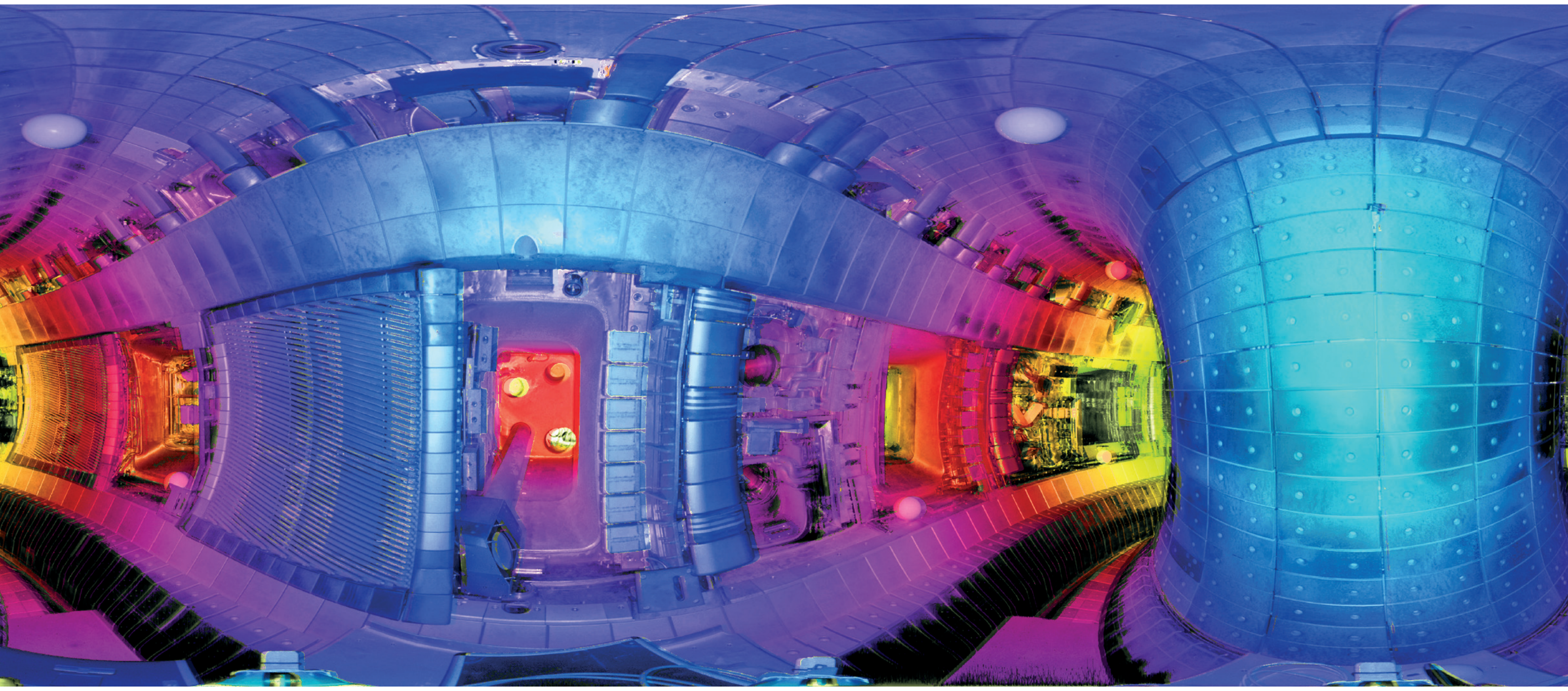
Max-Planck-Institut für Plasmaphysik

Annual Report 2006



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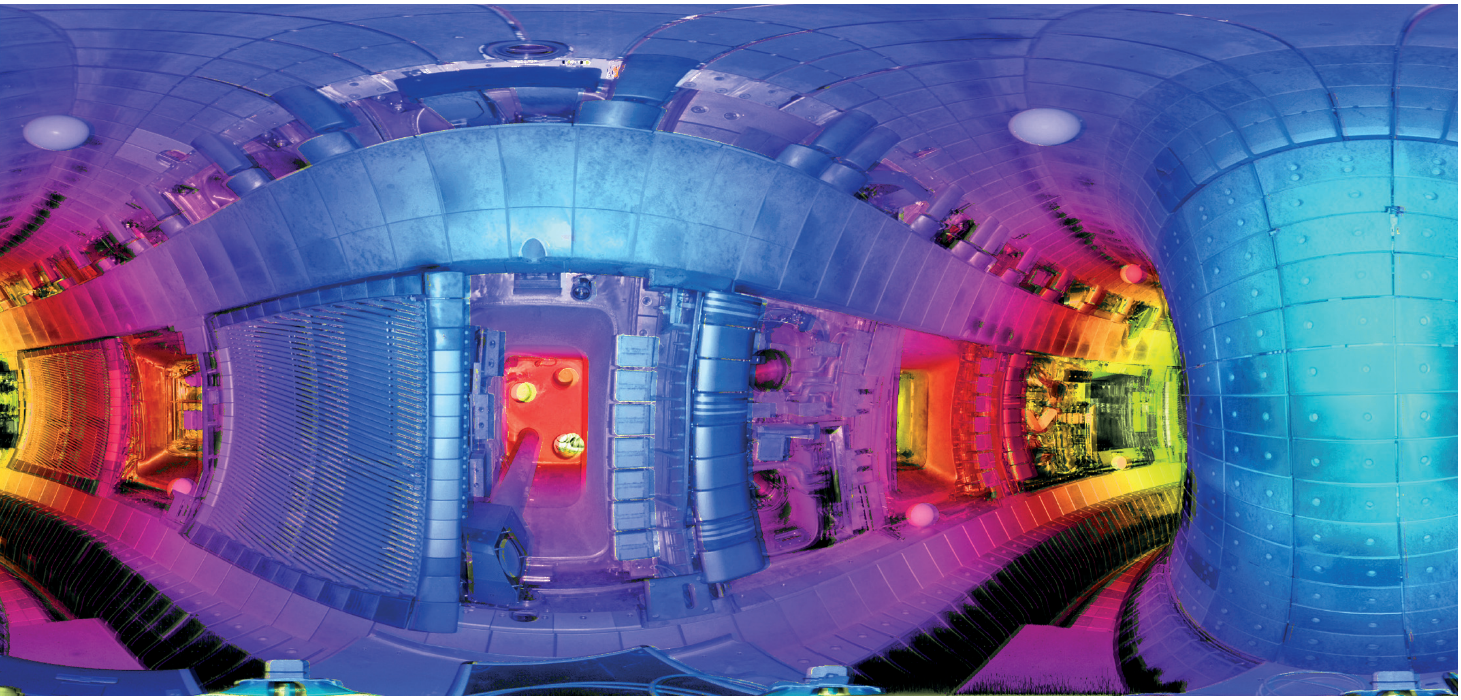

360 degree scan of the interior of the ASDEX Upgrade tokamak vacuum vessel as produced with a laser scanning system (FARO LS) showing the multi-faceted structure of the first wall. The big column on the right side of the picture represents the housing of the primary winding of the ohmic transformer (central column).

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The Max-Planck-Institut für Plasmaphysik is an institute of the Max Planck Gesellschaft, part of the European Fusion Programme (Euratom) and an associate member of the Helmholtz-Gemeinschaft Deutscher Forschungszentren.

On 21st November 2006 the international ITER organisation received the final go-ahead: Representatives of the seven ITER Parties – China, the European Union, India, Japan, the Republic of Korea, the Russian Federation and the United States of America – signed the agreement to establish the organisation that will implement the ITER fusion project. IPP is strongly involved in this important development, which will result in the world's largest fusion facility demonstrating the scientific and technical feasibility of fusion power.

