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1. Introduction

The Division of Fusion Plasma Physics participates in the worldwide effort to harness fusion energy for electric power generation. Fusion power has potential to provide a long-term solution to the world’s energy and climate problem. The international effort in realising fusion power is now focussed on the ITER experimental reactor in France. The name – ITER – stands for “the way” in latin, and it is to be understood as “the way to fusion energy”. The project is shared between seven partners around the world – EU, USA, Japan, China, Russia, India, and Korea. ITER construction started in 2010 and two-thirds of the project construction goals are now completed. The first experiments are planned to take place in 2025.

The involvement of the Division in the European fusion research programme has been maintained at a high level in 2019. The programme is carried out during the H2020 framework programme through a co-fund grant from Euratom, awarded to the EUROfusion consortium, formed by 27 partners distributed throughout Europe. Vetenskapsrådet is the Swedish member of the EUROfusion consortium administrating the participation of research groups at Chalmers, Uppsala University and KTH. At KTH, research groups from the EECS and SCI schools contributes to the programme, with the Division of Fusion Plasma Physics acting as the coordinator.

The contribution of the Division in the EUROfusion work programme during 2019 has been in Work Packages WPCD, WPEDU, WPENR, WPJET1, WPJET2, WPMAT, WPMST1, and WPPFC. The scope has been code development, research education, enabling research projects, experimental campaigns at JET, JET plasma components, fusion materials, experimental campaigns at the medium-size tokamak facilities AUG and TCV, and plasma facing components.

In total nine PhD students have been active at the Division during 2019, contributing greatly to the stimulating work environment and the productive research. This year, the research projects in the area of plasma-wall interactions and plasma-facing components has resulted in the completion of two PhD theses. The projects has focussed on the topics of surface analysis method development and impact of surface structures on deposition and erosion in tokamaks.

Per Brunsell
Head, Fusion Plasma Physics
2. Research projects

2.1. EXTRAP T2R device

The EXTRAP T2R device produces a hot and dense plasma that can be utilized also for basic plasma science, research on space plasmas, investigation of technical plasma applications, or plasma based material research. The device has excellent capabilities for material studies, which are not yet fully utilized. There are a number of access ports, through which material samples can be introduced into the plasma edge. Translation systems for insertion and extraction of material samples are available, also enabling in-vacuo transport of samples for post-exposure analysis elsewhere. Several ion beam based analysis methods are available through our collaboration with the Tandem Accelerator facility in Uppsala University.

EXTRAP T2R is a toroidal, circular cross-section plasma device with major radius 1.24 m and minor radius 0.183 m. The device operates as a reversed-field pinch, with plasma current of the order 100 kA, plasma density around $10^{19}$ m$^{-3}$, electron temperature around 300 eV and pulse lengths up to 0.1 s. A number of plasma diagnostic systems are available at EXTRAP T2R, such as magnetics, interferometer, Thomson scattering, SXR detectors, visible and ultra-violet light spectrometers, bolometers, Langmuir and collection probes.
Fusion research activities at the EXTRAP T2R are focused on active MHD control, in particular magnetic feedback control of resistive wall modes (RWM). A main aim of the research is to develop methods and physics understanding required for MHD control, while a particular goal is to develop control methods suitable for tokamaks that incorporate MHD control coils, such as ASDEX Upgrade and JT60-SA. The underlying motivation for the activity is the need for active MHD mode control in ITER advanced operation scenarios and in future tokamak reactor designs. The active control system has also been utilized for studies of applied Magnetic Perturbations (MPs) and for development of Error Field (EF) detection.

The main components of the MHD mode control system at EXTRAP T2R is an array of active control coils placed outside the conducting shell, and a corresponding array of sensor coils placed inside the shell.

![Control System Diagram]

The main features of system are:
- 128 magnetic flux loop sensors at 4 poloidal and 32 toroidal positions inside the shell.
- 128 active saddle coils at 4 poloidal and 32 toroidal positions outside the shell.
- Pair-connected at each toroidal position to 64 independent “m=1” coils
- Integrated digital controller unit including CPU board, ADCs and DACs.
- Control algorithms implemented in software.

The active coils are driven by a set of audio amplifiers with output power of 800-1200 Watt. Control algorithms are implemented in a Linux based PC with input/output boards connected via PCI bus. The input/output modules transfer data to a shared buffer in the host PC by Direct Memory Access. There are two data acquisition modules providing 16-bit analog-to-digital (ADC) for a total of 128 simultaneously sampled channels, and one digital-to-analog (DAC) module with 64 output channels. The minimum cycle time of the system with this channel configuration is of the order of 20 microseconds. Feedback control algorithms are written in C or C++. Various types of controllers have been implemented, such as the conventional Proportional-Integrating-Derivative (PID) controller, the Linear-Quadratic-Gaussian (LQG) control as well as modern model based controller algorithms such as the Model Predictive Controller (MPC).
2.2. Experimental validation of RWM models for active control  

*P. Brunsell, E. Saad (PhD student)*

The plasma model used in this work is the linearized ideal MHD model in cylindrical geometry. The thin shell dispersion relation for the resistive wall mode can be written for every \( \{m, n\} \) harmonic as

\[
\gamma_{mn} \tau_w = \left( \frac{r}{b_r m n} \frac{d}{dr} \right) (r_{w+} - r_{w-}).
\]

The resistive wall mode growth rate, \( \gamma_{mn} \), is obtained by solving the plasma equations with the constraint RWM dispersion equation. The experimental Fourier decomposed radial magnetic field may be compared with the theoretical time evolution without plasma (vacuum) and with plasma. For the case with only vacuum the time evolution of the radial magnetic field at the wall may be expressed according to

\[
\tau_{mn} \frac{db_r^w}{dt} + b_r^w = b_r^{ext}.
\]

This equation dictates the exponential settling with the rate \( \sim \frac{1}{\tau_{mn}} \) and

\[
\tau_{mn} = -\tau_{m n} w K_m^w (1 + (m R_0)^2 (nr_w)^{-2})^{-1}.
\]

The theoretical time evolution of the radial magnetic field at sensor position \( b_r^w \) obtained for the plasma case may be expressed as

\[
\tau_{mn} \frac{db_r^w}{dt} - \gamma_{mn} \tau_{mn} b_r^w = b_r^{ext}.
\]

The experiment proceeds to apply a step coil current waveform to all actuators with the objective to excite a given toroidal mode number \( n \). The direct excitable mode numbers in this device are \( n=\{-16, \ldots, 15\} \) and due to sideband it is possible to excite higher order modal numbers. The signal from the sensor array may be Fourier decomposed according to the expansion

\[
b_r^w(r, \theta, \varphi, t) = \sum_m \sum_n b_r^{w,m,n}(r, t) e^{i(m\theta + n\varphi)}
\]

for poloidal mode number \( m \) and toroidal mode number \( n \). experimental data.

