Fusion Plasma Physics
Annual Report 2012

Fusion Plasma Physics
School of Electrical Engineering
KTH Royal Institute of Technology

Stockholm, October 2013
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1. Introduction

The Department of Fusion Plasma Physics research activities are part of the European effort to demonstrate electricity production by fusion in the 2040-50 decade and commercial fusion power in this century. The programme is now being focussed on the construction of the ITER device in France and the preparation for the experiments on ITER. The European fusion programme includes development of operation scenarios for ITER, research training for young fusion scientists, and R&D for future fusion reactors.

The research activities at the Department of Fusion Plasma Physics are focussed on a few key areas where the Department has expertise, such as MHD stability and control, plasma-wall interactions, and wave-particle interactions for heating and current drive. The research during 2012 has continued to be very productive, with 54 papers published in international journals and conference proceedings. This Annual Report summarizes the main research results.

Research training and undergraduate education are both important parts of the Department activities. The Department of Fusion Plasma Physics are responsible for basic level courses at KTH and advanced level courses in the Electrophysics Master Programme. The research education is part of the track on Plasma Physics, one of five research tracks at the Doctoral Program of the School of Electrical Engineering. The Department played a key role in developing the new Doctoral Program, in particular the development of the compulsory general skills courses.

From 2012, Fusion Plasma Physics participates in the European BeFirst training program, which is planned to continue over the four-year period 2012-2015. The aim of the BeFirst program is the education and training or 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 DEMO first wall". The program is practically oriented, but will also include courses providing a theoretical background.

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Department Head
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2. Research projects

2.1. MHD stability and control

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The general goal of the research program at KTH on MHD stability and plasma control is the development of methods applicable to both tokamak and reversed field pinch devices. Finding optimized methods for active suppression of resistive wall modes remains the primary target. The EXTRAP T2R reversed field pinch has been utilized for the development and testing of various algorithms. The process control system strategy has been adapted for RWM mode control; system identification followed by controller design based on the identification results. A specific application for the work is the active RWM stabilization at the ASDEX Upgrade tokamak.
The main parameters of the device are listed in Table 2.2.1-1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Notation</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major radius</td>
<td>R</td>
<td>1.24</td>
<td>m</td>
</tr>
<tr>
<td>Minor radius</td>
<td>a</td>
<td>0.183</td>
<td>m</td>
</tr>
<tr>
<td>Wall diffusion time</td>
<td>( \tau_v )</td>
<td>6.3</td>
<td>ms</td>
</tr>
<tr>
<td>Plasma pulse length</td>
<td>( \tau_d )</td>
<td>&lt;100</td>
<td>ms</td>
</tr>
<tr>
<td>Plasma current</td>
<td>( I_p )</td>
<td>&lt;150</td>
<td>kA</td>
</tr>
<tr>
<td>Plasma electron temperature (typical)</td>
<td>( T_e )</td>
<td>300</td>
<td>eV</td>
</tr>
<tr>
<td>Plasma electron density (typical)</td>
<td>( n_e )</td>
<td>1x10^{19}</td>
<td>m^{-3}</td>
</tr>
</tbody>
</table>

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

The main features of system are:

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

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

Specifically, the usage of SIMs turns out to be efficient for multivariate signals of the present sizes and lends itself to (i) computational statistics to determine accuracy and (ii) cross-validation methods for model order determination. When applying the SIM, the resistive wall mode response is approximated as a linear time-invariant multi-input multi-output (MIMO) system. The starting point is a "black box" state space model with $n$ internal states and unknown system matrices. Initially, also the order $n$ of the state space system, i.e. the number of unknown states is undetermined.

Two sets of experimental data from T2R were analyzed in this work: (i) a vacuum-obtained, and (ii) a plasma-obtained set. First the model order $n$ is chosen in order to have optimum prediction accuracy. Too high model order results in over fitting to the specific dataset used for identification, too low model order may lead to a significant bias error. A cross-validation technique is utilized to determine the optimum model order based on the acquired data set. It is found that a good choice would be in the range $350 < n < 600$, and $n = 500$ was then used.

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

The result of system identification is shown in Figure 2.2.1-4. The eigenvalue stability criterion is $|\rho| < 1$ as implied by the conversion between discrete- and continuous-time $\gamma$ growth rates: $\gamma = \tau_s^{-1} \ln |\rho|$ where $\tau_s$ is the sampling interval. The observed branching in Figure 2.2.1-4a of the vacuum system eigenvalues can be attributed to horizontal gaps in the resistive shell (giving different penetration times for vertical and horizontal magnetic field components). Qualitatively good agreement is observed between plasma experiment (Figure 2.2.1.-4b, c) and theory.
Figure 2.2.1-4. T2R wavenumber stability spectra for vacuum and plasma.

(a) T2R vacuum diffusion response. Spectrum of $\tilde{G}_0$.

(b) T2R plasma response. Spectrum of $\tilde{G}_1$.

(c) T2R plasma response. Spectrum of $\tilde{I}$. 

Figure 2.2.1-4. T2R wavenumber stability spectra for vacuum and plasma.
2.1.2. Attempts at few coils and low-coverage RWM stabilization

The reversed-field pinch features multiple current driven RWM instabilities at any plasma pressure. The EXTRAP T2R device incorporates for stabilization of the unstable RWM spectrum an array of 64 independent active control coils that fully covers the toroidal wall.

The unstable part of the RWM spectrum consists of $m=1$ modes with varying toroidal mode numbers (in total about 15 unstable modes). An attempt to stabilize the full spectrum of these modes using both i) incomplete coverage and ii) few coils has been carried out on T2R. The T2R study attempts to make effective use of randomized coil subsets for the full multimode RFP instability problem.

Two empirically derived centralized model-based control algorithms are compared with a baseline decentralized intelligent shell type feedback. One interesting finding of this study is that the model-based controllers appear to outperform the decentralized intelligent shell method. However, experimental stabilization could not be achieved for the coil array subset sizes considered in this first study, in spite of the fact that numerical simulations of the models were predicting stabilization. The number of output channels (active coils) of the controllers is reduced using a random sampling methodology. Several subsets were tested in each case. Neighbouring coils were also bundled together to form larger coils. The subsets are characterized by two numbers; Degrees-of-freedom: $\text{DOF} \ (1<\text{DOF}<64)$ (Number of independent coils), Areal fraction covered by coils: $c \ (0<c<1)$. Since coils were bundled together, the DOF may be smaller than the actual number of physical coils used. The baseline controller used as a reference is the intelligent shell controller, a model-free, decentralized PID array with $\text{DOF}=1$-$64$, $0<c<1$. Recent system identification results have been exploited for the design of the model-based controllers. The first is a multi-variable controller (MVC) specially designed for each coil selection. Linear-quadratic-Gaussian control (LQG) design followed by aggressive model reduction was used to obtain a controller which could be deployed in the real-time control computer. The implemented controller has 64 inputs, 16 outputs, 8 states, and uses pairs of bundled coils ($\text{DOF}=16$, $c=0.5$). The second model based controller is a static-output feedback controller (SOF), designed in a similar way as the MVC, but it requires less real-time computation allowing deployment of a controller with 64 inputs, 24 outputs, 0 states, and uses pairs of bundled coils ($\text{DOF}=24$, $c=0.75$). Note that the requirements for real-time computations severely limited the complexity (number of states) of the model-based controllers.

2.1.3. ASDEX-Upgrade enhancement project

The on-going ASDEX Upgrade enhancement project for active MHD control is carried out in collaboration between Max-Planck-Institut für Plasmaphysik and includes 24 in-vessel saddle coils with power supplies. KTH involvement is mainly in the design of the RWM controller. At present, 16 coils have been installed at poloidal positions above and below the midplane, and manufacture of power amplifiers is ongoing at Max-Planck-Institut für Plasmaphysik.
2.2. T2R feedback system as a tool for tokamak-relevant physics studies

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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 sideband harmonics. On the contrary, the feedback system installed in EXTRAP T2R has the capability of suppressing the entire RWM and error-field spectrum and simultaneously producing a clean external perturbation. EXTRAP T2R is therefore a useful machine to investigate the magnetic perturbation effect on the plasma dynamics.