Alexander M. Bradshaw

The Wendelstein 7-X stellarator in Greifswald is now approaching the full-scale assembly phase. Numerous large components such as coils, vessel parts, ports and support elements, have arrived in Greifswald and are being prepared for assembly. More than 50 per cent of the superconducting coils have been completed by the manufacturers. Initial difficulties with the high-voltage failure of some of the coils and structural weaknesses have now been largely overcome. Since the assembly of a first-of-a-kind device like Wendelstein 7-X requires the development of a large number of demanding new technical solutions, there are still many challenging problems to solve. In 2006, the build up of engineering staff for the project was almost completed. Two new Scientific Members, Robert Wolf and Per Helander (experimental stellarator physics and stellarator theory, respectively), have taken up their appointments at IPP Greifswald. After completion, the Wendelstein 7-X stellarator will be a forerunner in steady-state high-performance plasma physics and fusion technology. During assembly it serves – as the only European superconducting device under construction – as a training ground for engineers working on the ITER Project.

The experiments on the ASDEX Upgrade tokamak in Garching are directed towards the next steps in fusion research – to prepare the physics base for ITER and its successor DEMO. The programme covers many of the "High Priority Physics Research Areas" identified by the International Tokamak Physics Activity (ITPA). During the last few years the base for ITER operation was significantly extended on ASDEX Upgrade in both the standard and the improved H-mode with its high potential to take ITER beyond its reference parameters. In 2006 it was found that the confinement improvement is based on increased edge pedestal pressure and reduced core transport. New insight was gained into the interaction of energetic particles with large scale MHD instabilities based on new diagnostics and, in particular, on a new theoretical gyrokinetic approach to the problem. Active control of MHD instabilities concentrates on electron cyclotron current drive as proposed for ITER. With its tungsten wall programme ASDEX Upgrade is already aiming at DEMO, where the erosion of low-Z materials such as carbon or beryllium will be unacceptable. In 2006 the main result on ASDEX Upgrade was the high erosion rate at the outboard limiters dominated by impurities accelerated by ion cyclotron radiofrequency. With increasing tungsten coverage of the wall, the carbon concentration was clearly reduced. With a full tungsten machine in 2007, important results for high-Z operation are expected. Unfortunately, the campaign in 2006 was terminated in April by a technical defect on one of the flywheel generators, which supplies part of the poloidal field coils and the heating systems. Nevertheless, a somewhat limited operation of ASDEX Upgrade is still possible with the remaining generators, so that the tungsten programme can be performed in 2007 almost without restrictions.

IPP scientists are also involved in experiments on the Joint European Torus (JET) in Culham, UK. After a series of technical difficulties, JET managed to come back on path in the second half of 2006. The tokamak operated reliable and reached significant performance leading to a variety of new results. In addition, the various enhancement projects are progressing well. IPP has successfully contributed to many JET experiments and has been involved in several enhancement projects, notably the development of tungsten coatings for the ITER-like wall. Our level of involvement, however, continuously decreases as a result of manpower shortages at IPP Garching.

With the signing of the ITER Implementing Agreement and the assembly of an ITER Team at Cadarache, the contribution of IPP to ITER increased significantly in 2006. This is expected to continue in future. IPP was chosen to lead a consortium of European Fusion Associations that will develop a project plan for the ITER bolometry diagnostic procurement package. IPP is also expected to lead the group that develops and procures the ion sources for the ITER neutral beam heating system. With the launch of the ITER design review, IPP has played a leading role in identifying the remaining physics issues in the ITER design and is now contributing actively to defining solutions.

Plasma-wall interaction studies at IPP are contributing strongly to the understanding of the accumulation of hydrogen isotopes in fusion devices. This subject is of highest importance for ITER safety and thus dominates the selection of the wall materials and the related plasma operational aspects. Equally important is the investigation of the erosion processes on wall materials, which allows the main sources for impurities during ITER operation to be determined. These activities are an integral part of the programme of the European Task Force on Plasma-Wall Interactions, which is led by IPP. The research on plasma-facing materials takes these aspects as input and focuses on tungsten-based plasma-facing materials, barrier coatings and high temperature heat sink materials. A large part of the materials development is being carried out within the European Integrated Project "ExtreMat". Coordinated by IPP this project unites 37 European partner institutions in developing materials for extreme environments.

