the breeding blanket module, integration issues, direct-to-scattered neutron calculations, detector assessment). The conclusions of this study indicated that:

1. a neutron diagnostic on DEMO should be feasible and compatible with DEMO design to provide the total and local fusion power;
2. a full poloidal coverage of the plasma volume is possible with detectors located at the far end of the equatorial and/or vertical ports although within the vacuum vessel;
3. placement of detector outside the vacuum vessel and/or the bio-shield requires modification to the blanket module in front of the equatorial port plug (no modification is needed for the one in front of the vertical port);
4. 10 cm collimator diameters are sufficient to provide the counts and count rates to insure statistically significant measurements with a 10 ms time resolution;
5. diamonds are the most likely suitable detectors (temperature, radiation damage, magnetic fields);
6. the scattered to direct ratio is estimated to be below 10 % for all the sight lines considered in this study;
7. stray magnetic fields too large for the use of PMT anywhere near the detector location unless massive or active shielding is provided.

The 2015 tasks were successfully concluded and reported in 2015.

Publications section 5.1

Peer reviewed journals
5.2 Participation in Legacy EFDA Activities

5.2.1 JET Fusion Technology Programme (EFDA JET-FT)


M. Skiba, A. Hjalmarsson, G. Ericsson, C. Hellesen

TOFu (Time-Of-Flight upgrade) is a data acquisition (DAQ) system prototype for TOFOR, which is installed in parallel to the original TOFOR DAQ. Based on 12 bit, 1 GSPS digitiser modules, the system provides unprecedented control over neutron-induced detector pulse shape analysis, enabling improvements of signal-to-background ratio and enhanced timing capabilities.

TOFOR consists of a stack of two sets of detectors, S1 and S2, providing the “start” and “stop” signals for the time-of-flight measurements. S1 is a stack of five, circular detectors situated in sight of the JET vacuum vessel interior, directly exposed to a collimated neutron stream originating in the JET plasma during operations. S2 constitutes a frustum of 32, elongated “stop” detectors exposed to a flux of neutrons scattered in S1. The kinematic background discrimination capabilities enabled by TOFu rely on digitisation of neutron-proton scattering induced light pulses, which carry information on the amount of energy imparted by the neutrons to the recoil protons and by extension, on the scattering angle of the neutrons in S1. Using this information, kinematic cuts can be introduced, mitigating some of the background present in TOFOR spectra due to accidental pairings of uncorrelated neutron scattering events.

At this time, the system only has a limited number of channels. Therefore, it has previously only been able to cover 20 of the 37 detector channels of TOFOR, including all the five S1 detectors and 15 of the S2 detectors.

During the fall of 2015, the efficiency of the system was improved to 90 % of that of the original TOFOR DAQ by pairwise summing of the signal paths originating in 30 of the 32 S2 detectors using FIFO modules. In this way, the TOFu system is now able to accommodate 30 of the 32 S2 detector channels. The process, illustrated in Figure 1 entailed time-alignment of the paired S2 signal paths using the reactor capture gamma response of the TOFOR/TOFu system and short, time-calibrated cables.

![Figure 5.2-1](image)

**Figure 5.2-1.** The gamma alignment process illustrated. Two spectra, constructed using data from one S1 detector and two (red and blue) S2 detectors in a pair are shown, before (top) and after (bottom) the alignment procedure.
5.2.2 Power Plant Physics and Technology

**MAT-IREMEV activity: Ab initio prediction of displacement events in tungsten**

*P. Olsson, KTH Reactor Physics*

Historically, in order to model the evolution of the microstructure of W under radiation conditions, empirical interatomic potentials (EIP) have been used. Such potentials are usually fitted on equilibrium properties and need to be “hardened”. For these short range repulsive interactions, very little useful information for fitting EP exists. Historically, for the very short range, the Ziegler-Biersack-Littmark [1] is used and spliced to the equilibrium potential using various interpolation schemes.