The experiment proceeds to validate the plasma-actuator response which are plotted in Fig. 2.1.2 for toroidal mode \( n=\{-15,14, -11\} \) that are examples of modes with different characteristics. These are plotted each for the case: without perturbation, with perturbation, vacuum case and the difference between the first two mentioned in reversed order. The exponential fit is done for this difference due to field errors. Field errors occur due to geometrical imperfections that resonate with the plasma and is modelled as an additive reproducible unknown magnetic field perturbation for EXTRAP T2R. The toroidal mode \( n=-15 \) is a resonant and initially stable mode and it can be seen that the magnetic field strength is larger compared to the vacuum case. The magnetic field rise time is different for the vacuum case and the plasma case. The rise time due to plasma has two distinct phases. The second unstable phase occur due the termination of plasma rotation. The toroidal mode number \( n=14 \) is a non-resonant stable mode and the magnetic field strength is lower than the only vacuum case during the plasma pulse discharge and after conforming to the vacuum case in steady state. The toroidal mode \( n=-11 \) is a non-resonant unstable mode. The plasma and the vacuum case may be fitted by exponential functions, as shown in Fig. 2.1.3. The magnetic field averaged over the
sensor area is a sum of odd modes $m=\{1, -3, 5\ldots\}$ due to aliasing but the contribution from higher mode number is small. Thus the vacuum case is fitted by a sum of only $m=1$ and $m=-3$ modes. The vacuum case, for fitting two modes $m=1, m=-3$, the following fitting function is used $b_T = \frac{b_{vac}}{(1+r_{31})((1-e^{C_1t}) + r_{31}(1-e^{C_1g_{31}t}))}$, where $b_{vac}$ is the vacuum steady state field. The parameters $g_{31} = \frac{r_{31}}{r_{3n}}$ and $r_{31} = \frac{b_{3n}}{b_{1n}}$ are obtained from theoretical model of sensors and coils.

Figure 2.1.2 Amplitudes of $n=\{-15,14-11\}$ without perturbation, with perturbation, vacuum and $\Delta$

Figure 2.1.3 Amplitudes of $n=\{-15,14-11\}$ with exponential fit for $\Delta$
2.3. 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) International Atomic Energy Agency (IAEA), (iv) Implementing Agreements of International Energy Agency (IEA). It is demonstrated by the participation in:

- EUfusion Work Programme:
  - Work package JET2: Analysis of Plasma-Facing Components from JET
  - Work package PFC: Plasma-Facing Components for ITER
  - Work package MAT: Functional Materials for DEMO

- Broader Approach Work Programme:
  - IFMIF Project Committee, Rokkasho, Japan
  - Material studies at Int. Fusion Energy Research Centre (IFERC), Rokkasho, Japan

- ITPA, IAEA and IEA activities.

Experimental work was carried out at home laboratory, JET, Forschungszentrum Jülich, Ruder Boscovic Institute in Zagreb, Warsaw University of Technology and at IFERC. The research programme is concentrated on:

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

2.3.1. First Mirror Test in JET for ITER: Overview after Three ILW Campaigns

Metallic mirrors will be essential components of all optical diagnostics and imaging techniques in next-step fusion devices. Transmission of light signals will rely on mirrors which are the first components of periscope-shaped systems to guide the light in the shielding block. According to the current plan, in the International Thermonuclear Experimental Reactor (ITER) there will be about 80 first mirrors. Therefore, their performance is crucial for reliable plasma diagnosis and safe operation. The main concern is the reflectivity degradation by phenomena arising from plasma-surface interaction (PSI): erosion and deposition. For that reason, a broad research program has been carried out both in tokamaks and in laboratories: exposures of mirrors made of different materials, detailed surface studies, development of cleaning and protection methods.
First Mirror Test (FMT) at JET for ITER started in 2002 with planning of mirror location and the design of test specimens and mirror carriers. During five campaigns, two in JET-C and three in JET-ILW over 100 mirrors were tested. The aim of work was to provide an overview of results obtained from the mirrors exposed during: (i) the third ILW campaign (ILW-3, 2015-2016) and (ii) all three campaigns (ILW1-3, 2011-2016).

**Experimental**  Test mirrors were placed in pan-pipe shaped cassettes installed on the main chamber wall and in the divertor: base under the bulk tungsten tile and in shadowed regions of the inner and outer divertor. The cassettes have several channels (2, 3 or 5) each housing one mirror with a small holder to fix the mirror in the channel. For a given cassette one mirror was placed at the mouth (0.0 cm), while other specimens were sitting deeper, e.g. 1.5, 3.0 cm, from the entrance, thus at the longer distance from plasma. Standard channels have square 1×1 cm cross-section. This has been the feature of all cassettes in the divertor. Only the construction of a five-way cassette installed at main chamber during ILW-3 was designed differently in order to test protection of mirrors against deposition by using baffled structures; a series of hollow (0.57 cm diameter) baffles, as shown in Fig. 2.3.1-1. One mirror placed at the entrance, two mirrors in baffled channels (1.5 and 4.5 cm) and, for comparison, two others were in straight channels of circular cross-section, also 0.57 cm in diameter. The exposure time of all three ILW campaigns (ILW1-3) was 63.52 h of plasma operations including 19.67 h of limiter discharges and 43.85 h of X-point plasma. For the last single campaign (ILW3), this was 23.33 h, 4.86 h and 18.47 h, respectively.

![Five-way cassette from main chamber wall. From the left: mirror at 0.0 cm at the cassette mouth placed in the standard square channel; 1.5 cm deep circular and baffled channels and a similar set with mirrors at the depth of 4.5 cm.](image)

Optical properties of mirrors were examined before and after plasma exposure. Total and diffuse reflectivity measurements in the wavelength range of 300-2500 nm and 400-1600 nm, the latter range in the case of mirrors with peeling-off layers. Surface composition of mirrors was analyzed by means of accelerator-based ion beam techniques at the 5 MeV Tandem Accelerator Laboratory (Uppsala University, Sweden). Concentration of species was measured using time-of-flight heavy ion elastic recoil detection analysis (ToF-HIERDA). Atomic force (AMF) and scanning electron microscopy (SEM) with energy-dispersive x-ray spectroscopy (EDS) were used to determine surface features.
**Divertor mirrors.** Images in Figure 2.3.1-2(a)-(b) show the appearance of two mirrors from the divertor. The colorful pattern indicates inhomogeneous deposition, while on the other mirror the co-deposited layers peels-off. On the contrary, mirrors exposed to plasma in the main chamber remained clean, i.e. free from co-deposited layers.

![Divertor mirrors](image)

Figure 2.3.1-2. Optical microscopy images of mirrors after ILW1-3: (a) non-uniform co-deposits on the mirror exposed in the divertor base; (b) flaking layer on the inner divertor mirror.

Graphs in Figure 2.3.1-3 (a) and (b) show total reflectivity of the outer divertor mirrors exposed during ILW-3 only and during all three periods ILW1-3, respectively. Initial reflectivity of the Mo mirror is shown on all graphs for comparison to post-exposure values. One perceives several general features: (i) distinct loss of reflectivity, 20-80 % from the initial value, for all mirrors and (ii) stronger loss of optical performance for mirrors exposed during all three campaigns; (iii) surfaces with flaking layers are, as expected, characterized by is the lowest reflectivity of all measured. The reflectivity of most mirrors is lower in short wavelength (UV and visible) and gradually increased in near infrared (NIR) range. Data presented above regarding reflectivity are fully consistent with all results obtained until now in JET-C and ILW.ILW for the divertor mirrors. There have been some differences between specimens, but the general outcome has always been the same: complete loss of reflectivity because the co-deposition covers the optically active layer of Mo (10-20 nm) and this turns mirror to a deposition monitor.