During 2012 a series of studies aimed at the understanding of the mechanisms that lead to the flow braking have been conducted. Moreover, the capabilities of the feedback system have been used to develop new techniques relevant to the suppression of error fields.

2.2.1. Flow braking due to resonant and non-resonant perturbations

The EXTRAP T2R feedback system has been used to generate magnetic perturbations with well defined harmonics, in order to study the mechanism that produces the flow braking. Two different mechanisms have been identified, depending on the harmonic of the field applied. In figure 2.2.1 the braking torque produced by the perturbation with a resonant harmonic and with a non-resonant harmonic is shown.

In the case of a resonant perturbation the torque is localized in a well defined position corresponding to the resonance of the harmonics. This result is in agreement with theoretical models that describe the braking has process due to the interaction of the static RMP with a rotating magnetic island.

In case of a non-resonant perturbation, the torque is global and affects a large part of the core region. This is in agreement with what expected by a braking produced by a
neo-classical toroidal viscosity torque. Further comparisons between experimental and theoretical results are ongoing.

### 2.2.2. A technique for the estimation of the wall diffusion time

The knowledge of the wall diffusion time is important to optimize the feedback algorithms necessary to control resistive wall modes (RWMs). Using the EXTRAP T2R, a method for the wall time estimation that employs rotating external perturbations has been developed. Figure 2.2.2 shows compares the wall time diffusion time as estimated with the new method and with an earlier technique. The agreement is reasonable.

![Figure 2.2.2. Wall diffusion time for different harmonics estimated using rotating perturbations (dots) and dithering-injection (colors).](image1)

In order to study the feasibility of the method in a tokamak, different coil configurations have been used. In fact tokamaks are typically characterized by active coils that cover the shell only partially. For these reason the method has been tested using only few coils (see figure 2.2.3 for an example) and/or trying to simulate active coils with a larger toroidal extent. Experimental results obtained with the new coil configurations are in reasonable agreement with those shown in figure 2.2.2, proving that the method might be applicable also in tokamaks.

![Figure 2.2.3. Coils arrangement using a low shell coverage in order to simulate a tokamak-like coil set.](image2)
2.2.3. Error field identification via external magnetic perturbations

Compensation of error fields in tokamaks are of great importance since they can have detrimental effects on plasma performance. Error fields are not known a priori, hence error field identification is mandatory before any attempt of compensation. Present techniques for error field detection may lead to disruption in ITER and is therefore necessary to modify the present techniques and/or develop new methods. Due to finite EFs, and in spite of the applied perturbations rotating uniformly and having constant amplitude, the kink modes were observed to rotate non-uniformly and be modulated in amplitude. This behaviour was used to precisely infer the amplitude and approximately estimate the toroidal phase of the EF. A subsequent scan permitted to optimize the toroidal phase. The technique was tested against deliberately applied as well as intrinsic EFs. Corrections equal and opposite to the estimated error fields were applied. The efficacy of the error compensation was indicated by the increased discharge duration and more uniform mode rotation in response to a uniformly rotating perturbation. The results are in good agreement with theory, and the extension to lower n, to tearing modes and to tokamaks, including ITER, is discussed.

Figure 2.2.4. (a) Minimum amplitude of probing field as a function of the MP strength for an error field amplitude 0.92 mT and MP rotation frequency 50 Hz (b) corresponding phase velocity at the time of minimum amplitude.
2.3. Plasma - wall interactions

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In collaboration with
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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:

- European Task Force on Plasma – Wall Interactions (EU-TF-PWI),
- EFDA-JET Work Programme: Task Forces and JET Enhancements (Phase 1 and Phase 2) including the ITER-Like Wall (ILW) Project, i.e. full metal wall at JET,
- EFDA-JET Fusion Technology Programme,
- ITPA, IAEA and IEA activities.

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

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

2.3.1. Tracer techniques for material migration study: Nitrogen-15

Plasma edge cooling by impurity is needed especially in the operation with high-Z metal plasma-facing components. Nitrogen seeding is used for that purpose. Some of the injected gas is retained in PFC. Quantitative determination of the deposition can only be achieved by ex-situ analysis of wall components. This is complicated by the fact that the adsorption of air nitrogen may have an impact on the measurements. For that reason Nitrogen-15 rare isotope (natural abundance 0.37%) was used. The first experiments with N-15 as a material migration marker were done in TEXTOR using a roof-shaped test limiter, shown in Figure 2.3.1-1. The main image shows the exposed probe, whereas the fresh unexposed W and C stripes are in the insert in the upper left corner. Limiter position in the tokamak is indicated by arrows and the analysed spots...
on both materials are marked with the numbered circles. It was composed of a graphite holder and four stripes: two made of tungsten and two made of graphite. The assembly was inserted into the machine from the top and placed in the scrape-off layer (SOL) plasma, and exposed to 18 discharges (112 s) in total $3.38 \times 10^{21}$ N-15 atoms were injected. The exposures were followed by IBA studies performed at the 5MV Tandem Accelerator in Uppsala University by means of time-of-flight heavy ion elastic recoil detection (ToF-HIERDA) with 26 MeV $^{127}$I$^{7+}$ ions.

In Figure 2.3.1-1 one perceives that after exposure most of the originally shiny W surface is coated with a blackish deposit containing mainly carbon eroded both locally from the adjacent plate and from all main toroidal and poloidal limiters of TEXTOR which are made of graphite. Only a small area on the top of the limiter remains brighter than the rest. These two distinct areas, the net erosion zone on top and net deposition below, are associated with differences in particle fluxes (and related heat) reaching the plates during the exposure. ToF-HIERDA spectra shown in Figure 2.3.1-2 reveal the presence of two nitrogen isotopes, thus proving that a certain fraction of the gas injected for edge cooling remains in the vessel either as co-deposited atoms or compounds (such as C-N, W-N) formed on PFC under plasma impact. The quantitative data for all four analysed points are collected in Table 2.3.1-1.

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

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

<table>
<thead>
<tr>
<th>Target</th>
<th>Isotope</th>
<th>Point 1</th>
<th>Point 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>D</td>
<td>0.5</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>$^{10}$B</td>
<td>2.2</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>$^{14}$N</td>
<td>&lt; 0.3</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>$^{15}$N</td>
<td>&lt; 0.3</td>
<td>7.4</td>
</tr>
<tr>
<td></td>
<td>$^{16}$O</td>
<td>0.7</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>$^{19}$F</td>
<td>&lt; 0.1</td>
<td>1</td>
</tr>
<tr>
<td>W</td>
<td>D</td>
<td>0.7</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>$^{4}$He</td>
<td>8</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>$^{10}$B</td>
<td>0.5</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>$^{12}$C</td>
<td>600</td>
<td>180</td>
</tr>
<tr>
<td></td>
<td>$^{14}$N</td>
<td>0.2</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>$^{15}$N</td>
<td>0.4</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>$^{16}$O</td>
<td>30</td>
<td>22</td>
</tr>
</tbody>
</table>
In summary, the measurements have allowed for a firm statement on the in-vessel retention of nitrogen by co-deposition or by the compound formation with the PFC material. This causes the “memory” effect of nitrogen in plasma. Understanding of the process may help developing tokamak operation scenarios and defining limits regarding nitrogen injection. This first and successful experiment with nitrogen-15 opens new possibilities in material migration studies in controlled fusion devices. It should also be noted that HIERD analysis lead to detection of helium in tungsten. This is the first measurement of that kind on metals exposed to tokamak plasma.