However, a more physically reliable way of obtaining information on the primary damage state, and the angular anisotropy of the creation of defects, one can directly use electronic structure calculations, where the Hamiltonian is well defined from short distances intrinsically. We have calculated the threshold displacement energies (TDE) of a number of directions in the crystal, as well as Replacement Collision Sequences (RCS), within the framework of Born-Oppenheimer density functional theory (BO-DFT) using two kinds of pseudo-potentials: the minimal set regular Projector augmented-wave (PAW) which considers 6s and 5d electrons as valence electrons and the semi-core PAW which also considers the 5p electrons explicitly in the core. The minimal set regular projector augmented-wave (PAW) will be referred to as Wsd, whereas the semi-core PAW will be referred to as Wpsd. A first-ever ab initio study of TDE in a metal (bcc Fe) was recently published [2].

The TDE is simulated by assigning an initial velocity to one atom in the simulation cell and then following the dynamics to determine if a stable Frenkel pair is formed or not. The connection to the impact energy is done in the non-relativistic limit since the kinetic energies in question are around 10-100 eV on a compound nucleus of about 0.2 TeV/c^2 mass. The TDE is then found through a dichotomy algorithm where the threshold value is quickly reached in a binary search. The simulations were done here using non-cubic super cells (to avoid dynamic self-interaction) of 6x6x9 bcc cells (648 atoms). The time step used was 3 fs, a single k-point was used to sample the reciprocal space and the plane wave energy cut-off was 230 eV. Both regular (Wsd) and semi-core (Wpsd) PAW pseudo-potentials were used.

We have computed the TDE in a number of directions using the two DFT methods. We expected to have a significant high performance computation allocation but were scaled down by a factor of 20. This did put strong brakes on the speed of progress. An optimization model has been developed where the atoms in the major part of the simulation cell are treated as Wsd while the atoms that will undergo strong compressions are treated as Wpsd. In this way the simulations gain a factor of 15 in efficiency while maintaining the physics of the Wpsd description. In Figure 5.2-2, we show the trajectory difference between the different ways of performing the calculations. The choice of background lattice parameter is seen not to be too critical, but the optimal one is to use that of the matrix (Wsd).
Basic defect properties in tungsten as predicted by $W_{sd}$ and $W_{psd}$ are listed in Table 5.2-1.

<table>
<thead>
<tr>
<th>$E_f$ (eV)</th>
<th>$W_{sd}$</th>
<th>$W_{psd}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Config</td>
<td>250 432 686 1024</td>
<td>250 432 686 1024</td>
</tr>
<tr>
<td>Vac</td>
<td>3.22 3.22 x 3.06</td>
<td>3.40 3.43 x 3.04</td>
</tr>
<tr>
<td>$\langle 110 \rangle$</td>
<td>10.1 9.93 9.90 9.84</td>
<td>10.8 10.9 10.2 10.1</td>
</tr>
<tr>
<td>$\langle 111 \rangle$</td>
<td>9.82 9.64 9.51 9.54</td>
<td>10.5 10.6 9.73 9.71</td>
</tr>
<tr>
<td>$\langle 221 \rangle$</td>
<td>9.75 9.54 9.53 9.50</td>
<td>10.5 10.6 9.78 9.71</td>
</tr>
<tr>
<td>FP</td>
<td>13.0 12.8 x 12.6</td>
<td>13.5 14.0 x 12.8</td>
</tr>
</tbody>
</table>

From the point of view of experiments, there have been a number of studies on tungsten. Maury et al [3] studied the angular dependence at least for the three high symmetry directions $\langle 100 \rangle$, $\langle 110 \rangle$ and $\langle 111 \rangle$. They concluded an absolute minimum of 42 eV. Similar results were obtained by Neely et al [4] with a minimum in the range of 38-42 eV, while Vajda et al [5] found 50 eV as the global minimum value. All the calculated TDE values are reported in Fig. 5.2-3a) below. It is there seen that the semi-core potential ($W_{psd}$) gives about 20% higher TDE values than $W_{sd}$ does. An estimate now shows that the average TDE from $W_{sd}$ is 60 eV and from $W_{psd}$ it is 75 eV. In comparison with the standard value of 90 eV, this will have consequences on dose estimates.
In Figure 5.2-3b) it can be seen that the DFT seems too soft, both in comparison with the ZBL solution for the dimer, as with the equation of state, as calculated using FPLAPW.

