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1. Introduction

Fusion energy research carried out at the Fusion Plasma Physics Laboratory is part of the European fusion research programme. The ultimate goal of the European programme is to develop fusion as an energy source for future generations. The focus is currently on the ITER project, an experimental fusion reactor that is under construction in France. The start of ITER operation is planned around the year 2018. ITER will produce about 500 MW of fusion power which is ten times more than the input power required for heating the fusion plasma, demonstrating the feasibility of fusion energy.

The world’s largest fusion research facility currently in operation is the JET device in UK. The experimental facility is collectively used by researchers in the EU countries. The Laboratory is contributing by providing competence with specialists in the areas of radio frequency heating, plasma wall-interaction and diagnostics development. Research is carried out during shorter visits to the JET site during experimental campaigns, or during long-term secondments to JET. Experimental research in support of the ITER and JET programmes are carried out at smaller specialized national fusion facilities located throughout Europe.

The Laboratory hosts the fusion experiment EXTRAP T2R. This device specializes in research on active control methods for fusion plasmas. It is equipped with a state-of-the-art control system installed during 2004-2006. Researchers at the Laboratory are also involved in the construction of an active control system at the ASDEX-Upgrade tokamak device in Germany.

The Laboratory is actively involved in undergraduate education at KTH and participates in the Erasmus Mundus European Master Programme in Nuclear Fusion Science and Engineering Physics (FUSION-EP).

Some highlights of the activity at Fusion Plasma Physics during 2008:

- The first batch of master students was graduated from the two-year European Erasmus Mundus Master Programme in Nuclear Fusion Science and Engineering Physics. In this group, 10 students received M Sc Diploma from KTH.
- Research productivity is maintained at a high level. Researchers at the Laboratory has during this year published 22 journal articles, 2 book chapters and 47 papers in international conference proceedings

This annual report summarizes the main research projects and educational activity at Fusion Plasma Physics during 2008.

Per Brunsell
Head, Fusion Plasma Physics
2. Fusion research projects

2.1. EXTRAP T2R device

Fusion Plasma Physics houses one of the small academia-based experimental devices that are part of the EU fusion program; the EXTRAP T2R reversed field pinch. The research program at EXTRAP T2R is presently focused on MHD instability control and studies of non-linear MHD dynamics. A system for active control of non-axisymmetric MHD modes was developed at EXTRAP T2R during 2004-2006 in collaboration with Consorzio RFX. The Active MHD Mode Control System installed at EXTRAP T2R provides excellent capabilities for research on MHD instability control.

![The EXTRAP T2R device at the Alfvén Laboratory](image)

The EXTRAP T2R device, shown in Fig. 2.1.1, has a close-fitting shell made of thin copper plate for ideal MHD mode stabilization. The shell magnetic flux penetration time is short compared to the plasma life time, which enables study of resistive wall mode stability and control methods.

A number of diagnostics systems are installed on EXTRAP T2R. The main emphasis is on magnetic diagnostics. A total of around 900 magnetic sensors have been installed on the vessel surface inside the conducting shell. These sensors are part of a comprehensive diagnostic system for studies of MHD instabilities and active MHD mode control. It consists of pick-up coils for the measurement of the poloidal, toroidal and radial components of the magnetic field at 4 poloidal and 64 toroidal positions. The data acquisition system limits the number of signals that can be collected in each pulse.

A single-point single-time Thomson scattering system provides the absolute value of the electron temperature in the 50 – 500 eV range and the electron density in the
plasma centre. The neutral particle analysis system, based on the time-of-flight technique, provides the ion central temperature as well as the charge-exchange neutral fluxes. An 8-chord bolometric system, based on gold thin film detectors, is used to measure the radial profile of plasma radiation losses in the UV-SXR wavelength range. A single line-of-sight two-color interferometer (CO₂ and HeNe) is used to measure the line integrated electron density along the plasma diameter. The SXR camera system consists of 12 line-of-sights that look at the plasma from the outboard side towards the inboard side covering 80% of the plasma poloidal cross section. The list of plasma diagnostics installed on EXTRAP T2R include

- Electric and magnetic probe array for turbulence studies.
- Collector probes for plasma wall interaction studies.
- VUV and visible spectroscopy.
- Thomson scattering.
- Interferometer.
- Neutral particle time-of-flight diagnostic.
- Bolometer array.
- SXR camera.

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<th>Table 2.1.1. EXTRAP T2R machine and plasma parameters</th>
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<td>Parameter</td>
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<td>Major radius</td>
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<td>Minor radius</td>
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<td>Wall diffusion time</td>
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<td>Plasma pulse length</td>
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<td>Plasma electron temperature (typical)</td>
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### 2.1.1. Active MHD mode control system

The active MHD mode control system installed on EXTRAP T2R is based on extensive arrays of active coils and sensors distributed over the toroidal surface as shown in Fig. 2.1.2. The main features of the active control system are:

- A two-dimensional array of radial magnetic flux loop sensors at 4 poloidal and 32 toroidal positions, a total of 128 sensors.
- A two-dimensional array of active saddle coils at 4 poloidal and 32 toroidal positions outside the resistive wall, a total of 128 coils.
- A set of power amplifiers units providing at total of 64 independent channels. Saddle coils and sensor flux loops are pair-connected at each toroidal position to form 64 independent m=1 coils and sensors.
- An integrated digital computer based controller unit.

Professional audio amplifiers are used with output power of 800-1200 Watt and bandwidth 1 Hz to 25 kHz. Amplifier output currents are up to 20 A, providing 800 At in the power coils and a maximum radial magnetic field at the coil centre of about 3 mT. The integrated controller unit is contained in a VME bus crate and includes ADCs for analog input of 64 magnetic sensor signals and 64 coil current signals, Board with PPC CPU, DACs for analog output of 64 amplifier control voltages. Controller algorithms are implemented in software.
2.2. MHD stability and control

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The general goal of the present research program on RWM physics and feedback
control is the development of advanced control approaches that are applicable to both
tokamak and RFP. There is also a specific aim to develop a controller design for the
planned experiments on active RWM stabilization at ASDEX Upgrade, which is
carried out in collaboration with Max-Planck-Institute für Plasmaphysik and
Consorzio RFX.

The basic philosophy is to develop RWM stabilization from the viewpoint of process
control, thereby gaining access to a number of tools that have been developed in this
field over many years. The engineering approach assumed is following the process
control methodology: system identification, selection of feedback interconnections,
and subsequently controller design and tuning. The scope of the research is wide:
modeling, mode identification, input design, real-world implementation and
conduction of the physical experiment; reflecting the possibilities for new ideas and
progression in control-oriented fusion research.

Figure 2.1.2. Two-dimensional arrays of sensor flux loops and active saddle coils installed at
EXTRAP T2R.
2.2.1. Closed loop RWM identification experiments
A method for efficiently measuring the plasma response to external fields is desired. This method runs parallel with RWM stabilization and dedicated open-loop plasma response shots are not required. The procedure is known in automatic control as closed-loop system identification. A structured and parametric RFP model for RWMs is assessed with three main purposes: 1) experimental MHD stability research, 2) prospecting identification for control and reconfiguration of the stabilizing circuit, and 3) development of generally useful identification methods and perturbation designs. The first step is to perform experiments to identify the external plasma response by pseudo-randomly perturbing it, while simultaneously stabilizing the plasma using established intelligent shell operation. In a second phase, the identification procedure is further developed by using the physics-based parametric cylindrical MHD model of the RWM instability in combination with the convex programming experiment design method. Success in this study has two significant spin-offs: 1) tailored control system reconfiguration/reimplementation, 2) testing of electromagnetic shell-plasma models. Large part of the work is directly applicable also to tokamak.

![Figure 2.2.1. Dithering signal applied to active coils for closed-loop RWM identification experiments.](image)

2.2.2. Model-based controller design for output tracking
A major step in RWM stability research is the development of model based control systems, both design evaluations and experimental deployment. Already, this has been partially achieved for the RFP configuration by the Clean-Mode-Control concept, conceived and operated at RFX, which handles spatial aliasing effect introduced by the sensor and actuator arrays. An extension of this idea has been studied, based on a dynamical model of the external plasma response. The aim is the development of a control system design for output tracking, and implementation and testing the system at EXTRAP T2R. In this context, output tracking is considered as a generalization of the original intelligent shell concept, which enables the control system not only to suppress modes, but also to sustain MHD modes in closed-loop operation. In principle, by active feedback, the plasma can be forced to user-specified helicities of prescribed amplitudes and phases. The controller design will be a versatile tool for experimental plasma dynamics and innovative RWM stability research. The model is developed using a state-space representation. An explicit multiple-input-multiple-
output (MIMO) model for the vacuum field diffusion is used. Together with knowledge of the actuator dynamics it provides the essential information required for nominal tuning of the output-tracking control system. The model is assembled from multiple-input-single-output (MISO) identification sub-problems, for which also is needed the single-input-single-output (SISO) identification results of the actuator dynamics. The actuator dynamics SISO model contains the active coil, power amplifier and control system delay.

2.2.3. Controller design with time-delay compensation

The aim of this project is to introduce and analyze a new model for RWM stabilization that takes into account sensors/actuators aliasing, actuator dynamics, and control time-delays. The model is then utilized to develop a model-based controller design that includes time-delay compensation. The approach, which takes into account the time-delays due to the control implementation, leads to a multi-variable time-delay model of the system. The importance of the delay effects can readily be investigated by performing a stability analysis of the resulting closed-loop delay differential equation (DDE). Based on the model, a structurally constrained optimal controller is then designed. The controller parameters can be determined using the method of direct eigenvalue optimization of the DDE.

2.2.4. Data driven controller tuning

The objective is to improve a baseline mode controller, prepared in some way related to identification data, and physical modeling. Having set up this nominal controller, it might be possible to optimize and more fully adapt it to experimental conditions. The tuning method is nonmodel-based, primarily concerned with structure, iteratively
modifying the arguments of a cost function so that the output of the cost function reaches a local minimum or local maximum. Iterative feedback tuning and extremum-seeking are related methods that will be assessed for applicability to the T2R plant.

2.2.5. Development of RWM control at ASDEX Upgrade

ASDEX Upgrade enhancement project for active MHD control is collaboration between IPP, Consorzio RFX and KTH. A set of 3x8 in-vessel saddle coils have been designed by IPP for the ASDEX Upgrade tokamak. The coils are to be used in future RWM stabilization experiments on the device. Expressions for the linear response of various components in the RWM control loop have been obtained by IPP. The description will be input to the RWM control design.

2.3. Non-linear MHD dynamics

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The experimental discovery of a new RFP dynamo regime termed Quasi-Single Helicity (QSH) is a major break-through in RFP research. In the QSH regime, the toroidal field reversal is sustained dominantly by a single tearing mode. The QSH regime contrasts to the standard Multi-Helicity (MH) dynamo regime. In the MH regime, the toroidal field reversal is sustained through the non-linear interaction of several tearing modes, causing magnetic island overlap and a stochastic magnetic field in the plasma core.