2.3.2. First mirror test at JET: Assessment of mirror cleaning techniques

Operation of optical diagnostic systems in ITER will rely on the performance of metallic first mirrors. As all plasma-facing components (PFCs), the first mirrors are a subject to degradation due to UV and γ radiation, neutron fluxes and impact of neutrals (e.g. charge exchange, hydrocarbons) which can lead to erosion and deposition processes. The ongoing research at the major fusion experiments, i.e. TEXTOR, DIII-D, Tore Supra, JET is to provide knowledge on the modification of mirrors and, to elaborate solutions for the prolongation of their lifetime.

The First Mirror Test (FMT) has been carried out at JET on the request of the ITER Design Team. The experiment in JET offers ITER-relevant combination of plasma configuration and placement of mirrors in critical locations. The overall aim of the project is to examine optical performance of tested specimens and to elucidate the cause of reflectivity losses. Two phases of the project in JET with carbon walls were completed: Phase I: 2004-2007, Phase II: 2008-2009. During this time a total of 61 metallic mirrors (stainless steel, molybdenum) were exposed at various locations in the JET divertor and on the outer wall providing a large database of exposure conditions. Optical properties of all mirrors exposed in the divertor region were degraded by heavy deposition of the first wall materials such as carbon and beryllium while erosion by plasma impurity species (C, D, Be, Mo, Ni, etc) influenced mirrors on the main chamber wall. Implementation of the deposition mitigation techniques may prolong the mirror lifetime but none of the methods discussed up to date is able to completely eliminate the growth of deposit. Even thin deposited layers (10 nm) can reduce reflectivity of a mirror due to interference effects, while the thickness of
deposits after exposure in JET often exceeds the micrometer range. Such effects may be expected in ITER, hence efforts are directed towards development and assessment of procedures for reflectivity recovery.

Some techniques for removal co-deposits are based on irradiation of PFC with a high-energy scanning laser beam. Photonic methods provide a possibility of remote operation for in-situ applications and demonstrate reliable removal of carbon layers under laboratory conditions. However, when tested on the Be-containing deposits from JET, the laser cleaning did not give satisfactory results. Despite multiple laser scans with the predefined laser parameters, it was not possible to remove all deposits while the damage to the mirror surface occurred: micro-cracking and local melting. The optimization of laser parameters would be challenging as each type of deposit has a different composition, thickness, density and adherence. This in turn, would require a specific set of parameters for each kind of co-deposit to ensure efficient removal. Hence the alternative cleaning techniques should be considered. The goals are: (i) to clarify whether mechanical cleaning would lead to efficient removal of deposits and recovery of high reflectivity; (ii) to gather more information on properties of mixed layers.

Cleaning and surface study techniques. Two different cleaning methods were tested on the mirrors exposed in JET: a) ultrasound cleaning (US) in organic solvent; b) a broad range of polishing conditions from manual buffing to machine polishing. In total 11 mirrors were treated by ultrasound and 13 mirrors were cleaned by polishing of which 7 mirrors underwent both cleaning procedures. The selection of mirror samples was representative for all the mirror locations: the main chamber wall, the inner and outer divertor legs, the divertor base.

After each significant step in the cleaning procedure a visual inspection and total reflectivity measurements in the range 350-1700 nm were carried out using a GetSpec spectrophotometer suitable for work with beryllium and tritium contaminated samples. After cleaning specular and diffuse reflectivity of all mirrors was recorded in a wider range of wavelengths (250-2500 nm) by Varian Cary 5 system. The mirrors have also been examined prior to and after the cleaning with microscopy, X-ray photoelectron spectroscopy (XPS), nuclear reaction analysis (NRA), ToF-HIERDA and secondary ion mass spectrometry (SIMS).

Ultra-sound cleaning. Many years of experience in storage and transportation the exposed mirrors with flaking carbon-based deposits demonstrated, that the exposure to air further enhances the brittleness of the layers. On several occasions the deposits partly peeled-off in the torus, during the dismantling of mirrors or during their transportation. These observations suggested that even moderate cleaning of such mirrors in ultrasonic bath could be considered as an efficient cleaning method.

The results of the ultrasound cleaning varied in a broad range of effects from the minimal impact on reflectivity to the complete removal of deposit. Figure 2.3.2-1(a) shows the case when the US cleaning did not lead to any noticeable effect, while the example in Figure 2.3.2-1(b) demonstrates a mirror with the fully restored reflectivity. For most mirrors the performed treatment resulted in partial recovery of reflectivity due to enhanced detachment of deposits. Typically 30%-50% of the original reflectivity was recovered in the visible range on spectra and 50%-90% for the infrared region. This result was expected since the longer wavelengths are less sensitive to the surface imperfections and a similar dependence in recovery efficiency was observed during the earlier cleaning attempts by laser pulses.
Polishing. Figure 2.3.2-2 demonstrates a successful cleaning process of a mirror exposed on the outer wall of JET. Restoring the initial level of reflectivity by polishing with 1µm diamond paste took about 30 minutes and gradual improvement in reflectivity was recorded after each 2 minutes of polishing (only a few reflectivity curves are included in the plot in Figure 2). Time required to clean a mirror varies from 2 to 40 minutes for different samples and depends on the exposure conditions such as location of a mirror in JET vessel or depth into the cassette channel and is ranging. Prolonged polishing (over half an hour) was required to clean the mirrors which were located on the outer wall during JET operation and deep in the cassette channel. Contrariwise, the thickest deposits from the mirrors in the divertor at the channel mouth happened to be poorly attached and cleaning of such mirrors required relatively little effort. Irrespective of the exposure location of mirrors, manual buffing and mechanical polishing with a clean soft cloth without diamond paste proved to have minimal impact on reflectivity of mirrors even in the case of flaking and loose deposits. The best observed effect was not more than 10% increase in reflectivity in the infrared range.

The incremental approach to the cleaning process allowed observing qualitatively different layers of deposit on some mirrors. Images in Figure 2.3.2-3 demonstrate the same mirror before the cleaning (a), after 6 minutes of polishing with 3µm paste (b) and after 16 minutes of polishing (c). The corresponding change in the reflectivity curve is shown in Fig. (d). This mirror was located in the inner divertor of JET and remained in the torus during two consecutive campaigns, i.e. it was exposed to ambient atmosphere during the shut-down period between the campaigns. As a result,
the lower older deposit was exposed to air with subsequent oxidation. The second layer of deposit was built up during the repeated exposure to plasma.

Figure 2.3.2-3: Results of mechanical polishing. Mirror appearance before cleaning (a), after 6 minutes of polishing (b) and after 16 minutes of polishing (c); corresponding reflectivity (d).

While cleaning efficiency of polishing may reach 100%, the usage of the diamond paste with large grain size (3 µm) increases the probability of damaging the mirror surface via scratching. However for most of the studied mirrors this type of damage did not affect the specular reflectivity. HIERDA studies proved that polishing completely removed the deposit from most of the surfaces. As revealed by XPS, molybdenum in the surface layer is oxidized.

In summary, satisfactory recovery of reflectivity may be achieved but cleaning conditions must be individually set for each mirror. Ultrasound alone is not sufficient for surfaces coated by deposited carbon-metal mixed material layer. In the case of mirrors modified by co-implantation of impurity species (on main chamber wall) the only way to recover the initial reflectivity of these mirrors is to remove the modified layer (50-200 nm) by polishing. The results indicate that the replacement - or repeated coating - of first mirrors may be needed in the case of their degradation in a reactor-class machine.