![Reflectivity graphs](image)

Figure 2.3.1-3. Total reflectivity of mirrors from the outer divertor after: (a) ILW-3 and (b) ILW 1-3.
Co-deposits on mirror surfaces contain a mixture of materials deposited during the plasma exposure. In Figure 2.3.1-4, there are two examples of depth profiling with ToF-HIERDA for mirrors from the divertor base at the same depth of 1.0 cm exposed during a single and three campaigns. The main components of the layers are: beryllium (41-50%) and oxygen (35-42%). This could suggest the presence of a beryllium oxide layer with the admixture of H, D, C, N, steel and Inconel constituents (Ni, Cr, Fe) and tungsten. After ILW-3 following amounts were determined: $1.9 \times 10^{16}(H)$, $1.3 \times 10^{17}(D)$, $2.4 \times 10^{16}(C)$, $4.1 \times 10^{16}(N)$, $2.1 \times 10^{16}(Ni)$ and $1.3 \times 10^{16}(W)$. The concentrations of respective species after ILW1-3 are about 3 times higher. It should be stressed that the C content is very low, both the total amount and relative to other species, especially Be.

![Figure 2.3.1-4. ToF-HIERDA depth profiling of co-deposits on mirrors from the divertor base at 1.0 cm exposed during: (a) ILW-3 and (b) ILW1-3.](image)

Micrographs documenting deposits and dust particles obtained in detailed examination of mirrors retrieved after ILW-3 and all three campaigns are shown in Figure 2.3.1-5 (a)–(f).

![Figure 2.3.1-5. SEM images of divertor mirror surfaces: (a) general view of the co-deposited layer with a large density of dust particles and (b) steel droplet, outer divertor, 1.5 cm, ILW1-3; (c) Be-rich co-deposit with C, N, O outer divertor, 1.5 cm tested during ILW-3; (d) Be droplet on rough co-deposit, (e) tungsten splash and (f) tungsten ball-like structure on the mirror from outer divertor 0.0 cm tested during ILW-3.](image)
**Mirrors from the main chamber.** Graphs in Figure 2.3.1-6 (a) and (b) show respectively the total and diffuse reflectivity of mirrors from the main chamber wall. Initial characteristics are also plotted for comparison. As inferred from Fig. 5(a), the total reflectivity is maintained in the entire examination range. There is a slight relative decrease (2-3%) in near infrared only for the mirror from the cassette entrance (0.0 cm), while there is even relative improvement by 2-10% in the ultra violet and a slight positive trend is in the visible range (< 900 nm) on other mirrors. This improvement is due to the removal of Mo oxide layer which was formed on surfaces before installation of the mirror. This reduction process of the oxide may be associated purely with exposure to hydrogen-rich atmosphere, but it also may indicate erosion by charge exchange neutrals. There is lack of any meaningful difference in reflectivity between mirrors from the baffled and circular channels.

![Figure 2.3.1-6. (a) Total and (b) diffuse reflectivity of mirrors from main chamber wall. The numbers in legend are distance (cm) of mirrors from the cassette entrance.](image)

As shown in Figure 2.3.1-6(b) the initial diffuse reflectivity ($R_d$) was on the level 1.3% in the UV range and 0.7-0.9 % in the rest of the spectrum. Analysis of surface composition shows that the main impurity is carbon at the level of $1-3\times10^{16}$ cm$^2$. It is immediately stressed that these concentrations are very small (close to the detection limits) corresponding to the layer thickness of 5 nm. The content of other constituents is even smaller. Be, N, O and Ni are on the level of $0.1-2\times10^{16}$ cm$^{-2}$, while deuterium and tungsten are below the detection limit of $5\times10^{13}$ cm$^{-2}$. This suggests that the carbon presence may be related not only to tiny amount of deposition from the plasma, but also to other sources including contact with during mirror installation, pump-down phase and retrieval procedure.

**Concluding remarks.** Results obtained for 15 test mirrors (main wall and divertor) after ILW-3 and 10 divertor mirrors exposed during ILW1-3 provide two sets of messages for diagnostic components in next-step devices. The pessimistic side is such that all tests in the divertor (JET-C and JET-ILW) consistently show that all mirrors, independently on the location completely lose reflectivity because of co-deposition. The growth rate of such layers in JET-ILW with Be as the main component in co-deposits is about 20 times smaller than with carbon PFC, but the final result is equally devastating. If such effects would occur in a reactor with similar intensity then neither periodic cleaning nor replacement of mirrors would be considered as an effective solution. On the optimistic side one finds main chamber mirrors with a very small change of the total and diffuse reflectivity for mirrors placed deep in the channels. It is about the design and construction of diagnostic channels to ensure optimal outcome. This includes identification and elimination of negative factors which may influence the surface state of mirrors.
2.3.2. Deposition on wall probes in JET with ITER-Like Wall

Introduction Plasma-wall interactions, material migration and the resulting surface modification of plasma facing components are identified as key elements in the preparation for future fusion devices. To facilitate material migration studies in the Joint European Torus (JET) with the ITER-like wall, a number of probes have been installed in the divertor and on the main chamber wall. They are retrieved for ex-situ analyses during major shut-downs. The primary aim of this work was to provide an account of the atomic composition of deposited layers on components retrieved from remote corners in the JET divertor between 2012 and 2017, i.e. after three ITER-like wall campaigns (ILW-1 to ILW-3).

Experimental The analysed components are 76 mm long stainless steel covers for quartz microbalance (QMB) deposition monitors. Two sets of covers for QMBs numbered 1, 2, 3 and 5 were studied. The first such set was present in JET between 2012 and 2014, during ILW-2, except the cover for QMB1 which was present from 2010 to 2014, during ILW-1-2. The second set was present during ILW-3 and removed from JET in 2017. QMB1 was located on the divertor carrier in Module 13 IW behind Tile 3. QMB2 and QMB3 were similarly positioned but in Module 2 IW. QMB5 was located in Module 2 outer wide (OW) behind Tile 7.

Results and discussion Four points, as shown in Figure 2.3.2-1, were selected for ToF-ERDA measurements on the QMB covers from ILW-3. The shutter was functioning properly for QMBs 1, 2 and 3 during ILW-3, and was open during 19,500 s, 25,700 s and 28,200 s respectively for these three units. Ref. [5] gives further information on how the QMB cover is shielded from particle impacts by the shutter in open and closed mode. For QMB 5, the shutter was opened permanently early in ILW-3 (halfway into the JET C35 campaign), and the open shutter time was therefore only a little less than the total divertor plasma time of ~67,000 s. Graphs in Figure 2.3.2-2 show representative depth profiles from QMB3. The large Be fraction shown in the figure is measured at most of the points on the QMB covers from ILW-3. While all other studied components have shown similar amounts of Be and O, we here see up to several times more Be than O. An especially Be-rich deposit is present at the 41 mm point on QMB5, with around 70 at.% of Be throughout the entire layer thickness of approximately 5e18 at/cm². We further note that a high atomic fraction of D is measured, typically between 10 and 20 at.% (without ion induced release compensation) near the surfaces of these QMB covers. This is higher than what is seen on both SB from ILW-3 and QMB covers from ILW-1-2, but similar to the levels in the C rich layers on SB from ILW-1.

Figure 2.3.2-1. Stainless steel covers for quartz microbalance deposition monitors from ILW-3. Dark blue ovals indicate the positions of ToF-ERDA measurement points.
Concluding remarks Analyses of co-deposits on QMB covers retrieved from remote corners in the JET-ILW divertor have shown that the layer thicknesses approximately 350 nm (QMB5 from the outer divertor in ILW-3). The main components of the co-deposits on QMB covers were Be and O. The elements occurred in similar concentrations possibly indicating the formation of BeO. Among the highest atomic fractions of D were found in the Be-rich layers with less O on QMB covers from ILW-3. We conclude therefore that the presence of C is not essential for D retention. Due to the fact that a larger fraction of D occurred in the layers where there was less O we may hypothesize on the formation of beryllium deuteride which could lessen the potential for O gettering in a Be-rich layer.
2.4. Theoretical fusion plasma physics

T. Johnson, P. Vallejos (PhD student)

In collaboration with the EUROfusion member CCFE, CEA, CIEMAT, ENEA, EPFL, IPP, IST, LPP-ERM-EMS, VTT, Wigner RCP, with PPPL, F4E and ITER-IO.