2.3.1. Magnetic topology of QSH regimes

In the theoretically predicted single helicity (SH) regime the dynamo is produced by the interaction of a single tearing mode with the velocity field produced by an electrostatic drift due to a small charge separation. The SH plasma core is characterized by a magnetic island generated by a single mode and has no magnetic chaos. On the experimental side, regimes in which the dynamo is produced mainly by a single (dominant) mode, but in which other (secondary) modes have a small contribution have been obtained, and are referred to as quasi single helicity (QSH) regimes. In these regimes the plasma core is still characterized by a magnetic island, but part of the core becomes chaotic due to the presence of the secondary modes. Transitions to QSH regimes are characterized by the decrease of the secondary modes. As a result, the magnetic stochasticity in the core decreases, improving the confinement.

Theoretical and experimental studies show that the core of QSH plasmas is characterized by the presence of a magnetic island. An important part of the project is to study the characteristics of the QSH island in EXTRAP T2R. The presence of the magnetic island is verified by studying the magnetic topology of the plasma core. The topology is determined from the equation of the magnetic field lines in flux coordinates, considering both the equilibrium field and the perturbations. In particular,
a Hamiltonian numerical code for field line tracing was developed and applied to the experimental data of EXTRAP T2R to obtain a Poincaré map of the magnetic field. By using the code for the determination of the Poincaré map of magnetic field lines, the magnetic topology of MH and QSH regimes were compared. The EXTRAP T2R plasma core was confirmed to be stochastic in the MH regime, while a clear magnetic island was present in the QSH regime, see Figure 2.3.1. The size of the island was correlated with the mode amplitude. A clear positive scaling with the dominant mode was found, see Figure 2.3.2.

2.3.2. Electron heat transport in QSH regimes
The conserved magnetic flux surfaces inside the magnetic island should be the origin of a strong local heat transport reduction, since the surrounding part of the core is characterized by a stochastic magnetic field. In principle, the QSH island should have better confinement properties than the standard MH regime. First, the heat diffusivity in the MH regime was determined by developing a 1D heat transport code to simulate the electron temperature profile. The effect of the magnetic island was taken into consideration in the second step, by considering the island as a perturbation of the MH profile. For this purpose, a perturbed heat equation was introduced in order to determine the temperature increment inside the island. The heat diffusivity was calculated by comparing simulated and experimental results.

Figure 2.3.1. Core magnetic topology in a QSH plasma.

Figure 2.3.2. Correlation of the island width with the dominant mode amplitude.
In standard MH plasmas, the core electron heat diffusivity is $1000 \pm 500 \text{ m}^2/\text{s}$. This value is consistent with those determined in other reversed field pinch devices. A clear reduction of the electron heat transport inside the QSH island is found. The application of the code to QSH plasmas shows that the island heat diffusivity is one to two order of magnitude lower, being in the range $10 – 200 \text{ m}^2/\text{s}$. The corresponding temperature increment inside the island is approximately $10 – 50 \text{ eV}$. In Figure 2.3.3., an example of the temperature increment inside the magnetic island of EXTRAP T2R is shown. More detailed studies show that the island heat diffusivity is reduced at high plasma current. This result is shown in Figure 2.3.4.
2.3.3. Active generation of QSH regimes

The QSH may in principle be a route to improvement of RFP confinement. However, the duration of spontaneous QSH is only 1% of the pulse duration in EXTRAP T2R. The active generation of QSH states by using the EXTRAP T2R feedback system is therefore an interesting possibility. The feedback system of EXTRAP T2R is utilized to apply an external resonant magnetic perturbation (RMP) to the plasma edge. The toroidal harmonic of the applied RMP corresponds to that of the \( m=1 \) tearing mode resonant closest to the minor axis.

Two strategies were tested to produce the RMP: the open loop operation and closed-loop operation. In the open loop, the active coils produce the RMP with the desired harmonic and no active control on the MHD modes is performed. In the closed-loop, the feedback tries to suppress all MHD modes excluding the one with the desired harmonic. Both the open-loop and the closed-loop operation significantly increase the number of QSH produced during the discharge. The role of the RMP amplitude was studied in detail. With sufficiently large RMP amplitudes, the QSH probability increases from 1% (spontaneous QSH) to nearly 10%. This is shown in Figure 2.3.5. The closed-loop operation allows the production of QSH islands with better characteristics. The induced QSHs are characterized by a magnetic island with a size larger than the spontaneous QSH island, as shown in Figure 2.3.6.
2.3.4. Tearing mode dynamics with resonant magnetic perturbation.
The behaviour of the internal tearing mode subject to an external RMP is interesting. The control coils at EXTRAP T2R are used to apply an external RMP at the plasma edge. The response of the tearing mode corresponding to the same harmonic as the RMP is studied. The attention is focused on the mode dynamics: the time evolution of the mode amplitude and mode velocity. The tearing mode dynamics is clearly affected by the RMP. The corresponding amplitude and velocity have a characteristic behaviour that is dependent on the RMP amplitude. An example is shown in Figure 2.3.7.

![Figure 2.3.7](image)

(a) TM amplitude

(b) TM velocity.

External RMP amplitude is 0.2mT (red) and 0.4mT (blue).
2.4. Plasma-wall interactions

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

- EFDA-JET Work Programme: Task Forces “E” (Divertor Physics) and “D” (Diagnostics) and JET Enhancements (Phase 1 and Phase 2) including the ambitious ITER-Like Wall (ILW) Project, i.e. full metal wall at JET.
- EFDA-JET Fusion Technology Programme.
- ITPA and IEA activities.

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

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

2.4.1. ITER-Like Wall Project at JET

To achieve further progress in controlled fusion, the ITER-Like Wall (ILW) Project at JET is under way in order to explore tokamak operation and plasma-wall interaction processes with a full metal wall: beryllium (Be) in the main chamber and tungsten (W) in the divertor. The main driving forces for a large scale test of the metal wall are: (i) expected reduced retention of hydrogen isotopes in operation with a metal wall in comparison to carbon PFC; (ii) good plasma performance and gettering of oxygen impurities by beryllium; (iii) low erosion of tungsten at low ion temperature in the divertor. Experimental campaigns with the fully modified PFC structure are planned to begin in year 2011.
The aim of the work was to develop and test Be components of two categories: (i) bulk limiter tiles including so-called markers designed for studies of beryllium erosion from the wall and (ii) Be-coated inconel plates for the inner wall cladding.

**Bulk beryllium components**

Images in Figure 2.4.1 show the present structure of the JET in-vessel components (a) and the distribution of materials to be implemented for ILW (b). Beryllium tiles are to be located in the main chamber wall. These are the inner wall guard limiter and the outer poloidal limiters, lower hybrid launcher frame, upper dump plates and other protection tiles (antenna private limiters, mushroom tiles, saddle coil protection tiles). Dump plates and mushroom-shaped limiters protect the upper part of the vessel. The size of the main limiter tiles (approx. 10x30x6 cm) has imposed the search for engineering solutions to ensure proper performance of the limiters. Figure 2.4.2 provides details of a wide poloidal limiter tile assembly consisting of seven bulk Be segments (Brush Wellman Inc. grade S65J, hipped structural Be) installed on a vacuum cast Inconel-625 carrier. The segmented construction reduces eddy currents, whereas the castellation is to improve thermal durability under heat loads. The optimized surface profile and lack of plasma-facing bolt holes ensure better power handling.

![Fig. 2.4.1. View inside the JET vessel: (a) present structure of wall components with CFC limiter and divertor tiles and Be ICRH Faraday screens; (b) planned distribution of beryllium and tungsten for the ITER-Like Wall operation.](image)

![Fig. 2.4.2 Structure of a carrier and a segmented Be tile (a); assembly of a poloidal limiter (b).](image)
Beryllium marker tiles

An important goal of the ILW Project is to assess the erosion of beryllium components in order to give best-possible predictions for ITER. To facilitate such studies, so-called marker tiles are being developed. They will be placed in several toroidal and poloidal locations in the vessel. A marker is a regular beryllium tile coated first with a high-Z metal film acting as an interlayer and then with a Be layer of density similar to that of bulk beryllium. To ensure good adherence and thermo-mechanical (best match of linear thermal expansion coefficients) and physical properties of the marker coatings nickel (2-3 μm) was selected as an interlayer material to separate the bulk Be tile from a 7-10 μm thick beryllium coating. The films are obtained by the thermionic vacuum arc (TVA) method which allows production of high-density layers. For measurements of erosion greater than 10 μm, there will be precise notches (10, 20 μm deep) on the tile surface. A series of marker coupons were produced and examined by several material analysis techniques before and after high-heat flux (HHF) testing with an electron beam in the JUDITH facility. HHF screening tests allowed the determination of power and energy density limits deposited onto the surface until the damage to a marker occurred. A cyclic test served to assess the thermal fatigue under repetitive power loads. Not coated Be blocks were tested for comparison. The major results may be summarised by the following: (i) the markers survived without noticeable damage power loads of 4.5 MW m⁻² for 10 s (energy density 45 MJ m⁻²) and fifty repetitive pulses performed at 3.5 MW m⁻² each lasting 10 s, i.e. corresponding to the total energy deposition of 1750 MJ m⁻²; (ii) in both cases the surface temperature measured with an infrared camera was around 600 °C; (iii) the damage to the Be coating occurred at power loads of 5 MW m⁻² for 10 s.

Plots in Figure 2.4.3 show depth profiles obtained by secondary ion mass spectrometry (SIMS) for two marker coupons: (a) unexposed to heat loads and (b) after HHF test carried out for 10 s at power density of 4 MW m⁻², i.e. total energy density of 40 MJ m⁻². Both profiles are quite similar (Be coating thickness ~9.5 μm) thus indicating that the applied power loads neither damage the coating nor cause intermixing of Be and Ni. There are some impurity species (Al, Si, Fe) but their content is below 1% as determined by ion beam analysis, energy and wavelength dispersive X-ray spectroscopy. Figure 2.4.4 shows a metallographic cross-section of the HHF tested coupon. A clear separation of beryllium and nickel proves the durability of the coatings.

Beryllium coatings on Inconel

The inner wall cladding and the dump plate tile carriers will be made of cast Inconel. These tiles are in the shadow of bulk Be tiles, but to minimize the risk of high-Z impurity (Ni, Cr, Fe) influx, the Inconel tiles will be protected by 8 μm thick evaporated Be coatings.

During regular plasma operation in JET, the estimated power load to the cladding is 0.5-0.7 MW m⁻² for 10 s corresponding to energy deposition of 5-7 MJ m⁻². To check the adherence and thermo-mechanical properties of the Be layer, a number of test coupons were exposed to high power loads in JUDITH. The screening test was carried out in the range from 0.4 MWm⁻² to 2.6 MW m⁻² in pulses lasting of up to 11 s. In the cyclic test fifty consecutive 10 s pulses were performed at the power of 1 MW m⁻², i.e. 10 MJ m⁻² per pulse. Figure 2.4.5 shows the layer structure before (a) and after the test at the power load of 1.8 MW m⁻² for 11 s corresponding to the energy load of 20 MJ
In both cases the coating topography is nearly identical. It proves that no damage (e.g. melting or exfoliation) is caused by energy loads exceeding at least three times the level characteristic for a regular plasma operation. As assessed, the coating on Inconel would melt at energy loads exceeding 30 MJ m\(^{-2}\).