2.3.3. Ion beam microanalysis of divertor surfaces in JET

The erosion and migration of first wall material gives rise to several critical plasma-surface interactions issues for ITER and for other future big and high duty cycle fusion devices. The balance between erosion and deposition at different surfaces in the device determines the net erosion rate and consequently the life time of the plasma facing component. Deposition of thick layers at some surfaces is linked with co-deposition of fuel and consequently to the tritium inventory in a reactor. The build-up of thick deposited layers also entails dust production due to subsequent breaking and flaking of the layers. Materials migration and mixing may also modify the erosion rate and other surface properties. To study these issues at JET, microscopy, ion beam analysis techniques and SIMS have been frequently used for post mortem analysis of plasma facing surfaces. In JET with carbon wall, layers with thicknesses up to about one mm are produced in the divertor over extended periods of plasma operation.
Microbeam analysis reveals that deuterium trapping at the divertor surfaces is nonuniform on a microscopic scale. Figure 2.3.3-2 shows an example of locally enhanced D trapping, which can be associated with structural features. Figure 2.3.3-3 shows Be segregated at the layer surface, while D is found mainly within a pit in the substrate. The Be distribution can be explained by negligible physical sputtering of Be due to the low electron temperature, whereas carbon is eroded chemically. The higher D-concentration within the pit in the substrate is probably due to reduced ion flux in such geometrically protected pockets. Locally enhanced D-retention has also been found in dust particles that have been buried within the deposited layers.

2.3.4. A \(^{10}\)Be marker experiment on beryllium migration in JET

An isotopic marker experiment has been designed to study the migration of beryllium from the main chamber to the divertor in JET with ITER-like wall. One of the beryllium tiles at the inner wall in JET has been enriched with \(^{10}\)Be through irradiation with thermal neutrons in a fission reactor. The tile was installed in JET in 2011 and exposed to the plasma throughout the first period of operations with ITER-like wall. Figure 2.3.4-1 shows a numerical simulation predicting the 3D large scale
redistribution of the marker using the ASCOT code, with a particular set of assumptions. Using the extremely sensitive accelerator mass spectrometry (AMS) method, the $^{10}$Be content in re-deposited beryllium layers all over the JET can be investigated after the first JET shut down in summer 2012, down to five orders of magnitude dilution with respect to the primary marker tile. Several numerical models exist for the materials migration and mixing problem in JET with ITER-like wall and the marker experiment is designed for comparison with the numerical models.

![Image](image.png)

Figure 2.3.4-1. Position of the $^{10}$Be enriched inner wall guard limiter tile in JET. ASCOT prediction of $^{10}$Be deposition after plasma exposure in limiter configuration, followed by diverted plasma. The source is above the midplane in octant 5.

During the shut down from July 2012 samples could be taken from the surfaces for $^{10}$Be analysis by accelerator mass spectrometry (AMS). Due to the limited availability of Be tiles for analysis, a new, non-destructive sampling method was developed. Samples of about 200 µg beryllium had to be taken at every sampled position. It was found that the sampling could most conveniently be done using SiC abrasive paper. The parameters were optimized and the method, including sample handling and transport could be approved for JET use. In the first version, sampling is made in the Be handling facility at JET, not in the JET vessel, but the sampled tiles can go back into the vessel again and continue to be used after sampling.
Following AMS analysis of at least 60 of the samples from the main chamber, the marker redistribution is to be compared with the ASCOT simulations. Comparison can also be made with 3D ERO simulations of the local erosion and deposition around the primary source tile. Later on, complete tiles from the divertor and from the main chamber will also become available for analysis, and depending on the results the data may also be comparable with WALLDYN simulations, including a more sophisticated treatment of surface processes, but with less elaborate geometry (2D).

2.3.5. Studies of mobile dust with aerogel and Si collectors

The possible accumulation of dust, particularly at hot surfaces, is a critical issue for ITER and other future big devices. The presence of dust in the plasma may also interfere with plasma confinement and other operations aspects. In fall 2012 an improved experiment with injection of tungsten dust in the TEXTOR tokamak was carried out, and dust particles that had travelled a long distance from the point of injection could be collected in the scrape-off layer in a time resolved way. The interpretation of the experimental results is in progress using the MIGRAINE dust dynamics code, which includes both plasma-dust interactions and a detailed treatment of dust particle bouncing at surfaces.
2.4. Theoretical fusion plasma physics

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In collaboration with CEA, CCFE, IST, TEKES, CRPP, ENEA associations

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 ion cyclotron resonance heating, ICRH, and validates them against experiments. The program is well integrated into the European fusion program through participation in: the Integrated Tokamak Modelling Task Force, and the exploitation of the JET facility.

The three main codes developed by the group are PION, FIDO and SELFO. PION was the first self-consistent code for modelling ICRH and NBI heating using a model for the power deposition and solves a simplified Fokker-Planck equation for the distribution function. PION has become the standard code for routine simulation at JET. The Monte Carlo code FIDO calculates the distribution functions of the resonant ion species taking into account effects caused by finite orbit width and RF-induced spatial transport due to absorption of the momentum of the wave. The SELFO code calculates the wave field, using the LION code, and the distribution function, using the FIDO code, self-consistency is obtained by means of iterations. The FIDO code is being upgraded to include interaction with MHD waves allowing self-consistent studies MHD modes during ICRH; at the moment by using simple models of the MHD-modes. A new code, SELFO-light, for routine simulation to be used as an ITM tool and for analysing JET experiments is being developed.

2.4.1. Integrated Tokamak Modelling Task Force

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

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

Heating and Current drive workflow. The workflow for heating and current drive, IMP5HCD has been upgraded to work in 4.10a and developed further during 2012. As a result the workflow now works as a standard module in the ETS workflow.
Figure 2.4.1. Work flow for heating and current drive. The picture illustrates how the workflow is partitions. On the top one finds physics modules separated into three categories Waves/Sources/Fokker-Planck models. Inside the Waves-model the workflow is further separated into IC/EC/LH waves. Finally each wave heating scheme may be represented by different physics models, e.g. the EC-wave model EVE shown above.

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

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

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

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

While the group has not participated in any JET experiments during 2012, the group have still been active in the analysis of JET data.

ICRF scenarios for the non-activated phase of ITER operation. In the autumn of 2010, experiments were performed to evaluate two scenarios for the non-activated phase of ITER operation. The analysis of these experiments were completed and published during 2012. Both scenarios were shown to be candidate scenarios for ITER, but with a rather low heating efficiency, ~40%. Higher heat efficiency is however expected in ITER where the ion temperature is higher.

RF-induced plasma rotation and relation to electron heating. Rotation has since a long time been observed in connection with RF heating with waves with no or little momentum. Some mechanisms causing the rotation have been identified. There seems to be other mechanisms not yet identified to explain the rotation in some of the experiments. Fast ions created by ICRH give rise to torques on the main plasma, which can explain some of the observed rotation. Relative strong counter rotation in the core is observed in experiments in mode conversion regimes and with direct electron heating with little direct ion heating demonstrating that there are other mechanisms producing rotation without involving fast ions or net momentum input from the wave. The effect was similar to those observed during ECRH in other tokamaks.

Scaling of the intrinsic rotation. The work on intrinsic rotation and inter-machine comparisons for the extrapolation to ITER has continued in collaboration with Filomena Nave of IST. It has been shown that the JET data from intrinsic rotation experiments do not fit the previously proposed scaling.

Modelling of fast particle driven MHD. A collaboration between experts on ICRH, NBI and MHD modelling has been undertaken to study in great detail JET pulses with fast particle drive MHD activity. This project to model the generation of fast ions by NBI and ICRF, the radial transport of these fast ions by MHD modes; primarily toroidal Alfven eigenmodes. This modelling was just started in 2012 and has continued during 2013.
Ion heat transport studies and relation to plasma rotation in JET. Previous work on ion heat transport and the formation of transport barrier, in collaboration with Paula Mantica of ENEA et al, has been extended by turbulence modelling with the GENE code and the inclusion of the fast ion pressure from SELFO. This work has continued into 2013.