In summary, we have performed a large number of dynamic DFT simulations of displacement events in order to determine the threshold values in tungsten. Preliminary results indicate good agreement with the few available experiments, at least for the softer DFT method. For the stiffer, but better physically motivated $W_{psd}$ method, the simulations overestimate the threshold values with respect to experiments, except for the $<110>$ direction.

This work still needs to be further completed by statistics of TDEs which will allow a better analysis of the relationship between TDEs and RCS, or with the evolution of the total energy of the system when one atom moves along a symmetric direction. A concerted effort with respect to studies of TDE using interatomic potentials and using DFT is imperative for success.

Perspectives include a fully automated optimization scheme for simulation efficiency, studies of light element effects and effects of alloying on the primary damage states.

**Publications section 5.2.3**

**Peer reviewed journals**

5.3 Participation in Fusion for Energy projects

5.3.1 The ITER Radial Neutron Camera project

*M. Cecconello, S. Conroy, C. Hellesen, A. Hjalmarsson*

During 2015, Uppsala University participated to the activities for the development and design of a radial neutron camera (RNC) and radial gamma-ray spectrometer for ITER in the framework of a partnership agreement between several European universities and research institutes and Fusion for Energy under the grant F4E-FPA-327. In particular, the activities were carried out within the specific grant SG03 “System Level Design for Radial Neutron Camera” and included:

- Development of the RNC functional breakdown up to generic component level and the propagation of the requirements to subsystem level,
- Definition of simulation tools and procedures, preparation of alternative simulation codes based on neural networks and their benchmark and performance, and neutron emissivity reconstruction
- Development of a set of System Architecture options for the RNC
- Consolidation of the test prototype plan and development of the final specifications of high priority prototypes.

The activity was mainly focussed on the development of framework for the modelling of the neutron emissivity for DD and DT ITER scenarios all the way to a fusion power of 500 MW, of different RNC architectural options (lines of sight, collimators diameters, detector types) and for the inversion of the RNC measurements (counts at the detectors) for the estimation of the neutron emissivity profiles using machine learning algorithms. In particular, a study was carried out for the optimization of the neural network topology based on the learning performance. This was coupled with the development and testing of a decision algorithm to select, among the multiple trained neural networks, which one provided the inverted neutron emissivity profile closest to the input one.

The results from this study indicated that neutron emissivity recognition via neural networks can achieve the accuracy and precision within the spatial and temporal requirements set by ITER for the RNC. In order to achieve such performances, the method relies on the a-priori knowledge of the equilibrium flux surfaces. The training of the neural networks especially if a wide typology of profiles has to be recognized, is computationally intensive; however, once the training is completed, the profile recognition is sufficiently fast that it is considered feasible to be implemented in a real time environment for plasma control in ITER, assuming that equilibrium reconstruction algorithms can provide the flux surfaces with the required duty cycle for real time control.
Figure 5.3-1. Left: neutron emissivity profile (black curve) and reconstructed emissivities by several neural networks trained on different plasma scenarios (top panel); predicted counts at the detectors from the reconstructed neutron emissivity (middle panel) and ratio between original and predicted counts (bottom): neural network (d) is clearly the one best estimating the neutron emissivity. Right: precision (middle panel) and accuracy (bottom panel) for low and high fusion power scenarios (top panel): both accuracy and precision are below the required 10% (with 10 ms integration time) for r/a < 0.8.