The fusion plasma physics theory group 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 is particularly active in developing numerical models and codes for studies of Ion Cyclotron Resonance Heating (ICRH), and in validating them against experiments. This work is well integrated into the European fusion program through participation in the integrated modelling activities in EUROfusion/WPCD and the exploitation of the JET and MST1 facilities.

The main codes developed by the group are FIDO, SELFO, SELFO-light, RFOF, FOXTAIL and FEMIC. PION was the first self-consistent code for modelling ICRH and NBI heating using simplified models and is used routinely at JET. For more advanced modelling the Monte Carlo code FIDO was developed to calculate the distributions of resonant ions taking into account effects of finite orbit width, RF-induced spatial transport and interaction between MHD waves and fast ions. By coupling the FIDO and wave code LION the self-consistent ICRH code SELFO was developed. The latest development is the FEMIC codes is combines state of the numerical techniques available in COMSOL in combination with advanced plasma physics implemented in MATLAB.

2.4.1. Integrated modelling within the EUROfusion-WPCD

The group participates in integrated modelling within EUROfusion under the Work Package for Code Development (WPCD), where Thomas Jonsson is the coordinator for the development of the European Transport Solver (ETS) in IMAS, as well as the activities related to Heating and Current Drive (H&CD).

Figure 2.4.1. The frontpage of ETS workflow.

Several deliverables for the ETS are set for the end of 2020, including commission deliverables. Thus, the work in 2019 include both planning and extensive developments of both the ETS and
the platform in which it will operate. A first release was created during October and a presentation with encouraging results were given at the ITER Modelling Expert Group meeting in November.

Within the heating and current drive activities the group was responsible for delivering a coupling between the Fokker-Planck and wave codes. This was achieved by supplying the LION code with a bi-Maxwellian representation of the distributions calculated by the Fokker-Planck codes. This development was performed in IMAS, thus it allows us to connect different LION with a number of Fokker-Planck codes and to include both NBI populations and ICRF accelerated populations.

2.4.2. New ICRF code FEMIC

A new ICRF wave solver, FEMIC has been developed. The code uses COMSOL Multiphysics for calculating wave field, in combination with a plasma model implemented in MATLAB and connected to COMSOL using Live-Link for MATLAB. The code has been used to study the effect of poloidal phasing of ICRF antennas. The work was published in [P. Vallejos et al 2019 Nucl. Fusion 59 076022]. The effects of poloidal phasing are important for ITER, since the ICRF antenna design enforces a 90-degree phase difference between the upper and lower straps, while present day antennas all run without such a phase difference. Modelling with FEMIC has shown that in ITER the effects of poloidal phasing on the coupling can be significant, while the effect on the heating profiles are localised to a small area in the very centre of the plasma, typically inside rho<0.1. In addition, the effects of the poloidal phasing depend sensitively on the width of the pedestal. The ITER ICRF system has only two options; the upper straps can have a phase that is either ahead or behind the phase of the lower straps. We show that a significant improvement could be achieved when the phase of the upper straps is ahead of the lower straps.

The potentials for studying poloidal phasing in the WEST tokamak has been investigated using the FEMIC code [T. Jonsson, 46th EPS Conference on Plasma Physics, 2019]. The study show that the conditions for poloidal phasing in WEST is very different from ITER due to the dimensions of the machines. Specifically, the wave propagation in the smaller device WEST is characterised by a higher Fresnel number and a weaker damping. Thus, the waves have less of a beam character and exhibit eigenmodes patterns that makes the impact of the antenna phasing less important.

Figure 2.4.2. Real part of the right-hand-polarised electric field component of the ICRF wave field in ITER. The simulation is performed with a 90-degree phase shift between the upper and lower antenna straps.

Figure 2.4.3. The ICRF wave field in WEST show eigenmode patterns.
The FEMIC code was also applied to model waves in full 3D geometry for the WEST tokamak [B. Ljungberg, 46th EPS Conference on Plasma Physics, 2019]. 3D wave modelling in tokamak is computationally very demanding, thus the main purpose of this work was to investigate what resolution can be achieved with present computational resources, what would be needed for more detailed calculations, but also to identify efficient ways optimise the grid.

2.4.2. JET and MST1 Work programmes

During 2019 the KTH group has participated in the analysis of JET experiment on plasma transport and in the preparation for the coming JET D-T campaigns [E Joffrin et al Nuclear Fusion 59 (11), 112021]. The work has been performed though ICRH modelling with the SELFO code and with the European Transport Solver, ETS.

The modelling of ICRH fast ion production in ASDEX-Upgrade using the SELFO code was completed and published. This required discharge analysis, as the fast ion populations are highly transient, and predictions of the 4D distributions in a format suitable for coupling with MHD codes like HAGIS and CASTOR-K. Results from SELFO were also used in the code LIGKA. The SELFO results were compared with experimental results showing that the transient response of the fast ion pressure was sufficiently fast to explain, in combination with estimates of the change in the Landau damping, the rapid control of the changes in the TAE stability when Electron Cyclotron (EC) heating was switched on or off. [Sharapov et al, Plasma Phys. Control. Fusion 60 (2018) 014026].
2.5. Computational methods for fusion plasmas, with a focus on time-spectral methods

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In collaboration with:
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In spite of their strong potential, time-spectral methods have not yet been extensively studied nor explored systematically for solution of initial-value problems in physics. The need for efficient multiple time and spatial scale fusion plasma simulations is clear. As an example, turbulence at high Reynolds or Lundquist numbers is presently addressed by so-called gyrokinetic codes that are allocated millions of CPU hours for parallel processing on supercomputers. If there is a new avenue that may alleviate the requirements on computer power for these crucial problems, it is of importance to explore it.

The present project concerns a time-spectral, computational approach termed the Generalized Weighted Residual Method (GWRM [1-3]). In this method, traditional finite time differencing is replaced by a spectral representation of the time domain. The computed solutions are truncated, approximate semi-analytical Chebyshev polynomial series valid for all time, spatial and, optionally, physical parameter domains and are immediately tractable for mathematical analysis. Scalings in physical parameters are thus obtainable in a single computation. The GWRM has during 2019 been successfully employed for solving an extensive set of problems, including drift wave turbulence. For the first time, we have shown that time-spectral methods can be successfully employed to solve problems in kinetic plasma theory.

The GWRM is also expected to be of commercial interest; it has the potential to provide the engine in a new generation of time-efficient solvers for nonlinear large scale simulations relating to subjects like fluid mechanics and meteorology. In a recent article [4] we show that chaotic elements of numerical weather forecasting may be modelled more efficiently with the GWRM than by standard time-marching methods. Now facing challenging fusion physics implementations, we develop essential elements like adaptive time and spatial domains in 2D and 3D and strong parallelisation of the time domain.

During 2019, our main emphasis has been on the following:

Tokamak turbulence
The diffusion of plasma across flux surfaces can be partly explained by classical/neo-classical effects. It is widely known that also anomalous transport, due to turbulence, plays an important role. One of the unstable modes that leads to microturbulence is the Ion Temperature Gradient (ITG) drift mode, also called the $\eta_i$ (ratio of density scale length and temperature scale length) mode. It is excited by universally present temperature and density fluctuations in the plasma.