2.4.4. Modelling of non-linear wave particle interactions
Excitation of Alfvén waves by fast particles can lead to degradation of heating by RF-waves, alpha particles and beams. A common assumption when modelling wave-particle interaction is that the interactions can be described by quasi-linear theory, which can be justified if the different interactions are decorrelated. Often the collision frequency is not sufficient to decorrelate the interactions to use the quasi-linear approximation. A model has been developed to study wave-particle interactions for arbitrary decorrelation. The model is suitable for describing excitation of Alfvén waves in Monte Carlo codes. It has been found that in the non-linear regime with weak decorrelation a strong coherence between the wave and structures in the phase space caused by resonant interactions develops leading to a much stronger interaction and relaxation of the fast ion distribution functions.

2.4.5. MHD control by ICRH
The group has over the last seven years been involved in collaboration with CRPP and CCFE on MHD control by ICRH. This collaboration has primarily concerned control of sawtooth and resistive wall modes by generating asymmetries in the fast ion distribution function that produce a stabilizing or destabilizing effect on the linear kink stability. During 2012 the collaboration has resulted in two publications [6] and.

2.4.6. Advanced Monte Carlo methods
Variance reduction and Multilevel Monte Carlo. The multilevel and the control-variate method are commonly used methods in stochastic analysis, but rarely used for Monte Carlo modelling in fusion research. A project was therefore initiated to review the methods and study their applicability to the modelling of Coulomb collisions in plasmas. As a test case we selected to study fast-ion relaxation from ion-ion and electron-ion collisions against a Maxwellian background. We showed that this process can be modelled by a Cox- Ingersoll-Ross equation, common in finance, which has a known analytical solution of the time evolved distribution function. The performance of the derived model is very good when electron collisions dominate, but breaks down when ion-ion collisions are important. The multilevel Monte Carlo method was tested on the same model and compared with the randomized quasi-Monte Carlo method and the standard Monte Carlo method. We showed that the multilevel Monte Carlo method is up to 21 times faster, measured in wall-clock simulation time, than the standard Monte Carlo method for similar mean error. The method requires fewer particles to be simulated than the randomized quasi-Monte Carlo code.

Monte Carlo schemes for pitch angle scattering. Monte Carlo representations of the pitch angle scattering by Coulomb collisions are implemented in a large number of Monte Carlo codes. Yet, most codes use a simple, but easy to implement numerical schemes. To improve on this scheme, two new schemes for pitch angle scattering by Coulomb collisions has been invented. The schemes are constructed using an operator splitting technique, along with analytical solutions to equations similar to the equation
for pitch angle scattering. The result is a second order scheme that has been shown to outperform the standard scheme already at very long time-steps. The scheme has been implemented in the Monte Carlo code ASCOT.

![Convergence of different Monte Carlo integration schemes](image)

Figure 2.4.3: Convergence of different Monte Carlo integration schemes; the traditional schemes by Euler and Boozer and the new schemes, which are shown to provide a significantly smaller error even at very long time steps.

### 2.4.7. On Monte Carlo solutions of orbit averaged equations

The presence of two classes of drift orbits, passing and trapped, give rise to difficulties in modelling collisions in toroidal plasmas associated with the neoclassical transport. A simple 2D model equation has been developed to study the numerical properties of orbit averaged collision neoclassical equations when solved by Monte Carlo methods, in particular the correlation between spatial transport and pitch angle scattering. The model has a discontinuity in the diffusion coefficient at the trapped passing boundary, which makes the Monte Carlo drift term unbounded and therefore unsuitable for numerical evaluation. Three different alternative models for the drift term have been derived. These do not solve the problem exactly, but preserve the key properties of the exact solution of the original partial differential equation. The model has also been used to test model Monte Carlo operators for driving the density profile to a prescribed shape. This is of important for long term simulations where the thermal particle density is obtained from experimental measurements or from a transport code. The model operator has been extended to 3D by including energy scattering. As a first step the model has been tested in conjunction with an RF-operator to model RF-heating demonstrating the importance of the evolution of the thermal particle density profile for modelling ICRH.
2.5. Computational methods for fusion plasmas

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

2.5.1. Theoretical and numerical modelling of RFP confinement

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

Classical linearized resistive magnetohydrodynamic (MHD) stability theory predicts unstable pressure-driven modes even at low plasma beta values for the RFP because of its unfavourable curvature and strong poloidal magnetic field. These resistive g-modes undermine energy confinement and are detrimental to the RFP reactor potential. In the classical analysis, one aspect is common, which is the usage of the adiabatic energy equation, ignoring the contribution due to thermal conduction effects. However, in more recent analysis, stabilization of pressure-driven modes is demonstrated through inclusion of thermal conductivity. In the present work, we compare the results obtained from both classical and thermal conduction modified boundary layer stability analysis with those from a time-spectral resistive linearized MHD code (GWRM; see below). Ohmic heating and thermal conduction effects are also included in the calculations. We have found that thermal conduction effects stabilize pressure-driven resistive g-modes only for very low values of plasma beta. In addition, analytical and numerical investigation of the equilibrium reveals that, for reactor relevant values of Lundquist numbers $S_0$ and tearing mode stable plasmas, the scaling $\gamma \propto S_0^{-1/5}$ for the growth rate of these modes is weaker than that for the adiabatic case $\gamma \propto S_0^{-1/3}$. Thus the stabilizing effects, due to heat conduction in the energy balance, on resistive pressure driven modes in the RFP are small at reactor relevant conditions.

2.5.2. The Generalized weighted residual method (GWRM)

Temporal and spatial subdomain techniques have been evaluated for a time-spectral method for solution of initial-value problems. The spectral method, called the generalised weighted residual method (GWRM), is a generalisation of weighted residual methods to the time and parameter domains. A semi-analytical Chebyshev
polynomial ansatz is employed, and the problem reduces to determine the coefficients of the ansatz from linear or nonlinear algebraic systems of equations. In order to avoid large memory storage and computational cost, it is preferable to subdivide the temporal and spatial domains into subdomains. Methods and examples to show how this can be achieved are now published.

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

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

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In collaboration with M. Beurskens, CCFE

2.6.1. Pedestal properties and confinement in JET

Operations in JET have been resumed in autumn 2011 after the shutdown necessary to install the ITER-like wall (hereafter called ILW).

In 2012, a detailed study of the pedestal properties in JET with the new ILW has been performed. Most of the work was devoted to the comparison between the ILW and the previous CFC wall.

**Confinement in hybrids and baseline plasmas in JET with the CFC wall.**

The confinement in JET baseline type I ELMH H-mode plasmas is compared to that in so-called hybrid H-modes in a database study of 112 plasmas in JET with the carbon fibre composite (CFC) wall. Based on a detailed confinement study of the global as well as the pedestal and core confinement, there is no evidence that the hybrid and baseline plasmas form separate confinement groups; it emerges that the transition between the two scenarios is of a gradual kind rather than demonstrating a bifurcation in the confinement. The elevated confinement enhancement factor in the hybrid plasmas may possibly be explained by the density dependence in the confinement scaling and the fact that the hybrid plasmas operate at low plasma density compared to the baseline ELMH H-mode plasmas. The core profiles show a strong degree of pressure profile consistency. No beneficial effect of core density peaking on confinement could be identified for the majority of the plasmas presented here as the density peaking is compensated by a temperature de-peaking resulting in no or only a weak variation in the pressure peaking. The core confinement could only be optimized in case the ions and electrons are decoupled, in which case the ion temperature profile peaking can be enhanced, which benefits confinement.

**Confinement comparison between CFC plasma and initial ILW plasma.**

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

A steady state H-mode profile database has been constructed from high quality kinetic diagnostics. It contains plasmas with low ($\delta\sim0.2-0.3$) and high ($\delta\sim0.38-0.42$) triangularity with both the CFC wall and the ILW. For the CFC wall, the database contains both baseline (BL) ELMH H-mode plasmas $q_{95}=2.8-3.6$ as well as Hybrid H-mode plasmas with $q_{95}=3.5-4.2$ and plasma current in the range 1-3MA. For the ILW plasmas, the database contains baseline ELMH H-mode plasmas at $q_{95}=2.8-3.6$, $I_p=1.0-2.5MA$ and hybrids plasma at $q_{95}=3.6-4.3$ with $I_p=1.5MA$. The low
triangularity ILW hybrids have $\delta$ larger than the corresponding CFC plasmas ($\delta \sim 0.3$ for ILW and $\delta \sim 0.22$ for CFC). The applied heating systems are mainly NBI for all plasmas and some ICRH for the baseline plasmas ($P_{\text{ICRH}}/P_{\text{NBI}} < 0\text{-}10\%$). The electron density and temperature parameters (pedestal heights and profiles) are obtained from the High Resolution Thomson Scattering diagnostic.