**Concluding remarks**

The best efforts have been taken to develop and test the performance of beryllium components being prepared for the installation in the ILW operation of JET. Power handling capabilities and purity have been of primary interest. The results of material analysis before and after HHF testing indicate that the coatings on Inconel and marker limiters should withstand conditions of the regular JET operation without melting,
exfoliation or phase transformation. This is particularly important in case of the marker tiles for long-term Be erosion studies in the main chamber. However, local melting of Be tiles (with and without markers) cannot be excluded in case of events resulting in deposition of excessive power loads. In this case the extent of erosion will be assessed by mechanical methods. The scientific and technical program has led to the selection of methods for a large-scale manufacturing of protective coatings on the inner wall cladding and marker tiles. The thickness of markers, prior to their installation in JET, will be determined by means of ion beam analysis methods.

2.4.2. Nitrogen-assisted removal of deuterated carbon layers

The reduction of long-term fuel inventory in plasma-facing components (PFC) is one of the most critical and challenging issues to be resolved in order to ensure safe and economical operation of a reactor-class device. Therefore, efficient methods for removal of hydrogen isotopes and co-deposited layers are to be developed and tested. In this process, three aspects must be taken into account for each technique: (i) removal efficiency of fuel and co-deposits, (ii) impact on the surface state of the PFC and (iii) dust formation caused by destruction/disintegration of co-deposits. To date, fuel removal based on glow discharge in hydrogen and helium, oxygen-helium glow and photonic methods with lasers and flash lamp have been tried. Nitrogen-assisted fuel removal is also considered a candidate method, and encouraging results have been obtained in laboratory experiments. The experiments were performed in nitrogen-assisted discharges in the TEXTOR tokamak and in the TOMAS experimental plasma device. This experimental program allowed for covering a broad of conditions. The results obtained during experiments in TEXTOR were described in the Report for year 2007.

**Experiments in TOMAS**

TOMAS (TOroidal MAgnetic System) is a plasma device with a major radius of 1.5 meters and a minor radius of 0.15 m. Two basic series of exposures to H\textsubscript{2}-N\textsubscript{2} plasma have been made to check the impact of gas mixture composition (0 to 100% N\textsubscript{2}) and temperature (40 – 290 °C) on the removal efficiency of carbon and deuterium from laboratory-prepared pure amorphous carbon films (a-C:D) deposited on silicon substrates. Most experiments were performed using glow discharge assisted by radio frequency (RF). In addition, one exposure was performed with microwave heated plasma to assess the impact of plasma heating. The temperature 200 °C was chosen because it is the wall temperature foreseen for ITER and because it is the wall temperature of TEXTOR, thus making comparison. The pressure during GDC was around 10\textsuperscript{-3} mbar and an accelerating voltage of 330 V was applied. When using pure hydrogen, the pressure was about a factor two higher – this was necessary to ensure plasma stability. The total plasma current was around 0.8 A, except when using pure nitrogen when the current was about 1.6 A. Since the total surface area of TOMAS is around 10 m\textsuperscript{2}, this corresponds to 8 mA/m\textsuperscript{2} and 16 mA/m\textsuperscript{2} respectively, or a flux of 5\times10\textsuperscript{13} cm\textsuperscript{-2}s\textsuperscript{-1} and 1\times10\textsuperscript{14} cm\textsuperscript{-2}s\textsuperscript{-1}. With the exposure normalized to 2 hours, or 7200 seconds, we have that the samples were exposed to 3,6\times10\textsuperscript{17} and 7,2\times10\textsuperscript{17} incident ions respectively. With dissociation energy for N\textsubscript{2} at 9.5 eV and for H\textsubscript{2} at 5 eV, and ionization energy at 14.5 eV and 13.6 eV respectively, it may be assumed that the impinging ions contains H\textsuperscript{+} and N\textsuperscript{+} ions in quantities proportional to the percentage of a given species in the H\textsubscript{2}-N\textsubscript{2} gas mixture feeding discharges in TOMAS. During
microwave heated exposures, a biasing voltage of -200 V was applied to the holder. In these discharges, the pressure was lower (3.8 x 10^{-3} mbar) because of heating limitations. Gas phase composition was continuously monitored with a quadrupole mass spectrometry (QMS).

Amorphous carbon films prepared in laboratory were used for all experiments reported below. Received samples have shown very smooth featureless surfaces as observed with high-resolution SEM. An exposure in TOMAS caused a change in the layer structure. The surface was covered by granule-like structures of approximately 20 nm in size. Plots in Figures 2.4.6 (a) and (b) show the change of D and C contents in the main series of experiments in RF-assisted glow discharge: dependence on gas composition (10-100% N₂) and temperature (40-290 °C) with the H₂/N₂=1 mixture, respectively. The results have been normalized with respect to the exposure time (7200 s) and ion current measured on targets during the exposure. QMS measurements detected H, N, N₂ as the main components. Smaller signals associated with M=16 (CH₄, O, NH₂), M=17 (OH, NH₃) and H₂O (M=18) were noticed. Only trace signals were recorded at M=26 (CN) and M=27 (HCN) thus showing that the involvement of chemical processes between nitrogen and carbon has rather negligible impact on the removal efficiency of D and C.

![Graph](image1)

**Fig. 2.4.6.** Deuterium and carbon removal efficiency as a function of: (a) nitrogen content in H₂-N₂ plasma and (b) target temperature.

Following main results have been obtained in exposures to different gas composition at constant temperature:

(i) in each exposure, the removal rates of deuterium and carbon are approximately the same;

(ii) 2h exposures at 200 °C to the H₂-N₂ mixture (10-100% N₂) result in removal of 20-30% of the layer with the maximum recorded for 25% N₂ when 31% deuterium and 33% carbon was removed; but at other gas compositions no clear trend could be detected;

(iii) the erosion rate is increased by a factor of 2 with microwave heating, to 58% deuterium and 52% carbon removed using 25% N₂, although this experiment is not exactly comparable to the others;

(iv) in the reference exposures using only hydrogen, ~60% of the layers were removed in two hours.

In summary, one can state that there is little influence of the gas composition on the removal efficiency of deuterated carbon films and 2h exposure to TOMAS plasma is not enough to erode approximately 2 μm thick layers. The experiments at the constant
50-50 gas mixture but increasing temperature (40-290 °C) show a decrease in the removal efficiency of carbon when the temperature rises. The efficiency of deuterium removal decreases up to 200 °C and then the increase is noted again at 290 °C. While the increased rate of D removal when the temperature rises from 200 °C to 290 °C can be attributed to thermal release, the other results - especially for carbon - are still to be better understood and clarified in future experiments in TOMAS and studies of the exposed layers with XPS. This is because the tendency in target temperature impact on the erosion of amorphous carbon films by H$_2$-N$_2$ is opposite than that measured for such films under the bombardment with H atoms or atoms.

**Concluding remarks**

The experiments performed under a broad range of conditions in with H$_2$-N$_2$ mixture have shown that: (i) no or little erosion of carbon and deuterium is induced by glow discharge ICRH-assisted pulses in TEXTOR; (ii) the erosion of a-C:D films measured after the exposures in TOMAS varies, but even in the best case (25% of N$_2$ in the mixture) the efficiency does not exceed 35% for a 2-3 μm thick layer after 2 hours treatment by RF-assisted glow discharge at 200 °C; (iii) greater efficiency, though not better than 60%) is determined in pure hydrogen and in discharges heated by microwaves. The results indicate that the major erosion mechanism is physical sputtering, which depends on the ion energy, i.e. the acceleration voltage under experimental conditions.

For the hydrogen-nitrogen mixture in TOMAS with ion flux of 5x10$^{13}$ cm$^{-2}$s$^{-1}$ in RF-assisted glow discharge the removal rate for carbon (see Table 3) was in the range 0.8-1.3 C/ion which is very higher than 0.5 C/ion for nitrogen bombardment of carbon. The effective removal rate of the layers is around 0.1nm/s for most exposures. This value, which is a figure of merit in the assessment of deposit and fuel removal methods, is much lower than the growth rate of co-deposited layers in carbon wall tokamaks like TEXTOR where the rates of 3 and 10 nm/s were determined for deposits on the main toroidal limiter and the neutralizer plates, respectively. Therefore, the results obtained do not lead to optimistic conclusions regarding the application of H$_2$-N$_2$ glow plasma for the removal of co-deposits from large areas in a device with carbon PFC.

**2.4.3. First Mirror Test for ITER at JET**

Metallic mirrors will be essential plasma-facing components (so-called first mirrors) of all optical spectroscopy and imaging systems used for plasma diagnosis on the next-step magnetic fusion experiment. Over 80 first mirrors are planned in ITER to enable detailed characterization of the main chamber and divertor plasma. They will be of different size (up to 350 mm in diameter or 440 mm high) and will be placed at different distance from plasma, starting even from 140 mm. When assessing the plasma impact on mirrors, three parameters are important: (i) the distance to plasma; (ii) solid angle resulting from the mirror-to-aperture distance and (iii) aspect ratio the aperture - mirror distance to aperture diameter or width. Any change of the mirror performance, in particular reflectivity, will influence and degrade the quality and reliability of detected signals. On the request of the ITER Design Team, a First Mirror Test (FMT) was initiated at JET. Recently completed experiment has been the most comprehensive test performed with a large number of metallic mirrors exposed in an
environment containing both carbon and beryllium. This paper provides an overview of results obtained for mirrors retrieved from the torus after campaigns covering the period 2005-2007.

**Experimental**

Details of the entire technical the program (design of mirrors and their carriers and installation in the torus) have been presented earlier, hence, only a brief summary of essential elements is given below. 16 stainless steel (316L) and 16 polycrystalline molybdenum mirrors were tested. The material selection was based on the advice of the ITER Design Team. Flat-front and angled (45°) mirrors were manufactured: blocks (1x1x1 cm³) with the plasma-facing surface of 1x1 cm² (flat-front) and 1x1.4 cm² (chamfered). Each mirror had a “feet” for unmistakable mounting in a “pan-pipe” shaped cassette with either three or five channels dependent on the availability of space in the place of installation. Cassettes were composed of two detachable plates in order to enable qualitative and quantitative studies of the composition of deposits along the channel. The mirrors were fixed in channels at different distance (0; 1.5; 3; 4.5 cm). This paper is focused only on the analyses of mirrors.