To analyse the ITG drift wave modes, we employ the two-fluid Weiland model. In Figure 2.5.1 we show a 2D GWRM computation of the perturbed electrostatic potential with Cyclone base case parameters. From the computational results we can verify the fastest growing ITG mode $\gamma_{ITG} = 0.3$ and the existence of so-called “streamers”. These are long radial structures in the linear growth rate phase that lead to enhanced turbulence. It has been shown that zonal flows tend to break these structures and dampen the turbulence to a saturated state.
Figure 2.5.1 The perturbed electrostatic potential calculated in a box of 100×100 Larmor radii and with Cyclone base case parameters; \( \eta_i = 3.14, \tau = 1.0, \) and \( \epsilon_n = 0.909. \)

The 2D code has also been restructured so that very little memory is used as compared to older codes. This allows new codes to solve non-linear 2D problems on large scale physical problems. A massive improvement is given by the potential for parallelization so that multiple CPUs/computers can solve for the individual spatial subdomains in parallel. Recently we have invented a method to drastically reduce the number of computational operations and the memory requirements for computing the Jacobians required for the GWRM root solver. For guaranteed convergence, the GWRM requires simultaneous information from all parts of the computational domain. A primitive algorithm would then simultaneously involve all the Chebyshev coefficient equations of all the subdomains. This would be costly - with \( N \) being the total number of Chebyshev modes the memory requirements scale as \( N^2 \) and computational CPU time scales as \( N^3 \), being prohibitive for advanced problems. With present optimization of the GWRM we have however obtained the very favourable scaling \( N^{1.4} \) for CPU time.

**GPU acceleration**

Nonlinear GWRM computations require computing the product of two Chebyshev series. The resultant Chebyshev coefficients \( c_k \) are computed by performing several summations (of multiplications) in each element of \( c \), this makes it a great candidate for GPU acceleration with the so-called Cuda toolkit, which was introduced to restructure the CPU host code so that the product could be performed on a GPU.

Figure 2.5.2. GPU acceleration (Parallel CPU) of a 1D (a) and 2D (b) Chebyshev series product algorithm. The two bars represent a monolithic kernel (red) and an optimized striding kernel (green).

The GPU acceleration achieved with a monolithic kernel is a good first step in parallelizing the Chebyshev product algorithm. However, to reach the full potential of the GPU a striding kernel was implemented that optimized several drawbacks of the monolithic kernel. First the thread strategy was changed to one thread block per output vector element, allowing for a reduction summation in each block. Second, the memory management was optimized by allowing threads in warps to read the registers of neighboring threads. This allows for efficient communication between the threads, leading to an optimal reduction sum. The most notable speedup results achieved with the GPU ranged roughly between 5k to 200k for the 2D case. Parallel speedup is only increased when simulating in higher dimensions.
Other algorithms such as the Chebyshev derivative and integral also show potential for being GPU accelerated. Already developed Cuda algorithms such as the reduction sum and prefix scan are suitable for GWRM simulations. Future GPU accelerated product of Chebyshev series research on accelerating the GWRM method will focus on other algorithms such as the derivative and integral, efficient ways of finding roots to the algebraic equations, and optimizing the transfer of data between host and device.

**Time-averaged GWRM plasma modelling**

In a recent, modified approach the GWRM computes solutions that are smooth functions, averaged over rapidly fluctuating physical phenomena, rather than the exact solution itself. This is a good idea since spectral methods perform best for smooth solutions and simplifies computations of phenomena with many details such as the Vlasov equation and turbulence, where long-term evolution is of higher interest than fine details of the fluctuations. Thus, rather than to determine the fluctuating function \( u( t, x) \) (in 1D) we compute the average

\[
U( t, x) = \frac{1}{2\Delta} \int_{t-\Delta}^{t} u(\tau, x) d\tau
\]

The parameter \( \Delta \) controls the smoothness of the running average. To the right is shown a simple GWRM example where an averaged particle orbit in a combined magnetic and electric field is computed. Both functions \( u( t, x) \) (exact) and \( U( t, x) \) (averaged) are shown. To enable time-averaged GWRM solution of the differential equations, we have developed a theory to convert any set of linear or nonlinear ODEs or PDEs to exact corresponding equations for the averaged variables. This averaging procedure will be employed when modelling 2D and 3D turbulence as well as kinetic effects.

When computing averages of physical variables, care must be taken so that certain quantities are obtained with sufficient accuracy. This holds for example for diffusion rates, which are obtained in the form of fluxes from the integrated product of density and velocity fluctuations; thus the relative phase is of importance. To this end we have developed a test problem from the Lorenz equations discussed above. By multiplying the Lorenz variables \( X( t) \) and \( Z( t) \) and integrating over time, we define a ‘flux’ that we wish to compute with a certain accuracy. Employing the time-averaged algorithm, we may now use GWRM time intervals of the order 10 time units rather than 1 as previously, considerably enhancing efficiency. Below some computations are demonstrated.

**Figure 2.5.3.** The left and middle figures show an example of time-averaged GWRM solution employing \( \Delta = 10 \) (red) as compared to exact solution of the chaotic Lorenz equations. The right figure shows that the averaged flux (red) of XZ compares well with the exact flux (green). The flux obtained by simply integrating over the averaged X and Z variables (blue) is also shown.
2.6. Confinement physics

L. Frassinetti and E. Stefániková in collaboration with JET, AUG and TCV researchers

2.6.1. Pedestal properties and confinement in JET

Operations in JET resumed in autumn 2011 after the shutdown to install the ITER-like wall (hereafter called ILW). In 2019, the study of the pedestal properties in JET with the ILW has continued. The electron temperature and density pedestals tend to vary in their relative radial positions, as observed in DIII-D and ASDEX Upgrade. This so-called relative shift has an impact on the pedestal magnetohydrodynamic (MHD) stability and hence on the pedestal height.

Role of the pressure position on the pedestal stability in AUG, JET-ILW and TCV and implications for ITER.

The role of the pedestal position on the pedestal performance has been investigated in AUG, JET-ILW and TCV. When the pedestal is peeling-balloonning (PB) limited, the three machines show a similar behaviour. The outward shift of the pedestal density relative to the pedestal temperature can lead to the outward shift of the pedestal pressure which, in turns, reduces the PB stability, degrades the pedestal confinement and reduces the pedestal width. Once the experimental density position is considered, the EPED model is able to correctly predict the pedestal height. An estimate of the impact of the density position on an ITER baseline scenario shows that the maximum reduction in the pedestal height is 10% while the reduction in the fusion power is between 10% and 40% depending on the assumptions for the core transport model used.

In other plasmas, where the pedestal density is shifted even more outwards relative to the pedestal temperature, the pedestal does not seem PB limited and a different behaviour is observed. The outward shift of the density is still empirically correlated with the pedestal degradation but no change in the pressure position is observed and the PB model is not able to correctly predict the pedestal height. On the other hand, the outward shift of the density leads to a significant increase of $\eta_e$ and $\eta_i$ (where $\eta_{e,i}$ is the ratio of density to temperature scale lengths, $\eta_{e,i} = L_{ne,i}/L_{Te,i}$) which leads to the increase of the growth rate of microinstabilities (mainly ETG and ITG) by 50%. This suggests that, in these plasmas,
the increase in the turbulent transport due to the outward shift of the density might play an important role in the decrease of the pedestal performance.