5.3.2 The ITER High Resolution Neutron Spectrometer project
A. Hjalmarsson, G. Ericsson, S. Conroy, C. Hellesen

In 2015, the consortium, awarded the Fusion for Energy (F4E) grant F4E-GRT-403, was finalised and consist of two beneficiaries, IFJPAN, Krakow, Poland and Uppsala University, and two third parties, CNR-Milano and ENEA-Frascati, Italy. The grant is to perform a conceptual design study of a system of high resolution neutron spectrometers for ITER and the title of the grant is “Conceptual Design and Interfaces of High Resolution Neutron Spectrometer”. During 2105 the conceptual design work started of a High Resolution Neutron Spectrometer (HRNS) system for ITER. The first activity within the HRNS design was to review requirements and establish realistic and feasible measurement specification for a HRNS system at ITER. From the review, it was concluded that the primary design drive for the HRNS system is to derive the fuel ion ratio, nt/nd, by the use of neutron spectroscopy. A realistic requirements for nt/nd measurements is a time resolution of 100 ms over the fuel ion ratio range 0.01 < nt/nd < 10 with an uncertainty of less than 20%. A supplementary design drive is to derive the fuel ion temperature, Ti, with a time resolution of 100 ms and an uncertainty of less than 10%, which is a realistic requirement for Ti > 5 keV. To fulfil the requirements, a conceptual design of the HRNS system was studied based on an array of four different neutron spectrometer concepts:
- Thin-foil Recoil Proton (TPR)
- Pixelated CVD Diamond detector
- Back-scattering Time-of-Flight (ToF) spectrometer
- Forward scattering Time-of-Flight (ToF) spectrometer
For each spectrometer concept the energy resolution is in the order of a few percent with a neutron detection efficiency ranging from $10^{-5}$ to $10^{-2}$, which is needed in order to span the operational range required. The main objective for the TPR, Diamond detector and Back-scattering ToF spectrometers are to perform spectroscopy of neutrons emitted form deuterium-tritium plasmas while the Forward scattering ToF main objective is to provide neutron spectroscopy data from pure deuterium plasmas. In 2015, the Uppsala group activity was mostly focussed on the assembly of required input data and implementation of software tools in order to achieve a performance analysis framework for the HRNS system. As input data, neutron energy spectrum impinging on the HRNS system was derived for 8 different ITER plasma scenarios. Instrumental response function, for the four spectrometers, was accomplished with the use of neutron transport calculations.

Moreover, a software package was developed to produce synthetic spectroscopy data with proper Poisson sampling. Also developed and included in the software package was a routine to perform fitting and determine fitting values of the model used for analysis of synthetic data. By repeating the generation of synthetic data many times and perform fitting, the mean and standard deviation can be calculated for the derived fitting values within the software package. From which, information on fuel ion ratio and ion temperatures can be obtained and used in the performance analysis. In the end of 2015, all required input data had been assembled, the implementation of the software framework was tested and completed, preliminary result on nt/nd and Ti with uncertainties was obtained. Within the grant, progress meetings have been held regularly and face-to-face workshops/meetings have been organised when needed. During 2015, 12 remote progress meetings have been conducted and 4 face-to-face workshops/meetings, three at IFJPAN in Krakow and one at the ITER facility.
6 ITPA and IEA activities

6.1 Overview of ITPA/IEA activities

The KTH PWI group (M. Rubel, P. Petersson, D. Ivanova, A. Garcia-Carrasco) contributed to work of ITPA groups on “Divertor and SOL Physics (D-SOL)” and “Diagnostics”. In the D-SOL the contribution was related to fuel retention in JET. In diagnostics KTH contribution was 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 2015.

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 2015 M.Rubel presented the report at the meeting held in ISFNT-12, Jeju Island, Republic of Korea.

The KTH Complex Plasmas group (S. Ratynskaia, P. Tolias, L. Vignitchouk) participated in the work of the ITPA "Divertor and SOL physics". At the ITPA DivSOL meeting in Princeton, USA, the material of the group on heat balance and remobilization of tungsten dust was presented.
7 Training and public information

7.1 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. There is typically 20-25 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.

The Department of Plasma Physics and Fusion Research at KTH and Department of Applied Physics, Chalmers are now members of FuseNet, an organization for increasing, enhancing and broadening fusion science and technology training in Europe. In particular, the PhD students are taking part in the FuseNet PhD Events, the aims of which are to enable students to disseminate their research, develop a network of contacts and learn from each other's experiences. Participation in two events allows the students to apply for a European Fusion Doctorate Certificate.

In order to guarantee a high quality PhD training, as well as to satisfy the requirements of the Swedish Higher Education Ordinance, the Chalmers and KTH course packages nowadays include compulsory generals skills courses in topics like theory and methodology of science, pedagogics, scientific writing and ethical issues. These comprise 10-15 ECTS credits in total.