Six units were installed in three locations in the divertor: inner leg, outer leg and under the load bearing tile on the base. In all locations the cassettes were mounted in the vicinity of deposition-erosion monitors. Two units with 5-channel cassettes, one with Mo and another with steel mirrors, were placed vertically (poloidal direction) on the outer wall in Octants 3 and 4, respectively. The unit installed in Octant 3 near the beryllium evaporator was equipped with a magnetic shutter protecting three mirrors placed near the channel mouth. Mirrors sitting deeper in the channel (3.0 and 4.5 cm) were not protected. This arrangement allowed for a check of possible impact of wall conditioning on reflectivity. The distance of mirrors in wall units to plasma was from 42 cm (mouth of the channel) to 46.5 cm, whereas in the divertor it was 10 to 14.5 cm. The range of solid angles for particle bombardment ($\Omega_{PB}$) was $6.3 \times 10^{-3} - 5.5 \times 10^{-2}$ sr. These solid angles and aspect ratio for mirrors in cassettes (depth in channel to aperture width: 1.5-4.5) simulated the experimental situation of many mirrors planned in ITER.

Total exposure time during 7048 pulses was 126 600 s (35 h) including 96900 s (27 h) of X-point operation. This corresponds by divertor operation time to about 240 ITER pulses lasting 400 s. However, this would be only 7-8 pulses scaled with energy input or less than one ITER pulse when divertor fluxes are considered. During the 2007 shut-down, 7 cassettes with 29 mirrors were removed for visual inspection and determination of total reflectivity and surface composition. Optical measurements were done in the range 400-1600 nm using equipment specially designed for handling materials contaminated by beryllium and tritium. Surface composition was studied by means of nuclear reaction analysis (NRA) with a 2.5 MeV $^3$He$^-$ beam and enhanced proton scattering (EPS) using a 2.5 MeV H$^+$ beam.

**Surface morphology**

Images in Fig. 2.4.7 show the appearance of mirrors retrieved from the inner divertor leg (steel, Fig. a) and base (Mo, Fig. b), whereas samples from the main chamber wall are in Fig. c (Mo, shutter protected) and d (steel, not protected). The position of mirrors in cassettes is given, i.e. depth in channels. The quality of images is somewhat obscured by photographing through a window of the isolator. Visual inspection
reveals distinct differences between mirrors from the two locations. Surfaces of all mirrors from the divertor are coated with deposits. In some cases, the layer had flaked and peeled-off. This process occur in-situ during the exposure because discoloration is seen on the flake-free surface thus indicating the formation of a new co-deposit. It is impossible, however, to conclude whether the flaking happened only once or several times during the long-term exposure. For mirrors from the outer wall the picture is more complex. As shown in Fig. 2.4.7 c, three Mo mirrors positioned near the mouth of the channel (0 and 1.5 cm protected by the shutter) are nearly free from a visible co-deposit, but some surface imperfections could be observed. Only a narrow deposition belt is noted on the chamfered surface. Mo samples from deeper locations (3 and 4.5 cm) are partly (not the whole surface) coated by thick films. Very similar deposition pattern also developed on steel samples located deep in the channel. In addition, a flat-front mirror at 1.5 cm was coated, whereas on the adjacent chamfered sample (1.5 cm at the center) the deposit covered only a small area, as inferred from Fig. 2.4.7 d. These results suggest that deposition on all mirrors in wall units took place during tokamak discharges and it was not connected with wall conditioning. Some differences in deposition, like those observed on two adjacent steel samples at 1.5 cm, are probably related to some local geometrical effects that are difficult to identify having in mind the complexity of wall structures in JET. Microscopy studies have not been accomplished yet for technical reason (Be and T contamination of mirrors), but one may suggest that lack of visible deposits on mirrors placed at the channel mouth in main chamber units is related to removal of deposited species by charge exchange neutrals reaching these surfaces.

IBA results are shown in graphs on Figure 2.4.8 (a) and (b) for Mo mirrors from the outer divertor leg and the main chamber wall, respectively. The most distinct difference is that the deposition on samples from the divertor decreases with the depth in channel for all studied samples, whereas the opposite trend is characteristic for wall samples: only 1.3-1.5x10^{17} C at cm^{-2} have been detected on the three front samples from the main chamber. Thus, IBA data confirm the general observation from the visual inspection. The quantitative results for carbon deposition on steel mirrors from the outer divertor were nearly identical, within ± 5%, to those shown for Mo in Fig 2.4.8 a. The recorded EPS spectra for thick carbon layers were modeled with SIMNRA to obtain the concentrations and layer thickness, e.g. 10 μm and 7 μm for
the thickest deposits on the samples from the main chamber and outer divertor, respectively.

![Graph](image)

Fig. 2.4.8. Carbon deposition on Mo mirrors in: (a) outer divertor; (b) main chamber wall.

The data obtained for the front mirrors (i.e. located at 0 cm) in the divertor agree qualitatively with the deposition pattern observed on the sensors of quartz microbalance (QMB) devices installed in the vicinity of the mirrors: most significant deposition in the inner divertor, less deposition in the outer leg. Only limited comparison can be made because the QMB crystals were exposed to selected discharges, whereas the mirrors were facing plasma continuously during all operation scenarios.

All deposits, whether thin or thick, contain carbon-12 and deuterium as the main components (D/C concentration ratio ~0.65 for the outer and inner divertor samples) and small quantities of beryllium and carbon-13. The concentration of these minority species was in the range 5x10^{16} \text{ cm}^{-2} - 1x10^{18} \text{ cm}^{-2}, but no systematic tendency regarding their deposition could be traced. The presence of C-13 in measurable quantity derives from three experiments using $^{13}$CH$_4$ tracer in material migration studies. The last experiment of this kind was performed just on the last operation day before the shut-down. The high D/C ratio indicates that mirror surfaces were not overheated during the exposure. The temperature of units in the main chamber (45-50 cm from the plasma) corresponded to the wall temperature (around 200 °C), whereas in the divertor it can be assessed in the range 150-200 °C as determined by thermocouples installed in the vicinity of the mirror carriers.

**Reflectivity**

Total reflectivity was measured for all 29 mirrors retrieved from the torus and it was compared with the initial reflectivity which was determined for all the mirrors before their installation; the scatter was well below 5%. The results regarding optical properties of all tested mirrors may be summarized as follows.

(i) In the divertor base very significant loss of reflectivity is measured close to the channel mouth: in the visible range by a factor of 6-10 at 0 and 1.5 cm.

(ii) In the outer and inner divertor reflectivity drop by a factor of 10 in visible range (400-800 nm) is recorded at all locations. At 1400 nm it reaches eventually 50% of the original value for mirrors deep in the channel (3 cm) and ~30% for mirrors located close to the channel entrance (0 and 1.5 cm).
(iii) On the main chamber wall, close to the channels entrances high reflectivity (~90%) is maintained at infrared range by both steel and Mo surfaces. However, in the range 400-600 nm the drop by 15% (steel) and 30% (Mo) is measured. 1.5 cm from the channel entrance the reflectivity drops by 35-50% and at deeper locations (3, 4.5 cm) it is only 20-25% of the original value due to deposits. These results suggest that fair reflectivity of mirrors near the channel mouth is due to the instant removal of deposits by the flux of charge exchange (CX) neutrals. However, the deposition prevailed over erosion deeper in the channel because of the decreased CX flux to that location.

(iv) No significant differences have been noted between Mo and steel mirrors, because their optical properties have been eventually governed by carbon deposition which occurs at the same pace on both polished substrates.

Concluding remarks

Taking into account that the entire test at JET has corresponded at the best to less than 10 ITER shots one may expect similar problems with at least some mirrors in vital diagnostic systems, especially if the option with a carbon divertor is pursued. Even mirrors accessed by CX fluxes will be damaged by erosion (increased surface roughness) or material mixing by implantation of incoming flux. Therefore, the main effort should be concentrated on the development of methods for in-situ cleaning and/or protection of mirrors in a reactor-class device. Protection by using replaceable transparent glass/ceramic filters in front of mirrors is difficult to conceive because filters would also quickly loose performance under gamma and neutron irradiation. A controlled gas puff in the vicinity of mirrors would change the erosion-deposition balance by decreasing the mean free path of species in the diagnostic channel, but such a puff may result in mobilization of dust or flakes of co-deposits present in that region, thus disturbing spectroscopy measurements. Cleaning of mirrors by laser-light would require knowledge on the deposit composition and thickness to set up proper irradiation conditions to avoid damage of the cleaned surface. Similar requirements apply to a local plasma glow in the diagnostic channel and the technique would be limited only to the periods when the magnetic field is turned-off. Heating of mirrors to remove carbon deposit may result either in the formation of dust from the peeled-off deposit or/and carbide formation on the mirror surface which would destroy optical properties. All these ideas have been discussed for some time, but no in-vessel experiments have been performed to prove the concept as a working solution. Another option is to implement a cassette with mirrors to replace periodically the degraded ones. This is difficult from the engineering point of view but feasibility studies should probably be performed in case no other viable solution to protect or clean mirrors is found.
2.4.4. Materials migration studies with nuclear microbeam

Under the JET fusion technology contract JW8-FT-3.40, cross sections of deposited layers at the JET divertor surfaces have been investigated with microscopy nuclear microbeam analysis methods. The elemental composition of the archeologically layered deposits is determined with the aim to draw conclusions about materials migration in the divertor region. The nuclear methods are easy to make quantitative compared to alternative methods and particularly sensitive to hydrogen isotopes and light elements like carbon and beryllium. The spatial resolution of a few micrometers is ideally suited for the layers deposited in JET, which are hundreds of micrometers thick. The influence of different polishing techniques in preparing the cross section samples has been investigated and detailed depth profiles as well as lateral elemental distributions have been determined for layers that are 100-800 μm thick, the thickest layers corresponding to JET operation 1998-2007.

Fig. 2.4.9. Optical micrograph of an 800 μm thick deposited layer from the JET divertor. At the bottom the carbon fibre composite substrate. At the top epoxy.
2.4.5. Materials migration studies with AMS

Under the JET fusion technology contract JW8-FT-3.40, a marker experiment with 10Be marker has been prepared for the ITER-like wall phase in JET. The background levels of 10Be in JET exposed beryllium have been determined by accelerator mass spectrometry (AMS) and were found to be low. The experiment in preparation involves enrichment with 10Be by neutron irradiation of one of the beryllium inner wall tiles to be inserted in JET. Thanks to the extreme sensitivity of the AMS technique it will then be possible to follow the migration of the marker over the plasma facing surfaces in JET and compare the results with models.
2.4.6. Studies of dust using aerogel collectors

A novel method to capture moving dust in fusion devices has been introduced. Silica aerogels are the lowest density solid materials that exist. These materials have already been employed in space research for dust capture, since they are able to capture fast dust, even dust moving at several km/s, without breaking the particles. From the track morphology, particle velocities can be estimated. Due to the extremely low density and low thermal conductivity there are limitations in the applicability for fusion plasmas, but we have demonstrated in EXTRAP T2R and in TEXTOR that the method is applicable also for dust capture in the edge plasma of fusion devices. The methods to study impact craters and captured dust particles include optical microscopy, SEM, X-ray elemental analysis, atomic force microscopy, stereographic SEM and FIB-SEM and nuclear microbeam methods. The purpose of the investigations is to quantify the amount of dust moving in the edge plasma and to improve the understanding of dust transport at the edge. This work has been done under the EFDA contract WP09-PWI-03-02/VR/BS.