In the datasets analyzed in this work, the normalized pressure gradient expected by the PB model is up to 90% higher than the experimental one, with $\alpha_{\text{crit}}/\alpha_{\text{exp}} \approx 1.9$ as shown in figure 2.6.1.

The PB stability in most of the earlier works (as well as in the present work) has been determined with the assumptions $T_{\text{sep}}=100\text{eV}$, $T_i=T_e$ and without including possible effects from rotation and diamagnetic terms.

It is reasonable to assume that $T_{\text{sep}}$ is not perfectly constant in the scans discussed in this work. For example, in JET-ILW, the EDGE2D-EIRENE suggest that gas and power scans without seeding can lead to $\approx 10\%$ variation in $T_{\text{sep}}$. However, the pedestal is very steep so a reasonable change in $T_{\text{sep}}$ has a minimal effect on $T_{e\text{pos}}$ and on the pedestal pressure. As a practical example, the effect on shot 84598 has been estimated. A 10% uncertainty in $T_{\text{sep}}$ leads to only a $\approx 0.0015\psi_N$ variation in $T_{e\text{pos}}$ from $\psi_N=0.985$ at 100eV to $\psi_N=0.9865$ at 110eV (a variation in $T_{e\text{pos}}$ that is lower than its experimental uncertainty). Such small variation has no significant effect on the predicted pedestal pressure. Figure 2.6.2 estimates the impact of $T_{\text{sep}}$ on the predicted $p_{e\text{ped}}$ assuming a more extreme (likely unrealistic) variations, from $T_{\text{sep}}=50\text{eV}$ to $T_{\text{sep}}=200\text{eV}$. The increase of $T_{\text{sep}}$ reduces the PB stability and the predicted pedestal height, from $p_{e\text{ped}}=4.5\text{kPa}$ at $T_{\text{sep}}=50\text{eV}$ to $p_{e\text{ped}}=3.8\text{kPa}$ at $T_{\text{sep}}=200\text{eV}$.

However, the predicted pressure still remains significantly higher than the experimental pressure.

The work has investigated the role of the pedestal position in the pedestal performance and has tried to resolve the apparent contradictions in the published results on the topic. A key point has been to distinguish between plasmas with a pedestal position.

![Figure 2.6.3.](image)

(a) Predicted total pressure height using Europed versus the shift of the density position. (b) Experimental electron pressure profile (blue dots) and corresponding critical profiles from Europed.

![Figure 2.6.4.](image)

Figure 2.6.4. Pedestal pressure versus $n_{e\text{pos}}$ in TCV. The stars shows the experimental data, while the squares the $p_{e\text{ped}}$ prediction for different values of $n_{e\text{pos}}$. 
that is PB limited and plasma with a pedestal that is not PB limited.

In plasmas that are PB limited, the outward shift of the density leads to the outward shift of the pedestal pressure which in turn destabilizes the PB modes, reducing the pedestal height, see figure 2.6.3. In this type of plasmas, the PB model describes the pedestal behavior well and EPED-like predictions reproduce the experimental data correctly once the realistic density position is used. A similar behavior has been observed in AUG and TCV, see figure 2.6.4

Assuming that the ITER pedestal is PB limited, this work has estimated the impact of the shift of the pedestal density on the ITER baseline scenario. The ITER pedestal is supposed to degrade at most by 10%, while the impact on the fusion power is supposed to vary between 10% and 40% depending on the critical $R/L_{Te}$. See figure 2.6.5

In plasmas that are not PB limited, the behavior of the pedestal structure with increasing gas rate is quite different. First of all, the pedestal widens instead of shrinking with increasing gas. Then, the density still moves outwards but no significant change has been observed in the pressure position. Therefore, the PB model cannot properly describe the pedestal behavior and EPED-like models significantly overestimates the pedestal height. The work suggests that the lower pressure gradient observed in the non-PB limited plasmas might be explained by an increase of turbulent transport driven by ETG and ITG modes. See figure 2.6.6 for details. This first linear analysis strongly suggests that the micro turbulence driving heat transport increases with increasing relative shift inside the pedestal top. $\eta_{e,i}$ are also substantially enhanced in the pedestal, so the increased heat transport is expected to continue into the pedestal itself, which would explain the low pressure gradient observed in these non-PB limited pedestals. More extensive linear and non-linear gyrokinetic simulations are needed to explore the dependence on radius and on $\theta_0$, and to compute the turbulent fluxes. Nevertheless, these results suggest that increased turbulent transport might explain the reduce pressure gradients in these non-PB limited pedestals.

Figure 2.6.5. (a) PB stability diagram for a ITER baseline scenario. (b) Dependence of predicted ITER pedestal pressure on the density shift. (c) Predicted $P_{\text{ fus}}$ for different $R/L_{Te,\text{crit}}$. Red and blue lines in frames (a) and (c) represents respectively the assumptions $n_{e,\text{pos}}=T_e^{\text{pos}}$ and $n_{e,\text{pos}}=T_e^{\text{pos}}+0.018\psi_N$. 

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The work on the non-PB limited plasmas is just at the beginning and several questions still remain open. Assuming that the lower pressure gradient is due to the increased turbulent transport, it is not yet clear which physical mechanisms trigger the ELMs. Moreover, it is not yet clear under which experimental conditions the plasma becomes non-PB limited. The increase of the gas rate seems a key factor, but a universal threshold has not been found yet. Finally, it is not clear why the pedestal widens with increasing gas instead of shrinking like in the PB limited case. Understanding the behavior of the pedestal width is a key factor for understanding why the pedestal position behaves differently in the PB limited and non-PB limited plasmas.

**Role of the separatrix density in the pedestal performance in JET-ILW.**

Since the initial JET operations with the metal wall (JET-ILW), the experimental results have shown a pedestal pressure in baseline plasmas that tends to be 10-20% lower than in the corresponding earlier carbon wall operations (JET-C). While this degradation seems mainly correlated with the high fueling rates typical of JET-ILW and/or the lack of carbon impurity, an exhaustive and comprehensive explanation for the lower pedestal performance has not been achieved yet. This work addresses the role of fueling and its goals are:

- to prove that the lower pedestal performance in D fuelled JET-ILW plasmas are due to the higher separatrix density \( n_{\text{sep}} \) produce by the higher neutral pressure,
- to describe the corresponding physics mechanisms that lead to the pedestal degradation.

In the baseline scenario of JET-ILW, operations with no gas fueling have been extremely challenging due to the problems related to tungsten influx and divertor heat loads. Since most of the JET-C plasmas have been performed with no gas fueling, a direct comparison of JET-ILW and JET-C pedestals obtained with identical engineering parameters is not possible. A further complication is related to the fact that the peeling-ballooning (PB) stability model (implemented with ideal MHD equations) does not describe correctly the experimental JET-ILW results since the experimental pedestal does not seem to reach the stability boundary when the ELMs are triggered. Therefore, the work is carried out on two levels. First, the work is focused on an empirical understanding of the pedestal behavior in JET. Then, based on these results, an investigation of the pedestal transport and an extension of the PB stability analysis is done with the GENE and JOREK codes.

Experimental results show a reduction of the pressure gradient with increasing \( n_{\text{sep}} \) (see figure 2.6.7) and increasing \( n_{\text{epos}} - T_{\text{epos}} \).