The results show that high $\delta$ BL plasmas seem to underperform with the ILW compared to CFC wall mainly because of the lower pedestal $T_e$. For low $\delta$ BL plasmas the confinement is similar in ILW and CFC shots, provided a low gas rate. At high input power, ILW Hybrids plasmas have confinement relatively similar to the corresponding CFC plasmas. ILW hybrids with low confinement are related to low pedestal $T_e$ due to low input power and/or high gas fuelling.

**ELM mitigation using magnetic perturbations in JET**

Mitigation of type-I Edge Localized Modes (ELMs) has been observed with the application of an $n = 2$ field in H-mode plasmas on the JET tokamak with the ITER-like wall. In low collisionality H-mode plasmas, the ELM frequency increased by a factor of four (from $\sim 20$ to $\sim 80$ Hz). Clear density pump-out was observed during the application of the $n = 2$ field. The effect of ELM mitigation with the $n = 2$ field was seen to saturate so that the ELM frequency did not increase further above a certain $I_{\text{EFCC}}$ level. The work was focused on the study of the ELM mitigation technique on the density and temperature profiles before and after the ELMs, see figure 2.6.3 for an example. During the ELM mitigation technique (right frame), the pedestal collapse of the electron pressure is significantly reduced.

![Figure 2.6.2. Temperature and density at the pedestal for high triangularity baseline plasmas (left) and low triangularity baseline plasma (right). Full symbols correspond to ILW plasmas, empty symbols to CFC plasmas.](image)

![Figure 2.6.3. Electron pressure before (full symbols) and after the ELM (empty symbols) without (left) and with $n=2$ field.](image)
2.6.2. ELM control by resonant magnetic perturbations

It was demonstrated on many tokamaks that the edge localized modes (ELMs) could be suppressed or mitigated by applying resonant magnetic perturbations (RMP) to the high confinement regime (H-regime) of a tokamak. The resonant coils for RMP are installed or planned on almost all large tokamaks: DIII-D, JET, MAST, ASDEX-Upgrade (AUG), NSTX and ITER. The widely accepted mechanism of ELMs suppression during RMP is the reduction of the pressure gradient in the pedestal region below the stability limit for type I ELMs. The main contribution to the pressure gradient decrease is the pedestal density drop – the so-called "pump-out effect", while the pedestal temperature does not drop and might even increase.

The new model invokes a perturbation of the magnetic field caused by polarised ELM’s plasma resulting in stochastization of plasma edge thereby violating ambipolarity. The counter perpendicular current is carried by ions and provides for the "pump-out" and the torque responsible for the spontaneous toroidal rotation. Hence, the project addresses the suppression of ELM’s by RMP. The issue of spontaneous rotation and ELM’s suppression is the first priority for the success of an implementation on ITER.
3. International collaborations

Active MHD mode control & Non-linear MHD
- UJF-INPG/GIPSA-Lab, Grenoble, France: Automatic control.
- Max-Planck Institute für Plasmaphysik, Garching, Germany: Development of RWM control at ASDEX Upgrade.
- Dept. Applied Physics and Mathematics, Columbia Univ., USA: Error field assessment
- Inst of Plasma Physics, Chinese Academy of Sciences, Hefei, China: NTV numerical code
- Center for Energy Research, Univ. California - San Diego, USA: NIMROD calculations
- MST, Univ. Wisconsin-Madison, USA: RFP physics.

Plasma-wall interaction & Diagnostic development
- EFDA-JET including the ITER-Like Wall Project and SIW diagnostic development (JET EP-2 Programme).
- EU Task Force on Plasma-Wall Interactions.
- Forschungszentrum Jülich, Institute for Energy Research, “Plasma Physics” (IEK-4, TEXTOR Team) and “Material Research”, Germany.
- University of Basel (Switzerland): Surface analysis and First Mirrors.
- TEKES, Finland: studies of plasma-facing components from JET.
- IPPLM, Poland: material mixing on PFC, structure & composition of dust, laser-induced detritiation, high-Z metals as PFC.
- MEdC, Romania: development and production of beryllium coatings for JET
- Josef Stefan Institute, Slovenia: fuel retention studies.
- CEA Cadarache, ToreSupra, France: structure and composition of co-deposits.
- University of California in San Diego (UCSD), PISCES Team: development of Be layers and marker tiles for the ITER-Like Wall Project.
- Kyushu University (Japan): tritium inventory and high-Z metals.
- CCFE, Culham Science Centre, Abingdon, UK, HRTS spatial resolution

Theoretical fusion plasma physics
- LPP-ERM/KMS, CCFE: ICRF scenarios for ITER and experiments at JET
- TEKES, CEA, EC, MEdC, IPP: Development of RFOF library for RF interactions in orbit following Monte Carlo codes.
- ENEA, IPP: Kepler model for integrated modelling of heating and current drive.
- IPP, CEA, IPFN, TEKES, ENEA: Heating and current drive in the ETS.
- MEdC: Development of Monte Carlo methods.
- Uppsala University and TEKES: Neutron modelling in the ITM
- IPFN, CEA, CCFE and TEKES: Experiments and modelling of plasma rotation
• CEA and CRPP: Studies of minority cyclotron heating and current drive for MHD control in tokamaks.
• ENEA and Uppsala University: modelling to predict the neutron energy spectra during ICRH heating in JET.
• ENEA: Modelling ICRH during ITG studies and ITG threshold studies.
• Chalmers University: Effect of ICRH and the stability of ITM and TEM stability.
• IPP, LPP-ERM/KMS: ICRF scenarios for Wendelstein 7X.

**Computational methods**
• University of Wisconsin-Madison, USA: Numerical MHD simulations.

**Confinement physics**
• ITER IO
• LHD Device, National Institute of Fusion Studies, Nagoya, Japan.
• EAST Tokamak, Institute of Plasma Physics, Hefei, China.
• KSTAR Tokamak, Daejoon, Korea.
• CCFE, Culham Science Centre, Abingdon, UK: Confinement in hybrid discharges, ELM energy losses, RMP Type-I ELM mitigation.
• General Atomics, San Diego, USA: Pedestal properties in JET and DIII-D.
• IPP-ASDEX, Munich, Germany. Comparison of the pedestal properties in JET and ASDEX
• COMPASS tokamak. Study of the pedestal pedestal properties.
4. Education and research training

4.1. Basic and advanced level education

Fusion Plasma Physics provides advanced level courses for the KTH Master Programme in Electrophysics. The programme is given in collaboration with the Space and Plasma Physics Lab and the Electromagnetic Engineering Lab at the EE School. The programme focuses on the foundations of electrical engineering such as electromagnetic fields and their interaction with matter. Physical principles, mathematical methods and numerical models make up the core of the programme, providing the tools and skills needed to describe electrotechnical processes and analyze complex systems and problems in the field.


**Basic level courses**

The following basic level courses are provided by Fusion Plasma Physics (Course responsible teacher in parenthesis):


**ED1110 Vector Analysis, 4.5 credits (J. Scheffel).** Learning oriented course in vector calculus. The course is useful for further studies of electromagnetic theory, wave propagation, fluid mechanics, plasma physics, gas dynamics and the theory of relativity.

**EH1010 Project Course in Electrical Engineering, 7.5 credits.** Course in development of new technological systems. First year students are offered hands-on projects, primarily carried out at the lab. The students are also trained in project management and presentation techniques.