On behalf of the Directorate and the Board of Scientific Directors I would like to thank the IPP staff for their untiring efforts and for the progress made in 2006. This has often been in the face of considerable adversity, due in particular to the severe budgetary restrictions, the generator problem and the manufacturing quality of the non-planar Wendelstein coils.

Content

Tokamak Research

ASDEX Upgrade

Head: Dr. Otto Gruber

The aim of the ASDEX Upgrade programme is to prepare the physics base for ITER and DEMO. Significant progress has been made in the operation with tungsten-clad walls, understanding of transport and impurity control, ELM mitigation by frequency control, and control of performance limiting instabilities. The improved H-mode (ITER "hybrid") operation was consolidated and extends beyond the ITER baseline specifications for $nT\tau$ and the pulse length.

1 Overview

1.1 Scientific Aims and Operation

The tokamak fusion experiment ASDEX Upgrade (AUG) is a medium size divertor tokamak (major radius R=1.65 m, minor radius a=0.5 m) with an ITER-like configuration, high shaping capability (single null and double-null divertor, elongation up to 1.8, triangularity δ up to 0.5) and a versatile heating system. The design combines the successful divertor concept with the requirements of a next step fusion reactor, in particular the need for an elongated plasma shape and poloidal magnetic field coils outside the toroidal magnetic field coils. AUG is close to ITER in its magnetic and divertor geometry and in particular the relative length of both divertor legs compared to the plasma dimensions. The installed heating power of up to 28 MW ensures that the power flux densities through the plasma boundary are equivalent to those in ITER. The scientific programme gives priority to the preparation of the design (heating, fuelling, first wall materials), physics basis and discharge scenarios of ITER and the exploration of regimes beyond the ITER baseline scenario.

The studies were guided by four Task Force (TF) groups which consisted of

- Confinement and performance of the ITER base-line scenario, the ELMy H-mode, and the advanced scenario of the "improved H-mode" leading to enhanced performance and longer inductive pulse lengths by non-inductive current drive,
- H-mode pedestal physics and ELM mitigation and control,
- Magnetohydrodynamic (MHD) stability, active stabilization of β limiting instabilities as well as avoidance and mitigation of disruptions,
- Scrape-off layer and divertor physics with the aim of optimizing power exhaust and particle control (ash removal) and optimization of first wall material with emphasis on tungsten.

The similarity of ASDEX Upgrade to ITER makes it particularly suited to testing control strategies for shape, plasma performance and MHD modes. The similarity in cross-section to other divertor tokamaks is important in determining size scalings for core and edge physics. In particular, the 2006 physics programme was based on our conclusions of the last years, persisting ITER requirements and tokamak concept improvement. Our programme largely covers the "High Priority Physics Research Areas" provided by the ITPA Coordinating Committee. Again, several items have been investigated in joint experiments at all major tokamaks as proposed by the ITPA Topical Groups. In summary, the AUG programme in close collaboration within the EU fusion programme is embedded in a framework of national (see section on University contributions to IPP programme) and international collaborations (see section 11).

The AUG Programme Committee established in 2001 enables the Associations to take responsibility for our programme. This body defines the Task Forces responsible for the different elements of our programme, and approves the experimental programme. Furthermore, the bodies that work out the programme proposals are open to external participants, and remote participation in the meetings is used. For the 2006 campaign 160 proposals were received including 60 proposals from outside IPP. With this structure, we have achieved a compromise between the increased international participation and the flexibility that has so far been typical for the AUG programme.