![Figure 2.6.6. Microinstabilities growth rate versus the perpendicular wavenumber for PB limited and non-PB limited plasmas of JET-ILW scan.](image)

![Figure 2.6.7 Correlation between \( p_{\text{ped}} \) and \( n_{\text{sep}} \) for a JET-C and a JET-ILW dataset with similar engineering parameters apart gas fueling rate and strike point position. The red line shows the predicted correlation between \( p_{\text{ped}} \) and \( n_{\text{sep}} \) obtained with Europed.](image)
Moreover, the disagreement with the PB model has been observed to increase with increasing resistivity. Therefore, the following hypothesis is emerging: Due to higher gas fueling rate / different recycling, JET-ILW has higher neutral pressure than JET-C. This leads to higher $n_{e\text{sep}}$ and higher $n_{e\text{pos}}$, producing higher $\eta_e$, increasing the turbulent transport mainly driven by ETG modes. Preliminary results obtained with GENE and GS2 seem to corroborate this idea. Then, the increase in transport reduces the pedestal gradients, which, in turns, lead to a lower temperature inside the separatrix. This increases the resistivity inside the separatrix making resistive effects on the MHD stability non-negligible. This is currently under investigation with the JOREK code.

2.6.2. Pedestal performance and separatrix density in TCV

An important open question in pedestal physics is the impact of the divertor configuration and the strike point positions on pedestal performance. Experimental results obtained in JET-ILW have shown that changes in the strike point position can have a significant effect on the pressure pedestal height ($p_{\text{ped}}$). While an explanation for this behavior is still lacking, some hypothesis have been proposed. The hypothesis that is tested in this work is based on the link between divertor configuration, gas fueling and separatrix density $n_{e\text{sep}}$. Recent studies in AUG and Alcator C-mod in gas and nitrogen seeding scans have shown that $n_{e\text{sep}}$ is well correlated to the pedestal performance. Large $n_{e\text{sep}}$ is also a key ingredient for reaching small ELMs.

The work investigates the role of $n_{e\text{sep}}$ in the carbon wall machine TCV. $n_{e\text{sep}}$ is varied using two methods, changing the gas fueling rate ($\Gamma_D$) and the strike point position. Due to its flexibility, TCV is an optimal device for this type study. The three investigated magnetic configurations are shown in figure 2.6.8.

The results show that both $\Gamma_D$ and strike point position affect $p_{\text{ped}}$ and suggest that $n_{e\text{sep}}$ is a good ordering parameter, as shown in figure 2.6.9. The degradation of $p_{\text{ped}}$ with increasing $n_{e\text{sep}}$ is likely due to the corresponding outward shift of the pedestal density position, $n_{e\text{pos}}$.

The emerging hypothesis is that the variations in $\Gamma_D$ and strike point position affect the recycling and the plasma fueling, leading to a change in $n_{e\text{pos}}$ and hence in $n_{e\text{sep}}$. In turn, this modifies the pedestal stability. This hypothesis has been tested using SOLPS to model the scrape-off layer effects and EPED to predict the effect on $p_{\text{ped}}$ of the PB stability, showing some encouraging preliminary results.

Figure 2.6.8. Magnetic configurations used.

Figure 2.6.9. Correlation between $p_{\text{ped}}$ and $n_{e\text{sep}}$ for three sets of $\Gamma_D$ scans in high-$\delta$ plasmas. The color code is consistent with figure 2.6.8 and shows the magnetic configuration used.
3. Education and research training

3.1. Basic and advanced level education

The following courses were given in 2019 by the Division of Fusion Plasma Physics:

**Basic level courses**

**ED1100 Engineering Science**  

**ED1110 Vector Analysis**  
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.

**Advanced level courses**

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

**ED2200 Energy and Fusion Research**  
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**  
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.

**ED2235 Atomic Physics for Fusion**  
The purpose of this course is to make the student familiar with those aspects of atomic physics that are most important in fusion research. The focus of the course is on basic understanding of atomic collisions and applications in plasma modelling, plasma diagnostics and plasma surface interactions. Much of the course content is applicable also in other contexts in plasma processing and technology, ion implantation and radiation effects.
ED2246 Project in Fusion Physics
The student will learn about practical experimental research work by carrying out a small research project. The projects are performed in a real research laboratory environment; utilizing the EXTRAP T2R fusion plasma experiment at the Division of Fusion Plasma Physics. The student will engage in a project that also leads to a more in-depth understanding of some common fusion plasma diagnostics methods.

Degree projects

The following degree project were completed in 2019:

Master Degree (30 credits)

Björn Ljungberg
3D Finite Element Modelling of ICRH in JET

Henrik Järleblad
Helical Magnetic Fields in the DFEMIC Code for RF Heating of Fusion Plasmas
3.2. Research training

The research training in Fusion plasma physics and technology at the Division is part of the Plasma Physics track of the Electrical Engineering Doctoral Program (E2DOC) of the School of Electrical Engineering and Computational Science (EECS). During 2019, there were altogether nine PhD students active at the Division.

The following PhD thesis defences took place during 2019:

**Respondent:** Petter Ström

**Thesis title:** Material characterization for magnetically confined fusion: Surface analysis and method development

**Date:** 13 February 2019

**Opponent:** Dr. Thierry Loarer, CEA Cadarache, France

**Abstract:** The present work deals with a small part of the fusion puzzle, namely the materials to be used in the first wall surrounding a magnetically confined plasma. Carbon, which has historically been considered as the most viable element for this role, has been ruled out due to issues with plasma-induced erosion, hydrocarbon formation and a buildup of thick deposited material layers on wall components. The latter two lead to an unacceptable accumulation of radioactive tritium, both in the deposited layers and in dust particles. A metal wall, which would alleviate these particular problems but increase the severity of others, is therefore envisioned for a future demonstration reactor. Three contributions to the overall research effort are made through this thesis. First, an increased understanding of plasma-induced erosion of so-called reduced activation ferritic-martensitic steels and preferential sputtering of light material components is provided. High-resolution ion beam analysis and microscopy methods are used to examine samples of such a steel after exposure to plasma under controlled circumstances. Model films consisting of a mixture of iron and tungsten deposited on silicon substrates are also studied as they constitute simpler systems where the effects of interest may be simulated. The knowledge obtained is necessary for an assessment of the possibility to use reduced activation steel as a plasma-facing material in specific regions of a reactor wall. The second contribution consists of reports on the composition of deposited material layers on wall components retrieved from the plasma confinement experiments JET and TEXTOR. These provide limited conclusions on the range and rate of material erosion, transport and deposition in two cases. Finally, a detection system for the ion beam technique elastic recoil detection analysis has been assembled, tested and put into operation. In addition to improving the quality of analyses performed on fusion-related materials, the system has become an established tool available for users of the 5 MV electrostatic pelletron accelerator at Uppsala University’s Tandem Laboratory.