**Advanced level courses**

The following advanced level courses are provided by Fusion Plasma Physics (Course responsible teacher in parenthesis):

**ED2200 Energy and Fusion Research, 6 credits (J. Scheffel, P. Brunsell).** An introduction to fusion oriented plasma physics is given. The central areas of fusion research are emphasised. The progress of fusion research and its present state are discussed in the perspective of future power generation.
ED2210 Electromagnetic waves in Dispersive Media, 6 credits (T. Hellsten). The course introduces students to methods of treating electromagnetic waves. The electromagnetic theory is described by Fourier transforms in space and time which is advantageous when treating propagation and emission of waves in dispersive, anisotropic media.

ED2220 Experimental Fusion Plasma Physics, 6 credits (P. Brunsell). The course gives the student an opportunity to become familiar with basic experimental and diagnostic techniques used in magnetic confinement fusion plasma physics research. In addition, the student will gain practical experience of using some diagnostics that are available at EXTRAP T2R and analyzing real measurement data.

ED2230 Chaos and Self-organization, 6 credits (M. Tendler). This course on self-organization, introduces a new way of addressing nature, economy, biology, and many other aspects of man and environment. The phenomena dealt with are typically far from static equilibrium and are strongly influenced by the external environment and organize themselves through chaotic fluctuations.

ED2235 Atomic Physics for Fusion, 6 credits (H. Bergsåker). The purpose of this course is to make the student familiar with those aspects of atomic physics that are most important in fusion research. The focus of the course is on basic understanding of atomic collisions and applications in plasma modelling, plasma diagnostics and plasma surface interactions. Much of the course content is applicable also in other contexts in plasma processing and technology, ion implantation and radiation effects.

ED2240 Introduction to Fusion Technology, 6 credits (M. Rubel). The course is designed for physicists and engineers who want to learn about technology and properties of wall materials applied under extreme conditions in operation of a reactor-class fusion device. The completion of the course should provide background for future work at fusion physics laboratories and fusion-related industry.

ED2245 Project in Fusion Physics, 4.5 credits (P. Brunsell). The student will learn about practical experimental research work by carrying out a small research project. The projects are performed in a real research laboratory environment; the EXTRAP T2R fusion research facility at the Alfvén Laboratory in KTH. The student will engage in a project that also leads to a more in-depth understanding of some common fusion plasma diagnostics methods.

EI2433 Electrotechnical Modelling, 7.5 credits (G. Engdahl). The course describes models for electrical systems and components and how these models can be used to solve design problems and provide understanding of electrophysical phenomena.

ED2250 Publication of Master Thesis in Fusion Plasma Physics, 7.5 credits. Students that have reached particularly high levels in their thesis work, learns in this course how to produce a publishable report, including submission.
**Degree projects completed 2012**

The following degree projects were completed at Fusion Plasma Physics in 2012:

**Master Degree Project (30 credits)**

Hawra Moustaphawi  
*Effects of magnetic boundary on edge plasma profiles studied using probe measurements in EXTRAP T2R*

Christian Gleason-González  
*Development of resistive MHD code in cylindrical geometry and its applications on EXTRAP T2R*

Jose Tarcisio Costa  
*Preparation and characterization of ODS-alloys for fusion reactor applications*

Hugo Alberto Peraza Rodriguez  
*Studies of radial correlation reflectometry to characterize the turbulence of fusion plasmas*

Tautvydas Jeronimas Maceina  
*Trapping of plasma components in neutron irradiated tungsten*

Hugo Arnichand  
*Study of turbulence asymmetries by reflectometry spectra analysis*

**Bachelor Degree Project (15 credits)**

Jesper Törnberg  
*Lunar power from solar panels in orbit around the moon*
4.2. Research training

Development and update of graduate level education is an important priority at the Department of Fusion Plasma Physics. The education is part of the track on Plasma Physics, one of five research tracks at the Doctoral Program of the School of Electrical Engineering, KTH. The Department played a key role in developing the new Doctoral Program, in particular the development of the compulsory general skills courses.

**Graduate level courses**

Courses for a Ph D Degree should cover 75-120 credits and thesis work 120-165 credits, with a sum of 240 credits. For a Licentiate degree, courses should cover 45-60 credits and thesis work 60-75 credits so that the sum becomes 120 credits. Courses at the advanced undergraduate level may be included, insofar as they are not requirements for admission. For licentiate and Ph D degrees at most 15 credits or 30 credits from undergraduate courses may be included, respectively. The main institutional work carried out by the Ph D students is within teaching. Thus all teaching Ph D students take a 3 credits pedagogical course at KTH.

General skills in oral and written communication, as well as in pedagogic, research methodology and research ethics are now emphasized. All students accepted in the new E2DOC Doctoral Programme should now take four new courses, amounting to 10 credit points, in these areas.

The compulsory **general skills courses** are:
- LH200V Basic Communication and Teaching
- AK3014 The Theory and Methodology of Science – Minor Course
- AK3015 The Sustainable Scientist
- DS3103 Introduction to Scientific Writing for Doctoral Students

The following **basic** graduate level courses in the subject area are recommended (course responsible teacher in parentheses):
- ED3220 Motion of Charged Particles, Collision Processes and Basis of Transport Theory, 8 credits (T. Hellsten)
- ED3230 Magnetohydrodynamics 8 credits (J. Scheffel)
- ED3240 Plasma waves I, 8 credits (T. Hellsten)
- ED3260 Fusion Plasma diagnostics, 8 credits (P. Brunsell)
- EF3215 Computer Methods in Electrophysics, 4 credits (A. Kullen)

The following **advanced** courses are recommended:
- ED3305 Magnetohydrodynamics, advanced course, 6 credits (T. Hellsten)
- ED3330 Transport Theory, 8 credits (M. Tendler)
- ED3320 Fusion research, 8 credits (J. Scheffel)

**EFDA Goal Oriented Training programmes**

Fusion Plasma Physics has since 2008 participated in the EFDA Goal Oriented Training programs. The **GOTiT** program (Goal Oriented Training in Theory) that started in autumn 2008 finished in 2011. From 2012, Fusion Plasma Physics 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 or 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 DEMO first wall". The program is practically oriented and will be realized through performing a set of practical exercises, 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.

**Licentiate degree 2012**

No Licentiate degrees were awarded at Fusion Plasma Physics during 2012.

**PhD degree 2012**

**K Erik J Olofsson**  
*Thesis title:* Nonaxisymmetric experimental modal analysis and control of resistive wall MHD in RFPs  
*Supervisor:* Per Brunsell  
*Date of PhD dissertation defence:* June 1, 2012  
*Faculty opponent:* Marco Ariola, Università degli Studi di Napoli Parthenope  
*Abstract:* Feedback control technology appears to enable a robustly stable RFP operation. Experimental control and identification of nonaxisymmetric multimode MHD is pursued in this thesis. It is shown that nonparametric multivariate identification methods can be utilised to estimate MHD spectral characteristics from plant-friendly closed-loop operational input-output data. It is also shown that accurate tracking of the radial magnetic field boundary condition is experimentally possible in the RFP. These results appear generally useful as tools in both control and physics research in magnetic confinement fusion.