![Fig. 2.4.12. SEM image of impact craters in Silica aerogel exposed in EXTRAP T2R.](image)
2.5. Plasma diagnostics

T. Elevant, J. Brzozowski and M. Cecconello

2.5.1. SIW Project

Spectroscopy in Support of the ITER-like Wall (SIW) is part of a package of diagnostic enhancements which is to be implemented and used at JET during operation with an ITER-like wall during Framework Programme 7.

Background

The primary material choices for ITER is a full beryllium main wall with CFC (carbon fibre composite) at the strike points together with tungsten at divertor baffles and dome. Since this combination has not been tested in a tokamak previously, the ITER-like Wall project has been launched at JET implying replacement of the present first wall by an ITER-like wall followed by tests and operation with an adequate set of diagnostics. Presently, the JET wall and divertor consist of CFC, while the RF and LH antennas consist of Be and Cu coated stainless steel, respectively, with CFC protection tiles. Small amounts of Be are introduced by evaporation, and noble gases are frequently injected for transport studies (4He, Ne, Ar), or as minority species for RF-Heating (3He). The reference species for low Z elements for core and edge emission is C. The reference species for medium Z species in the VUV, XUV and X-ray region is Ni (an estimate of the Ni concentration is routinely performed using a high resolution Xray crystal spectrometer).

Installation of the ITER-like wall and a new divertor on JET will result in qualitatively different spectroscopic needs and technical challenges. The metal surfaces can be subjected to large power density and thus high erosion rates. In case the full W divertor option is selected, it is conceivable that C levels will be so low that Be has to act as the reference species for low Z elements, while it will be necessary to quantify the degree to which C is reduced. Spectra from W are very rich, and may result in blending with spectral lines from other elements in all wavelength ranges. The spectral line best suited to study W erosion is the one at 401 nm because modelled and experimental results are available to convert photon fluxes into erosion rates. However at this wavelength transmission losses by optical fibres are high, quantum efficiency of detectors is low and absolute calibration more difficult than for the spectral lines that best characterise C. For Be, spectral lines in the normal visible wavelength range exist, but many other suitable lines are in the blue as well. It will also be necessary to quantify the amount of Be released from W surfaces, the amount of W released from Be surfaces, and later in the experimental campaigns the release of Be and W from Be/W alloys once these have formed on the various surfaces. Both elements, and their alloys, are prone to melting; therefore specific spectral lines from several locations need to be provided in real time for possible use in machine protection. Core concentrations of Be and W and their relationship with erosion rates need to be studied in detail to allow a meaningful prediction of the same wall mix on ITER which is presently foreseen to be W/Be/C.

Features of the enhanced systems

To meet the new demands a number of spectroscopic diagnostic systems are modified and enhanced. All instrumentation that is not installed in the torus hall will be located
in a dedicated laboratory ("spectrometer room") in J1D, with a number of optical fibres routed from the various locations around the torus. Fibre patch panels in the spectrometer room will make the instrumentation interchangeable between different lines of sight should such need arise. The core emission from W is spread from the VUV (10nm-13nm) and XUV (4nm-7nm) to the Xray (0.1nm-0.4nm), with each spectral region being representative of a different part of the plasma, depending on the degree of ionisation and hence electron temperature. This motivates the enhancements to the diagnostics KT4, KT7 and KX1 to complement the information from KT2 and KS6, which are not being modified since they are already adequate.

The diagnosis of wall sources is a multi-dimensional task: high time resolution, good spatial resolution, large spectral coverage with good spectral resolution cannot be achieved simultaneously by a single instrument. The enhancements to KL1, KT1 and KT3 address the need for spatial coverage and resolution for spectral lines characteristic of Be, C, and W with slow time resolution. The enhancements to KS3 and KS8 provide partly wide spectral coverage for more detailed physics studies of erosion processes and partly ELM resolved time resolution, in specific locations on the inner wall and in the divertor.

**Role of Fusion Division at KTH**

The responsibilities of VR are dealt with by the Fusion Division at KTH. This includes technical specifications, purchasing, installation, calibration, commissioning and tests of:

- 24 units of Polychromator Assemblies for PM Tubes (Art. 7 contract)
- Mounts, tables, optical components, fibres, fibre connectors and patch panels in the spectrometer room
- Production, acquisition and analysis of KT1 data.

**2.5.2. Work with JET diagnostics during JOC secondments**

J. Brzozowski works during January-March 2008 at EFDA-JET under a JET Operation Contract (JOC) with UKAEA where duties are divided between tasks as Session Leader and as Spectroscopy Diagnostician. Appointments include Deputy Task Force Leader for Diagnostics, Project Manager of one of the JET-EP2 Spectroscopy Enhancement Projects and Scientific Contact Person for the Swedish Euratom Association with EFDA JET. The work as Session Leader includes participation in teaching and supervision of Trainee Session Leaders. The work as Deputy TFL includes participation in JPEC, JET Programme Execution Committee.

M Cecconello works during January-March 2008 at EFDA-JET under a JET Operation Contract (JOC) with UKAEA as Responsible Officer (RO) of Neutral Particle Analyzers (NPA), in support of the research activity and operation of JET. Duties as RO include diagnostic support and development, data analysis and modeling, code maintenance and development. Research activity is carried out in two areas: modeling of neutral fluxes at low energies (< 1 MeV) due to NBI heating, toroidal field ripples and Edge Localized Modes and fast ion production, confinement and losses (with energies up to 4 MeV) during ICRH.
2.6. Theoretical fusion plasma physics

T. Hellsten, T. Johnson, M. Laxåback, A. Hannan (PhD student), K. Holmström (PhD student), J. Höök (PhD Student), Q. Mukhtar (PhD student)

In collaboration with CEA, IPFN, TEKES, UKAEA, CRPP, ENEA, Hellenic associations, Courant Institute New York

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

The three main codes developed by the group are PION, FIDO and SELFO. PION was the first self-consistent code for modeling 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.

**Exploitation of JET**

Thomas Johnson and Martin Laxåback have been long term seconded at JET. Thomas Johnson has been involved in analysing the experiments at JET and Martin Laxåback in the planning, coordination and monitoring of the JET programme.

**ITM task force**

The group participates in the Integrated Tokamak Modeling Task Force. Torbjörn Hellsten is project leader for IMP5, the project for developing models for heating, current drive and fast particle effects for ITER. Our group participates in the development of codes for simulating heating and current drive in the ion cyclotron frequency range and with interactions of fast particles with low frequency Alfvén waves. The group is involved in developing two new codes for ICRH, one for routine analysis, replacing PION, and one for advanced simulation including finite orbit effects to replace FIDO. The work on the advanced code based on Monte Carlo methods for solving a 3D distribution function have been focused on developing methods to improve the Monte Carlo method comprising of an adaptive δf-method and a higher order method to improve the convergence near boundaries where the diffusion coefficients vanish.
2.6.1. Development of codes for modelling ICRH

A fast code for routine simulations of ICRH is being developed. The code is based on the formulation used for the PION code using a 1D–Fokker-Planck solver with a model for the parallel velocity. The upgrading of the code consists of using replacing the formula for the power deposition with direct solution of the wave equation. This enables calculation of the power deposition with several cyclotron resonances or harmonics of it at different locations and to calculate electron current driven by the magnetosonic waves, which in the past have to be done with more advanced codes.

**Adaptive Monte Carlo δf-method**

Calculations of the distribution functions, which because of the complicated geometry are done with Monte Carlo methods, are time consuming. In order to speed up the calculation and/or to make them more accurate an adaptive δf-method has been developed and tested for one dimension, with promising results. The drawback with conventional δf-methods is either that they only allow a small local deviation of the distribution function or that new particles have to be continuously added. These problems are solved by resampling the distribution function and improving the approximation of the distribution function in when it is resampled in order to minimize the source term and the number of simulated particles.

**Stochastic differential equations with singular diffusion coefficients**

**Monte Carlo operators**

When calculating the distribution function one experience in inhomogeneous plasmas that interacting regions and phase space are limited. At the boundaries the diffusion coefficients vanishes or become discontinuous resulting in poor convergence. To speed up the calculations and/or to improve the convergence higher order methods are developed. Promising results have been obtained for 1D-models.

**Coulomb collision operator for neoclassical calculations**

A method to include collisions with background plasmas consistent with neoclassical transport in the banana regime has been developed; suitable for orbit averaged Monte Carlo codes. By shifting the parallel velocity of the test particles, the collision operators can be expressed in terms of standard Coulomb collision operator for isotropic Maxwellian background distribution functions. The shift is determined from quasi-neutrality and can be expressed in terms of flux functions \( \Omega_{\text{eff}}(\psi)R_0 \), which depend on the density gradients, ion temperature gradients and fluxes caused by wave-particle interactions or particle losses. As the shift, which determines the radial electric field, increases and becomes comparable to the thermal velocity of the ions the relation between this shift and the temperature gradients and the losses become strongly non-linear with the possibility of bifurcated solutions. It is found that at large gradients the relationship between radial electric field, parallel velocity, temperature and density gradient in the neoclassical theory is modified such that coefficient in front of the logarithmic ion temperature gradient, which in the standard neoclassical theory is small and counteracts the electric field caused by the density gradient, now changes sign and contributes to the build up of the radial electric field.

**Wave-particle interaction in toroidal plasmas**

A comprehensive treatment of wave-particle interactions in toroidal plasmas including collisional relaxation, applicable to heating or anomalous wave induced transport, has
been obtained by using Monte Carlo operators satisfying quasi-neutrality. This approach enables a self-consistent treatment of wave-particle interactions applicable to the banana regime in the neoclassical theory. The possibility to drive current by absorbing the waves on trapped particles has been studied and how the wave-particle interactions affect the bootstrap current. Three mechanisms appear: detrapping into co- and counter-passing orbits; changes of the bootstrap current due to wave induced particle transport; broadening of the trapped orbits producing dipolar like current. Wave-particle interactions by directed waves occurring only at one of the legs of trapped particles result in a selective detrapping into co- or counter-passing orbits, depending on the propagation direction of the waves. A factor of order unity, depending on the ratio of the effective detrapping by wave-particle interactions and collisions, can be recovered of the momentum absorbed on the trapped particles for current drive. This new current drive mechanism by selective detrapping of orbits during ELD/TTMP may partly explain the observed enhanced current drive in recent fast wave current drive.

**Upgrade of the PION code to treat the Iter-like antenna in JET**

The PION code has widely used at JET to study ICRF heating. However, the code was built to handle only one type of ICRF antenna at a time. The installation of the ITER-like ICRF antenna in JET has therefore require an upgrade of the code to treat scenarios where the plasma is heated by several antennas with different geometry, and frequency. This upgrade has been completed.