KTH participates in the BeFirst program, which is planned to continue over the four-year period 2012-2015. The aim of the BeFirst training program is the education and training of early stage researchers in the field of "Plasma-Facing Components". It will be achieved by performing cooperative research and training programs in the area "Beryllium for the first wall". The program is practically oriented and will be realized through performing a set of practical exercises in laboratories experienced in beryllium handling and analysis, but will also include courses providing a theoretical background. The program is jointly undertaken by the Euratom Associations KIT, CEA, ENEA, FZJ, AEUL, and finally VR, represented by Department of Fusion Plasma Physics at KTH.

KTH staff regularly gives tutorials in the field of PWI at summer or topical schools in fusion plasma physics and at introductory courses before major conferences on fusion technology. In 2015 lectures were given at: (a) the 12th Carolus Magnus Summer School; (b) the 1st PhDia School on Plasma Diagnostics and (c) the course preceding the 15th International Conference on Plasma-Facing Materials and Components.

**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 10-15 MSc thesis students.

Swedish PhD and Master courses, related to fusion, are now coordinated nationally (http://www.fysikersamfundet.se/sektionen-for-plasmafysik-doktorandkurser) so that the students can obtain the best training possible.
An aspiration is to make fusion energy more visible in master programme courses. To this end, a set of video lectures on were recorded at KTH; see http://www.kth.se/ees/omskolan/organisation/avdelningar/fpp/education/education-related-links-1.52164. The lectures were developed to contribute to e-learning in a course on Sustainable Power Generation, but are useful also in other courses.

7.2 Public information

Within EUROfusion a public information officer represents each member country in the so-called FuseCOM network. The Swedish Public Information (PI) representative is presently Henric Bergsäker at the Department of Fusion Plasma Physics, KTH in Stockholm. Also Jan Scheffel and Thomas Johnson, at the same department, are engaged in public relations and outreach within fusion.

The Swedish public information activities, at all involved universities, 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 essentially unchanged since the early 1990’s, and the situation is quite difficult with regards to retaining competence and enrolling younger scientists. The Swedish Energy Authority has a mission to consider fusion but has so far in practice only marginally supported fusion research. Funding from external sources derives essentially from the Swedish Research Council (VR).

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. Thus we have substantial contact with these groups, including supervision of a great number of project works on fusion, being carried out by upper secondary students in the Stockholm region and elsewhere.

A problem with actively pursued PI is that the costs and timetable for the construction of ITER are constantly increasing. In spite of the scientific and technological advancements, the informed general public is thus presently relatively reluctant to be inspired by fusion’s energy potential. The failure of inertial fusion through its flagship National Ignition Facility (NIF) in California does not improve the situation. The younger public, however, is often unaware of these circumstances and is quite curious about the general scientific, technological as well as societal prospects of fusion.

It is thus quite gratifying that we, in 2015, finished work on a popular brochure on fusion, titled “Fusion Energy Research In Sweden”. The 32 page brochure provides a brief introduction to fusion and describes the Swedish fusion organization in general, including research areas and personnel. All research areas are briefly, and colourfully described, with pictures and highlights of the activities. It is now handed out whenever we meet audiences during public presentations of fusion. The scientific level is such that an audience with elementary physics knowledge should be able to read and understand with pleasure. The plan is to revise and print new editions in three-year periods.

Lobbying ambitions

- 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 takes place continually. Examples are:

- Presentations on fusion for Young Researchers and various other organizations
- Interview for Swedish national television.
- Supervision of upper secondary student fusion projects.

Contacts with students, taking university courses
- Several students at KTH, studying to become upper secondary school teachers, take a course on fusion and energy.
- A number of fusion related MSc courses are given at KTH: “Energy and Fusion Research”, “Experimental Fusion Plasma Physics”, Electromagnetic Waves in Dispersive Media”, “Atomic Physics for Fusion”, Introduction to Fusion Technology” and “Project in Fusion Plasma Physics”.
- A popular KTH course on Sustainable Power Generation includes lectures on fusion by J. Scheffel.
- MSc course on Fusion Energy (7.5 ECTS) and lectures on fusion energy in the course “Sustainable power production and transportation” are given at Chalmers.

Publications

FuseNet
- J. Scheffel participated in the FuseNet general meeting in February 2015.
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