**Darya Ivanova**  
*Thesis title:* Plasma-facing components in tokamaks: material modification and fuel retention  
*Supervisor:* Marek Rubel  
*Date of PhD dissertation defence:* December 12, 2012  
*Faculty opponent:* Bernard Pégourié, Nuclear Research Centre Cadarache  
*Abstract:* Fuel inventory and generation of carbon and metal dust in a tokamak are perceived to be serious safety and economy issues for the steady-state operation of a fusion reactor, e.g. ITER. These topics have been explored in this thesis in order to contribute to a better understanding and the development of methods for controlling and curtailing fuel accumulation and dust formation in controlled fusion devices. The work was carried out with material facing fusion plasmas in three tokamaks: TEXTOR in Forschungszentrum Jülich (Germany), Tore Supra in the Nuclear Research Center Cadarache (France) and JET in Culham Centre for Fusion Energy (United Kingdom). Following issues were addressed: (a) properties of material migration products, i.e. co-deposited layers and dust particles; (b) impact of fuel removal methods on dust generation and on modification of plasma-facing components; (c) efficiency of fuel and deposit removal techniques; (d) degradation mechanism of diagnostic components - mirrors - and methods of their regeneration.
5. Personnel

**Professor**
- Torbjörn Hellsten
- Marek Rubel
- Jan Scheffel
- Michael Tendler

**Professor, emeritus**
- James Drake
- Bo Lehnert

**Associate Professor**
- Henric Bergsåker
- Per Brunsell (Department Head)
- Lorenzo Frassinetti

**Assistant Professor**
- Thomas Johnson

**Post-doctor**
- Sheena Menmuir
- Per Petersson

**Administrator**
- Emma Geira

**Engineer**
- Håkan Ferm
- Lars Westerberg

**PhD student**
- Igor Bykov
- Alvaro Garcia Carrasco
- Richard Fridström
- Abdul Hannan
- Josef Höök
- Darya Ivanova
- M. Waqas M. Khan
- Ahmed Mirza
- Qaisar Mukhtar
- Erik Olofsson
- Agung Chris Setiadi
- Stefan Schmuck
- Simon Tholerus
6. Professional activity

Torbjörn Hellsten, Professor

- Board member of the European Topical group on heating and current drive.
- Monitoring of the EU fusion programme for STAC.
- Member of CCFW/CD.
- Member of STAC.
- Member of scientific committee for Varennna - Lausanne International Theory Fusion Theory Workshop.
- Participation in the committee for proposing an EFDA Goal Oriented Training of Programme (GOT) (the proposal were later approved by EU).

Marek Rubel, Professor

- Principal investigator for the Plasma-Wall Interaction Project funded by VR
- Member of the European Joint Undertaking for ITER and the Development of Fusion Energy (F4E), Barcelona, Technical Advisory Panel (TAP).
- Member, European Microbeam Analysis Society.
- Council of the Polish EURATOM Association, Chairman.
- EU Task Force on Plasma-Wall Interactions, Deputy Task Force Leader, contact person for the Swedish Euratom Association.
- International Energy Agency (IEA) - Task Leader in the Implementing Agreement on Fusion Reactor Nuclear Technology.
- Int. Workshop on Plasma Facing Materials and Components, Programme Committee member
- Int. Workshop on Hydrogen in Fusion Reactor Materials, Int. Programme Committee member.

Jan Scheffel, Professor

- Deputy Head of the Swedish Fusion Research Unit, Association EURATOM-VR.
- Public relations officer for the Swedish Fusion Research Unit, (a task within EFDA; European Fusion Development Agreement).
- Vice director of the Dept. of Fusion Plasma Physics, EES, KTH.
- Director of graduate studies at the Dept. of Fusion Plasma Physics, EES, KTH.
- Chairman of undergraduate studies for the M Sc programme in Engineering and Education at KTH.
- Chairman of undergraduate studies for the Open Entrance programme at KTH.
- Member of the Central Appointments Committee (CTFN), KTH.
- Member of the Education Committee (Utbildningsutskottet), KTH.
- Member of the Plasma Physics Section board, Swedish Physical Society.
- Member of the House of Science board (Vetenskapens Hus, www.vetenskapenshus.se).
- Member of the School of Electrical Engineering board, KTH.
**Michael Tendler, Professor**
- Member of the Executive Committee, Royal Swedish Academy of Engineering Sciences, Division of Basic and Interdisciplinary Engineering Sciences.
- Member of Royal Swedish Academy of Engineering Sciences, Division of Basic and Interdisciplinary Engineering Sciences.
- Foreign Member of Russian Academy of Sciences, Division of Energy
- Recipient of the Golden Medal of Merit awarded by the Institute of Applied Astronomy
- Director of the KTH program within the Erasmus Mundus consortium.
- Member of the International Advisory Committee of the International Congress on Plasma Physics
- Member of the Program Committee of Annual Workshop: Role of Electric Fields in Plasma Confinement
- Member of the Program committee of Latin American Workshop on Plasma Physics

**James R. Drake, Professor Emeritus**
- Member of the Royal Swedish Academy of Engineering Sciences.
- Member of the EU Consultative Committee for the Fusion Programme
- Member of the European Fusion Development Agreement Steering Committee.
- Member of the Scientific and Technical Committee for the Consorzio RFX (Padova, Italy).
- Member of the Programme Advisory Committee for the MAST experiment Association UKAEA-EURATOM (Culham, England)
- Member of the Governing Board for the European Joint Undertaking for ITER and the Development of Fusion

**Bo Lehnert, Professor Emeritus**
- Member of Royal Swedish Academy of Sciences, Physics Class.
- Member of Royal Swedish Academy of Engineering Sciences, Division of Basic Science.
- Fellow of the Alpha Institute of Advanced Study, Budapest.
- Member of Electromagnetics Academy, Cambridge, MA, USA.
- Member of Advisory Council at International Biographical Centre, Ely, England.

**Henric Bergsåker, Associate Professor**
- First responsible officer for JET Fusion Technology tasks JW12-FT-3.74 (Microanalysis of deposited layers at JET divertor surfaces) and JW12-FT-3.75 ($^{10}\text{Be}$ marker experiment in JET with ITER-like wall).
- Principal investigator for EFDA tasks WP12-IPH-A03-2-18/BS/VR and WP12-IPH-A03-2-13/BS-01/VR on dust in fusion devices
- Co-investigator for an EXTRAP T2R experimental project founded by VR
Per Brunsell, Associate Professor

- Department Head, Fusion Plasma Physics, EES, KTH.
- Project Leader for the EXTRAP T2R experiment
- Principal-investigator for an EXTRAP T2R experimental project funded by VR.
- Director of undergraduate studies, Dept Fusion Plasma Physics, EES, KTH

Lorenzo Frassinetti, Associate Professor

- Co-investigator for an EXTRAP T2R experimental project founded by VR
- Responsible for data analysis of Thomson Scattering in JET
- Project Leader for the EFDA task agreement "Multi device research to understand the pedestal stability through the study of the edge barrier evolution between ELMs", (WP13-IPH-A08-P2).

Thomas Johnson, Assistant Professor

- Integrated Tokamak Modelling Task Force, Deputy Project Leader for IMP5.
- Responsible for Heating and Current Drive module in the ETS.
- Responsible for ITM infrastructure related to Heating and Current Drive.
7. Income & Expenditures

The accounts for Fusion Plasma Physics for the year 2012 are summarized in the table below:

<table>
<thead>
<tr>
<th>Income &amp; Expenditure 2012</th>
<th>kSEK</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Income</strong></td>
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<tr>
<td>KTH</td>
<td>11 192</td>
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<tr>
<td>Undergraduate education (GRU)</td>
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<tr>
<td>Research and research training (FOFU)</td>
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<tr>
<td>External research grants</td>
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<tr>
<td>Swedish Research Council (VR)</td>
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<td>European Framework Programmes (Euratom)</td>
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<tr>
<td>Other research grants</td>
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<tr>
<td>Other external income</td>
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<td><strong>Total</strong></td>
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<tr>
<td><strong>Expenditure</strong></td>
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<td>Salary</td>
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<td><strong>Total</strong></td>
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<tr>
<td><strong>Result</strong></td>
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</table>
Bibliography


F Volpe, Lorenzo Frassinetti, P Brunsell, James Robert Drake, and E Olofsson. Error Field Assessment from Driven Mode Rotation : Results from Extrap-T2R Reversed-Field-Pinch and Perspectives for ITER. In *54th Meeting of the APS Division of Plasma Physics, November 2012, Providence, USA*, 2012.