**2.6.2. RF-induced rotation**

Rotation in plasmas can have beneficial effects. For instance, it can enhance the stabilizing effect of a resistive wall. Shear in the rotation is also believed to be an important factor for transport barriers. In ITER and future reactors the ratio between beam momentum and energy will be low because of the high energy required for central heating the induced rotation by the beam is not expected to give rise to strong plasma rotation, it is interesting to consider other mechanisms with a potential to produce rotation. Intriguing observations of rotation in plasmas heated by Radio Frequency (RF) waves with little or no external momentum input have been made in several machines. There is as yet no complete understanding of the mechanisms behind the observed rotation. Effects due to fast ions, MHD and transport have been proposed, but reliable theoretical predictions of rotation in ITER or a reactor with low momentum are not yet available. In this respect, measurements of rotation profiles are crucial.

Experiments in JET have been carried out to study the effect of ICRH on the toroidal rotation of the plasma. In the outer part of the plasma a co-current rotation appears correlated with the magnitude of heating but independent of the cyclotron resonance position (frequency) or antenna phasing. This is in contrast to the central plasma rotation, which was affected by the frequency and wave spectrum. When applying the heating at the high field side, a central counter torque was found producing hollow rotation profiles most pronounced for waves propagating counter to the plasma current. The changes in the rotation profile depend on antenna phasing, frequency, plasma current and current profile. Hollow rotation profiles were seen either for hollow current profiles produced with LH or for low current with peaked current profiles.
2.6.3. Intrinsic rotation experiments with ripple

Recently experiments have shown that the level of toroidal field ripple can have a major impact on plasma performance. In the light of this work, the design of the ferritic inserts in ITER has been re-evaluated. One issue that has not been previously investigated is the role of ripple in plasmas with little momentum input, e.g. Ohmic or RF heated plasmas. Although these plasmas have low performance in present day machines the rotation is believed to be comparable to that in ITER, where the momentum injection will be significantly lower and the intrinsic rotation is expected to play an important role. Furthermore, the ripple tends to drive rotation counter to the neutral beam driven rotation, thus reducing the already small rotation.

We have therefore performed experiments at JET to study Ohmic and RF heated plasmas with ripple levels ranging from 0.08% up to 1.5%; compared to expected levels in ITER of 0.5-1%. Rotation analysis of charge exchange measurements (from short NBI pulses used for diagnostic purpose only) as well as MHD mode numbers and frequency data, shows that ripple indeed changes the rotation of both Ohmic and RF heated plasmas. In both cases ripple drives counter rotation. In Ohmic plasmas rotation is changed roughly rigidly by the same amount in the core and at the edge suggesting the presence of an edge localised torque source. Observation of increased counter-rotation in Ohmic plasmas indicates a strong torque due to non-ambipolar transport of thermal ions. In ICRH plasmas the rotation change in the plasma core is larger (see figure) indicating that the torque source in this case would be less edge localised and that fast-ion as well as thermal ion effects may be involved. To test this hypothesis numerical modelling has been performed with the Monte Carlo codes ASCOT and SELFO to calculate the toroidal torques and the plasma rotation, driven by non-ambipolar transport of ions. In Ohmic discharges these torques appear when thermal ions are transported by the ripple in the outer parts of the plasma, while in ICRF heated plasmas the ripple-induced transport of fast ions provides also a source that extends further towards the plasma core.

Figure 2.6.1. Toroidal rotation profiles from charge exchange measurements for ICRF heated pulses with $I_p=1.5$ MA and $<B_T>=2.2$ T, $P_{\text{ICRF}}=3$ MW for two ripple levels. Top: pulse # 74688 with 0% ripple and $P_{\text{ICRF}}=3.1$ MW; bottom: pulse # 74686 with $P_{\text{ICRF}}=2.9$ MW. The plasma centre is at $R_0=3.02$ m, the ICRF resonance is off-axis on the high-field side at $R_{\text{res}}=2.71$ m.
2.6.4. Fast ion losses in ITER due to non-axisymmetric magnetic fields

The wall loads due to fusion alphas as well as NBI- and ICRF-generated fast ions have been simulated for ITER Reference Scenario-2 and Scenario-4 including the effects of ferritic inserts (FI), Test Blanket Modules (TBM), and 3D wall with two limiter structures. The simulations were carried out using the Monte Carlo codes ASCOT and SELFO. The ferritic inserts were found very effective in ameliorating the detrimental effects of the toroidal ripple: the fast ion wall loads are reduced practically to their negligible axisymmetric level. The thermonuclear alpha particles overwhelmingly dominate the wall power flux. In Scenario-4 practically all the power goes to the limiters, while in Scenario-2 the load is fairly evenly divided between the divertor and the limiter, with hardly any power flux to other components in the first wall. This is opposite to earlier results, where hot spots were observed with 2D wall. In contrast, uncompensated ripple leads to unacceptable peak power fluxes of 0.5 MW/m² in Scenario-2 and 1 MW/m² in Scenario-4, with practically all power hitting the limiters and substantial flux arriving even at the unprotected first wall components. The local TBM structures were found to perturb the magnetic field structure globally and lead to increased wall loads. However, the TBM simulation results overestimate the TBM contribution due to an over-simplification in the vacuum field. Therefore the TBM results should be considered as an upper limit.
2.6.5. Sawtooth destabilisation by kinetic effects

The restricted frequency range of the planned ICRH antennas in ITER are such that minority He3 is likely to be employed. Due to the negligible or reverse current drive contributions from minority He3, it was thought [M. Laxaback and T. Hellsten, Nucl. Fusion, 45, 1510 (2005)] that MHD control with toroidally propagating waves would not be viable. In contrast, the new explanation recently been given in Ref. [J P. Graves et al, Phys. Rev. Lett. 102, 065005 (2009)] for the sawtooth control mechanism does not rely on net driven current, and was therefore predicted to function even with minority He3. Consequently, minority He3 experiments in JET have been devised and carried out and interpreted with simulations in order to demonstrate the viability of sawtooth control using He3 minority in ITER, and to conclusively show that the previously assumed classical mechanism [V.P. Bhatnagar, et al, Nucl. Fusion 34, 1579 (1994)] cannot explain ICRF sawtooth control experiments in JET. The experiments demonstrate the viability of sawtooth control using ITER relevant He3 minority at low concentration. Simulation of RF induced currents have been confirmed to be negligible, as expected, but the recently developed fast ion mechanism [J P. Graves et al, Phys. Rev. Lett. 102, 065005 (2009)] has been analysed for these discharges, and shown to be responsible for sawtooth control (see figure). The success of these experiments in controlling sawteeth in JET greatly improves the prospect of using the planned ICRH system in ITER to shorten or lengthen sawteeth.
2.6.6. ITG turbulence, 2D electric fields, fishbone induced losses

**ITG turbulence threshold**
Experiments were carried out in the JET tokamak to determine the critical ion temperature inverse gradient length for the onset of Ion Temperature Gradient modes and the stiffness of Ti profiles with respect to deviations from the critical value [P. Mantica, et al, Physical Review Letters, 175002, 2009]. Threshold and stiffness have been compared with linear and non-linear predictions of the gyro-kinetic code GS2. Plasmas with higher values of toroidal rotation show a significant increase in R/LTi, mainly due to a decrease of the stiffness level. This finding has implications on the extrapolation to future machines of present day results on the role of rotation on confinement.

**Neoclassical particle losses with static 2D electric fields**
It has been proposed that the so called “convective cells“ or poloidally localised 2D electric fields could be at least partly responsible for the loss of particle confinement (i.e. density pump out) observed in experiments where non-ambipolar losses are expected to be present. These include both toroidal magnetic field ripple experiments (ion loss channel) and resonant magnetic perturbation experiments (electron loss channel). In such experiments the poloidally localised losses could lead to the creation of poloidal electric fields and thus to localised 2D potential.

We have been studying, both numerically and analytically, Neo-Classical (NC) losses in the presence of such an electrostatic and axisymmetric 2D potential. Analytical theory here covers presently non-collisional effects only. As a simulation tool for this analysis we use XGC-0 which is a guiding centre following Monte Carlo code developed for resolving NC transport. XGC-0 is able to follow both ions and electrons and it solves the radial electric field self-consistently from the radial current balance. On top of the existing functionality a simple model for a static 2D potential field was added either near X-point or at outer midplane.

In collisionless simulations without the self-consistent radial electric field we found that losses are not much affected by the 2D static potential unless the potential is located in X-point region. This is in line with our analytical understanding showing...
that losses increase towards the inner target due to the modification of the loss cone. When we turn on the self-consistent radial electric field and collisions the significance of location of the 2D potential becomes much smaller as for both outboard- and X-point potential losses become similar. For the case where we use 500 V negative potential (with plasma pedestal temperature 1 keV) the NC loss rate is roughly doubled. Our findings would, in principle, suggest that a 2D potential could be a candidate for explaining the density pump out. To get quantitative results one would, however, have to solve the 2D electric field self-consistently.

**Fishbone induced losses of ICRH accelerated fast ion**

A new collaboration has been started with the UKAEA modelling group to study interactions between ICRF accelerated fast ions MHD modes by coupling the SELFO code that calculates the ICRF ions and the HAGIS that describes the interaction of fast ions with MHD modes. Initial studies have shown that core localized Fishbone perturbations can drive losses of fast ions to plasma facing components.
2.7. Computational methods for fusion plasmas

J. Scheffel, A. Mirza (PhD student)

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

Theoretical and numerical understanding of RFP confinement
Theoretical and numerical models for reversed-field pinch confinement modelling need further refinement. Because of the complexity of the strongly nonlinear MHD phenomena and the strongly separated Alfvén and resistive time scales, relatively limited physical effects have so far been included in the numerical computations. As a result, we have not yet been able to reach reliable results on the operational limits of confinement in the RFP. The fusion potential of the RFP certainly is of significant interest, since an RFP reactor could feature high plasma beta (resulting in compact physical dimensions), using little or no beam or radio frequency heating and using normal magnetic coils, resulting in low capital costs and low cost of produced electricity.

Our numerical simulations of RFP plasmas in the advanced regime, where current driven tearing modes were eliminated by current profile control, have provided favourable scalings of on-axis temperature \( T(0) \propto (I^2 / N)^{0.74} \) and poloidal beta \( (\beta_p \propto (I^2 / N)^{-0.12}) \). To better understand and possibly find modifying effects to the limited energy confinement scaling \( (\tau_e \propto (I^2 / N)^{0.50}) \), improved modelling is required. The causes for the development to quasi-single helicity states with a superimposed strong \( m = 0 \) mode, the role of pressure driven instabilities and the possible stabilising mechanisms from two-fluid and kinetic effects are all addressed in this study.

In the project, we extend our earlier work to more precise numerical studies of the effect of pressure driven modes in the high beta scenarios. It has been claimed that resistive-g modes may be eliminated by inclusion of heat conduction in the energy equation. We test this conjecture, carried out in traditional delta-prime theory, by developing a GWRM (see below) code, which solves the resistive MHD equations in the entire plasma domain. In particular, it is essential to determine the effect at higher, reactor relevant beta values. Studies of two-fluid effects, in particular the Hall and diamagnetic contributions to Ohm’s law will be included. The effect of Larmor radius on the resistive g-modes in the RFP will be subsequently addressed using the Vlasov-fluid model.