**Respondent:** Yushan Zhou

**Thesis title:** Impact of Surface Structures on Deposition and Erosion in a Tokamak

**Date:** 8 March 2019

**Opponent:** Prof. Ivančica Bogdanović Radović, Ruđer Bošković Institute, Zagreb, Croatia

**Abstract:** Fusion is a potentially unlimited and environmentally friendly energy source for human society in the future. However, along the way towards the production and application of fusion energy there are still unresolved complex issues. Among them, material erosion, re-deposition and fuel retention are of critical nature. Deposition of fuel and impurity atoms may
lead long-term fuel retention which would cause safety issues and limit the economic efficiency of fusion devices. Moreover, the erosion of the vacuum vessel wall in a fusion device generates impurities which contaminate core plasma and can restrict the life time of plasma facing components (PFC). The work in this thesis focuses on erosion and deposition on tiles in the JET-ILW project, which consist of tungsten (or tungsten coated carbon fibre composites) in the divertor and beryllium for limiters. For the deposition studies, micro ion beam analysis (µ-IBA) was used for observing deuterium and beryllium distributions over the tile surfaces. The surface topography was obtained from SEM, optical microscope and confocal laser scan microscope. Distribution maps from IBA were compared with surface topography. To explain experimental results, modelling of ion trajectories was applied on real and artificial surfaces. Micro IBA results show that deuterium and beryllium are accumulated in depressed areas, e.g. pits, cracks or craters. Modelling implies that ion gyration, surface roughness and inclination of the magnetic field could to some extent explain this non-uniform distribution of deuterium and beryllium. The same kind of issue, although on different scale length, occurs also for penetration of impurities into the grooves of castellation, also studied experimentally in the thesis. For the erosion issue, the thesis includes analysis of a limiter marker tile which is designed for observing material erosion in JET. A new method to acquire erosion data from such marker tiles is proposed, by combining micro IBA and SEM image. This method could separate the influence on IBA from roughness, a problem in applying IBA on rough surface. Similar technique is applied to improve the interpretation of IBA measurements of deep penetration of deuterium into layered surface structures.

**Doctoral programme development and reorganisation**

The E2DOC doctoral programme is one of KTH’s largest, encompassing some 250 doctoral students. The program director from January 2018 (Jan Scheffel) and onwards is employed at the Division of Fusion Plasma Physics. Among the events within the program in 2019 the following may be highlighted.

- Concerning zero tolerance for discrimination and harassment, and how to encourage division heads to deal with these issues, a message from the E2DOC Council, expressing concerns based on a survey conducted among the doctoral students, was sent to all division heads within Electrical Engineering.

- The KTH Sustainability office approved the E2DOC plan to meet requirements for inclusion of sustainability by including a new module in the course The Sustainable Scientist and having two courses in the main curriculum with sustainability as part of the course and part of examination requirements. Thus all PhD students will discuss these issues in their research training.

- Routines for gathering and saving course analyses have been looked over and improved.

- A new general study plan has been approved, where a second specialization track, intended for international doctoral programme collaborations has been introduced. This specialization requires only 60 hp courses, whereas the main Electrical Engineering specialization requires 75 hp courses.

- The advanced level of doctoral courses has been removed, so that there is now only two levels of doctoral courses within the programme: general skills courses and subject courses.

- A working group within the EECS school has suggested that a mentoring programme for recruitment of female doctoral students will be developed. This entails offering female master students mentors (PhD students or faculty), closer contacts with the divisions and laboratories,
3-6 months of pay for work as research engineers when performing their Master theses as well as club rooms, both at Campus and in Kista. The EECS school management will support the project financially.

- New routines are in place for the individual study plans, that will now be checked and given feedback by programme directors during a specific period annually.

**FuseNet**

The Department of Fusion Plasma Physics is a member of FuseNet since a few years. This is an organization for increasing, enhancing and broadening fusion science and technology training in Europe. In particular, our PhD students are taking part in the FuseNet PhD Events, the aims of which are to enable students to disseminate their research, develop a network of contacts and learn from each other's experiences.

**Graduate level courses**

In E2DOC, courses for a PhD Degree should cover 75-120 credits whereas thesis work should cover 120-165 credits, altogether 240 credits. For a Licentiate degree, courses should cover 45-60 credits and thesis work 60-75 credits, adding up to 120 credits. Courses at the advanced undergraduate level may be included, insofar as they are not requirements for admission. For licentiate and PhD degrees at most 15 credits or 30 credits from undergraduate courses may be included, respectively. The institutional work carried out by the PhD students is mainly within teaching (ED1100 Engineering Science and ED1110 Vector Analysis).

All students enrolled into the new E2DOC Doctoral Programme should take four general skills courses, amounting to 10 credit points, in the topics of oral and written communication, pedagogics, theory of science and research methodology, and research ethics:

- FLH3000 Basic Communication and Teaching
- FAK3014 The Theory and Methodology of Science – Minor Course
- FAK3127 The Sustainable Scientist
- FDS3103 Introduction to Scientific Writing for Doctoral Students

The following **basic** graduate level courses in the subject area of fusion plasma physics are recommended, depending on the doctoral student’s research direction (course responsible teacher is given in parentheses):

- FED3220 Motion of Charged Particles, Collision Processes and Basis of Transport Theory, 8 credits (T. Jonsson)
- FJD3300 Kinetic Plasma Theory (J. Scheffel)
- FED3230 Magnetohydrodynamics, 8 credits (J. Scheffel)
- FED3240 Plasma waves I, 8 credits (T. Jonsson)
- FED3260 Fusion Plasma diagnostics, 8 credits (P. Brunsell)

The following **advanced** courses are recommended:

- FED3305 Magnetohydrodynamics, advanced course, 6 credits (J. Scheffel)
- FED3320 Fusion research, 8 credits (L. Frassinetti)
4. Personnel

**Professor**
- Per Brunsell (Division Head)
- Marek Rubel
- Jan Scheffel

**Professor, emeritus**
- James Drake
- Torbjörn Hellsten
- Bo Lehnert
- Michael Tendler

**Associate Professor**
- Henric Bergsäker
- Lorenzo Frassinetti
- Thomas Johnson

**Researcher**
- Per Petersson

**Engineer**
- Håkan Ferm

**PhD student**
- Kristoffer Lindvall
- Björn Ljungberg
- Sunwoo Moon
- Erik Saad
- Stefan Schmuck
- Estera Stefániková
- Petter Ström
- Pablo Vallejos Olivares
- Yushan Zhou
5. Income & Expenditure

The accounts for the Division of Fusion Plasma Physics for the year 2019 are summarized in the table below. Note that from the year 2019, all income and expenditure related to education is allocated at the Department of Electrical Engineering, and therefore removed from the Division accounts.

<table>
<thead>
<tr>
<th>Income &amp; Expenditure 2019</th>
<th>kSEK</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Income</strong></td>
<td></td>
</tr>
<tr>
<td>KTH</td>
<td>6 939</td>
</tr>
<tr>
<td>Research and research training (FOFU)</td>
<td>6 939</td>
</tr>
<tr>
<td>External research grants</td>
<td>11 181</td>
</tr>
<tr>
<td>Swedish Research Council (VR)</td>
<td>5 551</td>
</tr>
<tr>
<td>European Framework Programmes (Euratom)</td>
<td>5 630</td>
</tr>
<tr>
<td>Other external income</td>
<td>63</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>18 183</td>
</tr>
<tr>
<td><strong>Expenditure</strong></td>
<td></td>
</tr>
<tr>
<td>Salary</td>
<td>10 415</td>
</tr>
<tr>
<td>Travel</td>
<td>825</td>
</tr>
<tr>
<td>Equipment</td>
<td>123</td>
</tr>
<tr>
<td>Operation and other costs</td>
<td>547</td>
</tr>
<tr>
<td>Rent</td>
<td>2 886</td>
</tr>
<tr>
<td>KTH and School central costs</td>
<td>3 770</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>18 566</td>
</tr>
<tr>
<td><strong>Result</strong></td>
<td>-383</td>
</tr>
</tbody>
</table>
Bibliography


[29] Petter Ström, Per Petersson, Marek Rubel, Henric Bergsäker, Igor Bykov, Lorenzo Frassinetti, Alvaro Garcia Carrasco, Torbjörn Hellsten, Sheena Menmuir, Simon