The Generalized weighted residual method (GWRM)
During later years, we have developed new computational tools for initial-value problems. Employing generalized spectral residual methods, solutions to the initial-value partial differential equations are determined as finite, approximate Chebyshev polynomial expansions. The solutions, being semi-analytical in form, represent not only space but also time and physical parameters explicitly. Time stepping is avoided completely. This eliminates numerical stability restrictions on the time domain and
problems with vastly separated time scales can thus be efficiently solved, as shown in this application. The efficiency of the Generalized weighted residual method (GWRM) will be further addressed, in particular through an optimized use of subdomains. The project thus combines two vital areas of research in fusion plasma physics and computational physics.

A number of benchmarking tests of the GWRM has been carried out. For a set of pde’s with wavelike solutions on two separated time scales, the solution traces the slower dynamics using less computational time than both the explicit Lax-Wendroff scheme and the implicit Crank-Nicholson scheme. We have further shown that the GWRM provides accurate solution of the nonlinear Burger equation, which features shock-like structure for weak dissipation, using only a few Chebyshev terms. Also the temporal solution of the linearized, Fourier-decomposed, resistive and compressible MHD equations for a cylinder has been computed, confirming the applicability of the GWRM to systems of MHD equations.

As a spin-off result, a globally convergent and highly efficient root solver for systems of nonlinear algebraic equations has been developed. The Semi-implicit root solver (SIR) is shown to be efficient, robust and simple in comparison with the standard Newton method using line search and completely avoids landing on spurious roots.
2.8. Chaos and self-organization

M. Tendler

The radial velocities and radial scale lengths of high-density (turbulence-induced) filaments, named blobs, in the peripheral region of the High Field Side of the FT-2 tokamak are obtained using data from Langmuir probes set measurements. Also, the edge poloidal fluctuation velocity is obtained from cross-correlation analysis (plasma poloidal velocity is measured through cross-correlation of floating potential signals). The results report to new experiments with enhanced Lower Hybrid Heating (PLHH \( \approx 180\text{kW} \)) and a faster data acquisition system with 50 MHz sampling rate. The experimental results are compared with existing theoretical models. The magnitude of values found are comparable with the proposed models though the agreement with the predicted dependence between blob sizes and blob velocities is only in agreement with the analytical expression derived for the ballooning modes. We observe as well blobs with movement both in inward and outward radial direction, which is not yet understood theoretically since only the outward direction is explained.

A theoretical model for the toroidal rotation spin-up and generation of the positive radial electric field during the stochastization of plasma edge is put forward. During rise of the MHD activity the change of the edge radial electric field from negative (directed inward) to positive (directed outward) values has been observed on many devices. There are also experimental evidences that MHD activity is associated with the rise of magnetic island at \( q=3 \) flux surface in the core few centimetres inside from the last close flux surface (LCFS), also rise of smaller islands at \( q=4 \) and \( q=2 \) surfaces, and formation of a stochastic layer in the LCFS vicinity. The model for the origin of the positive radial electric field during the rise of the MHD activity is put forward. It is based on the assumption of the existence of a strong electron radial flux associated with the formation of an ergodic layer.

It is important to bear in mind that stochastization of the magnetic field and corresponding loss of electrons is typical for Resonant Magnetic Perturbation experiments used for ELM mitigation. The latter is extremely important for the success of ITER.
3. Plasma application projects

3.1. Plasma based waste treatment

*M. Tendler*

By application of a plasma based system to a wide range of possible feedstocks which are CO2 neutral, a clean syngas of high caloric value is produced from the organic substances simultaneously with a non-leachable vitrified lava from the inorganic substances.

The gasification process and the production of hydrogen (H2) in particular, will be the focus as it is especially useful in other industrial applications. Using an equilibrium approach, we aim to study the relations between the waste input and the output. We will focus on the thermodynamic approach. We will perform the calculation for some typical compositions of waste. The ultimate purpose is to provide a general framework for the properties and specifications for the facility that will be constructed by the Swedish cleantech company Plagazi AB.

The results will provide the advanced technology for the environmentally friendly treatment of hazardous wastes, biomass and low grade fuel. The driving force behind the task is to give priority to the environmental quality at affordable cost. Thus, the investigation of ways to increase the efficiency of the process is very important. A plasma based remediation system is the only technology that prevents undesired pollution in the by-products and end product (such as syngas or other gases). The problem to be solved is two fold: recuperate clean energy from waste and renewables without pollution at affordable cost. Such technique fulfils the objectives of sustainable development.

Today one of the main reasons that restrict use of plasma based methods is the cost of electrical energy. The crucial element is the plasma torch performance. Hence, the physics of modern plasma torches is very important.

High temperature plasmas can be used for treatment of solids, liquids, and gases. They can be employed for melting of waste and formation of stable non-leachable products. In addition, these plasmas can provide thermal decomposition of toxic molecules into simpler molecules that are benign. DC and AC plasma torches provide efficient means for melting solids or waste materials into magma or lava form, after a short time interaction between the plasma ($T > 2000 ^\circ C$) and the solids. Vitrification is a solidification process that combines semi-liquid waste with glass, resulting in a stable glass form. An important application is for remediation of radioactive waste. In this process, highly radioactive liquid and sludge is mixed with glass particles and heated to very high temperatures to produce a molten glass. When the mixture cools, it hardens into a stable glass that traps the radioactive elements and prevents them from moving through the air or water into the environment.
4. 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.
- MST, Univ. Wisconsin-Madison, USA: RFP physics.

**Plasma-wall interaction & Diagnostic development**
- EFDA-JET including the ITER-Like Wall Project (JET EP-2 Programme).
- EU Task Force on Plasma-Wall Interactions.
- FZJ, Institute for Energy Research-4, “Plasma Physics”, TEXTOR Team (Germany).
- University of Basel (Switzerland): 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.
- The Belgian Nuclear Research Centre, Mol: studies of contaminated first mirrors.
- 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.

**Theoretical fusion plasma physics & Computational methods**
- TEKES, UKAEA and JAERI on modeling of fast ion losses and transport with toroidal field ripple in JET, ITER and JT-60U.
- IPFN, CEA, UKAEA and TEKES on experiments and modeling of plasma rotation.
- CEA and CRPP on studies of minority cyclotron current drive for sawtooth control in tokamaks.
- ENEA and University of Uppsala modeling has been performed to predict the neutron energy during ICRH heating in JET.
- ENEA and Hellenic association on modeling ICRH during ITG studies and ITG threshold studies.
- Chalmers University on studies of fast particle driven MHD activity in tokamaks.
- Dalton Schnack, University of Madison, USA, collaboration on numerical MHD simulations, in particular the DEBSP code.
Chaos and Self-organisation

- INTAS project with the T-10 at the Kurchatov Institute in Moscow, TEXTOR-94 at the Forschungszentrum Jülich, FT-2 and TUMAN-3M at the Ioffe Institute in St. Petersburg, and CASTOR at the IPP Prague. Carried out by FOM, ERM/KMS, the University of Ghent and IPP CR with HUT Helsinki and St. Petersburg Politechnic.
- LHD Device, National Institute of Fusion Studies, Nagoya, Japan.
- EAST Tokamak, Institute of Plasma Physics, Hefei, China.
- K STAR Tokamak, Daejoon, Korea.
5. Education and research training

Courses given by the Division for Fusion Plasma Physics attract an increasing number of diploma, exchange and other international master students. For this reason, plans to launch new courses in Atomic physics for Fusion, Reactor technology and Experimental fusion plasma physics during 2009 have emerged.

Supervision of upper secondary school students was intense during 2008; some six groups with altogether about 20 students visited the lab and wrote their projects within the field of fusion. See also www.alfvenlab.kth.se/edu/gymsam.html for more information on collaboration with secondary schools. This is part of the Alfvén laboratory effort to strengthen connections with Stockholm schools in the fields of mathematics and physics with the aim of increasing student interest in these subjects.

5.1. Undergraduate education

Our new KTH Master of Science programme in Electrophysics, a collaboration between the divisions of Fusion Plasma Physics, Space and Plasma Physics and Electromagnetic Engineering started in 2008, with nearly ten students attending.

The Division of Fusion Plasma Physics also participates in the Erasmus Mundus European Master Programme in Nuclear Fusion Science and Engineering Physics (FUSION-EP). The programme started in 2006. Other participants are Ghent University (Gent), Universidad Carlos III (Madrid), Universidad Complutense de Madrid, Université Henri Poincaré (Nancy), and Universität Stuttgart.

Undergraduate level courses
An overview of the courses at the Division for Fusion Plasma Physics follows:


ED1110, Vector Analysis, 4.5 hp E, 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 hp E, ME M Sc programmes. 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.
ED2200 Energy and Fusion Research, 6 hp, 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 hp, 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 hp, 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 hp, M. Tendler. A course on self-organization as 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.

E12333 Elektroteknisk modellering, 7.5 hp, 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.

ED225X Master Thesis in Physical Electrotechnology, 30 hp. This course (Examensarbete) is based on a research project which is usually connected to the research activity of the Laboratory.

ED2250 Publication of Master Thesis in Physical Electrotechnology, 7.5 hp. Students that have reached particularly high levels in their thesis work, learns in this course how to produce a publishable report, including submission.

Master thesis projects completed during 2008

- Darya Ivanova, Development of power amplifier model and feedback controller design for active MHD mode control at the EXTRAP T2R reversed field pinch device
- Moseev Dmitry, Studies of crashes on T2R
- Chen Kui, Analysis of nonlinear processes in turbulent plasmas
- Jose Vicente de Almeida, Analysis of the plasma periphery fluctuation
- Karol Rohraff, Reflectometry as a tool to characterize stellarator
• Mochalskyy Serhiy, *Automatic processing of correlation reflectometry*

• Nepal Manich, *Characterizing mode coupling in turbulent plasma*

• Tesfaye Girma Wurgie, *Dynamics of hydrocarbon fragmentation in hot plasmas*

• Wondwossen Wubie, *Microwave technology*

• Maria Kirjaeva, *Anläggning för rening av vattnet med hjälp av elektrisk urladdning*

• Martin Löfstrand, *Att skapa förutsättningar för lärande på science center*

### 5.2. Graduate education

**EU training programme GOTiT**

The group was one of the applicants in the EU training programme GOTiT (Goal Oriented Training in Theory) covering 16 trainees at 6 institutes started in autumn 2008, where four of our students are involved and Torbjörn Hellsten participates in the training. The aim of the programme is to train modellers to the most recent mathematical and numerical methods and best practice in the use of high performance computers as well as to the state-of-the-art theoretical models developed and applied by the fusion community. Characteristics for the programme are monthly teleconference seminars, intense High Level Courses given at the members laboratories with participants from the whole programme.

**Graduate level courses**

A major revision of the syllabus and courses for postgraduate education has been carried out during 2008. In particular, the content has been extended to be more complete as well as becoming up to date with the present status of research. For all courses, course descriptions with explicitly written objectives have been produced. Our aim has here been to increase clarity and elucidate the course requirements, being beneficial for both students and teachers.

Courses for a Licentiate degree should cover 35-60 hp and thesis work 60-85 hp so that the sum becomes 120 hp. For a Ph. D. Degree, courses should cover 60-90 hp and thesis work 150-180 hp, with a sum of 240 hp. 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 hp or 30 hp from undergraduate courses may be included, respectively.

The main institutional work is carried out within teaching. Thus all teaching Ph D students take a 3 hp credits pedagogical course at KTH Learning Lab.
**Recommended graduate courses, with course responsible**

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Title</th>
<th>Credits</th>
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<tbody>
<tr>
<td>F2A5035</td>
<td>Motion of charged particles, collision processes and basis of transport theory</td>
<td>4.5-7.5</td>
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<td>3-6</td>
<td>J. Scheffel</td>
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<td>F2A5042</td>
<td>Magnetohydrodynamics, advanced</td>
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<tr>
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<td>1.5-4.5</td>
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<td>F2A5071</td>
<td>Plasma diagnostics</td>
<td>6</td>
<td>P. Brunsell</td>
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<tr>
<td>F2A5087</td>
<td>Research methodology and presentation techniques</td>
<td>3-4.5</td>
<td>J. Scheffel</td>
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<td>F2A5089</td>
<td>Computer methods in electrophysics</td>
<td>3</td>
<td>L. Blomberg</td>
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<td>F2A5093</td>
<td>Transport processes</td>
<td>3-6</td>
<td>M. Tendler</td>
</tr>
</tbody>
</table>

**PhD degrees 2008**

During 2008 no PhD degrees were awarded.
6. Personnel

Professor
James Drake
Torbjörn Hellsten
Jan Scheffel
Michael Tendler
Bo Lehnert (Emeritus)

Associate Professor
Henrik Bergsåker
Per Brunsell (Head)
Marek Rubel
Einar Tennfors (Emeritus)

Researcher
Jerzy Brzozowski
Marco Cecconello
Thomas Elevant
Thomas Johnson
Martin Laxåback

Post-doc
Lorenzo Frassinetti (Euratom Fellowship)

Administrator
Karin Demin, Jeanette Jansén, Ingeborg Mau

Research Engineer
Gunder Hägerström, Gunnar Kindberg

Technician
Håkan Ferm, Lars Westerberg, Jesper Freiberg

Ph D student
Abdul Hannan, Kerstin Holmström, Josef Höök,
M. Waqas M. Khan, Ahmed Mirza, Qaisar Mukhtar,
Erik Olofsson, Per Sundelin
7. Professional activity

7.1. Membership, honours, responsibilities

James R. Drake, Professor
- Member of the Royal Swedish Academy of Engineering Sciences.
- Chairman of the Academic Position Recruitment Committee for the Schools of Electrical Engineering, Information and Communication Technology, and Computer Science and Communication.
- Director of the Alfvén Laboratory Centre for Space and Fusion Plasma Physics.
- 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
- Head of the Swedish Fusion Research Unit, Association EURATOM-VR.

Torbjörn Hellsten, Professor
- Project leader for the IMP5 project in the ITM task Force.
- 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 Varenna - 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).

Jan Scheffel, Professor
- Director of undergraduate and graduate studies at the division of Fusion Plasma Physics, Alfvén Laboratory, KTH.
- Chairman of undergraduate studies for the M Sc programme in Engineering and of Education at KTH.
- Chairman of undergraduate studies for the Open Entrance programme at KTH.
- Vice director of the Fusion Plasma Physics division at the Alfvén Laboratory.
- Public relations officer for Swedish fusion research, (a task within EFDA European Fusion Development Agreement).
- Board member of the Plasma Physics Section, Swedish Physical Society.
- Board member of Vetenskapens Hus (House of Science, www.vetenskapenshus.se).
- Board member of the School of Electrical Engineering.
Michael Tendler, Professor
- Member of the Executive Committee, 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.
- Leader of the Alfvén team in the INTAS project.
- Member of the Program Committee of Annual Workshop: Role of Electric Fields in Plasma Confinement

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.

Henrik Bergsåker, Associate Professor
- Co-investigator for an EXTRAP T2R experimental project founded by VR

Per Brunsell, Associate Professor
- Division Head, Fusion Plasma Physics, EES, KTH.
- Principal-investigator for an EXTRAP T2R experimental project funded by VR.
- Member of S-STAC, Swedish Fusion Association Scientific and Technical Advisory Committee.

Marek Rubel, Associate 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).
- Swedish Research Council, evaluator of projects in the field of Atomic Physics, Molecular Physics, Plasma Physics and Fusion
- Member.European Microbeam Analysis Society,
- Vice-chairman Advisory Council of the Polish EURATOM Association,
- International Energy Agency (IEA) - Task Leader in the Implementing Agreement on Fusion Reactor Nuclear Technology.
- Workshop on Plasma Facing Materials and Components, Programme Committee member and Editor of the proceedings in Physica Scripta.
- Int. Workshop on Hydrogen in Fusion Reactor Materials, Int. Programme Committee member.
- Int. Vacuum Congress, Stockholm, Programme Committee member, section: Plasma Science & Technology.
- EU Task Force on Plasma Wall Interactions, member, contact person for the Swedish Euratom Association.
• EFDA JET: Task Forces: Divertor Physics, Fusion Technology, member, contact person for the Swedish Euratom Association.
• Leader for several projects within JET-EP-2 (ITER-Like Wall).

**Jerzy H. Brzozowski, Ph D**
• Coordinator for VR - EFDA JET Contacts (Scientific Contact Person).
• Session Leader in the JET experiment.
• JET Secondee, JET Operation Contract from 2004-03-29.
• Project Leader in JET-EP II, KT1 visible diagnostics and Polychromator Assemblies (until June 2008).

**Marco Cecconello, Ph D**
• Responsible officer for the low and high energy neutral particle analyzers at JET.

**Thomas Elevant, Ph D**
• Project Leader in JET-EP II, KT1 visible diagnostics and Polychromator Assemblies (from July 2008).

**Thomas Johnson, Ph D**
• Responsible officer for ion cyclotron resonance modeling tools PION, FIDO, LION and SELFO available at JET.
• Scientific Coordinator for experiments on intrinsic rotation experiments with ripple at JET.

**Martin Laxåback, Ph D**
• Programme Department Responsible Officer for Task Forces H (Heating), S2 (Advanced Scenarios) and M (Magnetohydrodynamics) at EFDA-CSU Culham.
• Member of the JET Programme Execution Committee.
• Responsible for the staffing under Scientific / Technical Orders of the JET Experimental Campaigns.
• Responsible for the scheduling of JET experimental sessions.
7.2. Academic and expert activity

**Opponent, examination committee**

*T. Johnson*

**Technical adviser, expert**

*J. R. Drake*
- Evaluation for professor appointment Princeton University, Princeton New Jersey, USA
- Evaluation for appointment as Director Max Planck Institute for Plasma Physics, Garching/Greifswald

**Journal referee**

*J. R. Drake*
- Nuclear Fusion (2)
- IEEE Conference on Decision and Control (1)

*T. Hellsten*
- Nuclear Fusion
- Plasma Physics and Controlled Fusion
- Physics of Plasmas

*P. Brunsell*
- Nuclear Fusion (1)
- Physics of Plasmas (1)

*M. Rubel*
- Fusion Engineering and Design
- Journal of Nuclear Materials
- Journal of Physics - Conf. Series (IoP)
8. Income & Expenditures

The accounts for Fusion Plasma Physics for the year 2008 are summarized in the table below:

**Income & Expenditure 2008**

**Income**

- **KTH**
  - Undergraduate education (GRU) 1 218
  - Research and research training (FOFU) 11 598

- **External research grants**
  - Swedish Research Council (VR) 2 681
  - European Framework Programmes (Euratom) 7 830
  - Other research grants 192

- **Other external income**
  - Orders industry 147

- **Total** 23 666

**Expenditure**

- Salary 13 646
- Travel 890
- Equipment 141
- Operation 1 034
- Rent 3 777
- EES central 313
- KTH central (HSG) 3 377

- **Total** 23 178

**Result**

488
9. Publications

*Article in Journal*


11. E Kaveeva, V Rozhansky, M Tendler, "Interpretation of the observed radial electric field inversion in the TUMAN-3M tokamak during MHD activity", Nuclear Fusion, vol. 48, 2008


**Article in book/collection**


**In Proceedings**

25. JR. Drake T Bolzonella KEJ Olofsson PR Brunsell L Frassinetti et al, "Reversed-field pinch contributions to resistive wall mode physics and control", 2008


29. S. Brezinsek, M.F. Stamp, J.P. Coad, A. Widdowson, Marek Rubel, "JET: campaign integrated dust and erosion", 11th ITPA Meeting (International Tokamak Physics Activity) on SOL and Divertor Physics, Nagasaki, Japan, Talk 5.7., 2008


31. P. Sundelin, Marek Rubel, Birger Emmoth, V. Philipps, G. Sergienko, "A test of fuel removal from plasma-facing components by ICRF-assisted nitrogen plasma


47. Marek Rubel, "Analysis of plasma-facing materials and components", 7th Kudowa Summer School: Fusion and Technology, Kudowa, Poland, 2008


50. Marek Rubel, "Mixed material layers on plasma-facing components from JET and TEXTOR", EU TF PWI, SEWG Meeting on Material Mixing, Garching, Germany, 2008


57. M. Rubel, P. Sundelin, G. De Temmerman, P. Coad, D. Hole, J. Vince, "An overview of comprehensive First Mirror Test for ITER at JET", Proc 18th Int. Conf. on Plasma-Surface Interactions in Controlled Fusion Devices, Toledo, Spain, 2008


63. E. de La Luna, D. Farina, L. Figini, G. Grossetti, S. Nowak, C. Sozzi, M. Beurskens, O. Ford, T. Johnson, JET EFDA contributors, "Recent results on the discrepancy between ECE and Thomson Scattering measurements at high Te in JET", Proceedings of the 15th Joint Workshop on ECE and ECRH, California, USA, 2008


71. J.R Drake, "Advanced RWM control methods on EXTRAP T2R", US-Japan Workshop on MHD Control, Magnetic Islands and Rotation http://fusion.gat.com/conferences/mhd08/ held at the University of Texas, Austin, Texas, USA, AT&T Executive Education Conference Center, 2008

Master's Thesis


73. Jose Vicente de Almeida, “Analysis of the plasma periphery fluctuation”, 2008

74. Karol Rohrff, “Reflectometry as a tool to characterize stellatorator”, 2008


77. Tesfaye Girma Wurjek, “Dynamics of Hydrocarbon fragmentation in Hot plasmas”, 2008

78. Wondwossen Wubie, “Microwave Technology”, 2008

79. Darya Ivanova, “Development of power amplifier model and feedback controller design for active MHD mode control at the EXTRAP T2R reversed field pinch device”, 2008

80. Maria Kirjaeva, ”Anläggning för rening av vattnet med hjälp av elektrisk urladdning”, 2008


Technical Reports