The flexible heating systems consist first of the neutral beam heating (NBI) with powers up to 20 MW. The ion cyclotron resonance system (ICRH) is capable of routinely coupling up to 7 MW in ELMing H-mode discharges. The present electron cyclotron system was kept available up to a coupled power of 1.2 MW allowing pure electron heating (ECRH) and current drive (ECCD). These versatile heating methods allow the effects of heat, particle and momentum deposition on energy and particle transport, MHD stability and fast particle physics to be separated. In 2006 the coverage of the AUG vessel interior with tungsten was further extended up to 85 % (36 m^2 with <5 μm W) with the coating of the poloidal limiters at the low field side which receive the highest load in the main chamber. The W concentration could still be kept at an acceptable level over a broad range of discharge scenarios. The complete W coverage is being done in the present shut-down, namely the 200 μm coating of the lower LFS divertor targets.

Stationary discharges with up to 10 s flat-top allow steady state investigations not only on the transport and MHD time scales but also for up to 10 current diffusion times. The new fast integrated control and data acquisition system (CODAC) with a reduced cycle time was fully commissioned. It is specially adapted to ITER needs with its machine-independent design, its integrated discharge scenario control and protection functions and the large number of real-time diagnostics. This extremely flexible system is now in routine use at ASDEX Upgrade (section 7.3).

The 2006 experimental campaign started in mid December 2005 and had to be terminated on 27 April 2006 when there was a technical defect in the flywheel generator EZ4 (supplies a part of the poloidal field coils and heating systems) which resulted in undefined braking. Previously we had conducted 37 shifts at high availability with a total of 500 pulses (technical tests, diagnostic calibrations and plasma discharges).

This technical problem caused a considerable reduction of the 2006 programme by roughly 65 % of the high priority discharges foreseen.
Meanwhile the cause of the malfunction has been clarified and appropriate improvements based on appraisals of external experts will be implemented. The damage assessment points to no damage of the generator runner and flywheel, while the stator must be newly manufactured. The successful repair of the EZ4 generator seems possible, but presumably it will not be completed before summer 2008. The operation of AUG in 2007 with the remaining generators EZ2 (for the TF coils) and EZ3 (poloidal field coils and heating systems) is possible. The main thrust for the 2007 campaign, the W programme can be performed almost without restrictions at plasma currents up to 1 MA at limited triangular plasma shapes, heating powers up to 7.5 MW and flattop times up to 4 s. This was achieved by the optimisation of the static inverter configuration and by reducing the secondary voltage for the electric circuits of various poloidal field coils. This new configuration was successfully tested in July 2006. The incident with EZ4 caused us to examine the existing safety concepts of all three generators and to initiate suitable measures where necessary. The latter essentially means the installation of an additional brake for generator EZ2 which is considered as a prerequisite for the restart of EZ2. Also, for the end of 2007 an upgrade of the EZ3 brake is planned. In medium-term the full power/energy supply is needed for all relevant ITER programmes.

1.2 Main results in 2006 and relevance for ITER

During the last year on ASDEX Upgrade the physics base for ITER operation was significantly extended in both the foreseen standard H-mode scenario as well as the stationary improved H-mode scenario. A central part of our effort remains the development of the “improved” H-mode, realized in ASDEX Upgrade in 1998 and now forming the basis of the long pulse ITER “hybrid” scenario, with its high potential to guide ITER beyond its reference parameters (section 2). Based on ASDEX Upgrade kinetic profiles it promises at full current (q_{95}=3.1) a fusion performance up to ignition with a performance factor $H_{98(y,2)}\beta_N/q_{95}^2 \approx 0.4$ (ITER reference value 0.2). At lower I_p in ITER (9-11 MA), a significant fusion power of 400 MW can still be achieved at very long pulse lengths up to 1 hr (hybrid scenario). On AUG the operational range of this tokamak operation mode is extending, spanning to either the ITER collisionality or high edge density (divertor relevant), q_{95} ranging from 3 to 5, non-inductive current drive fractions above 50 %, and operating with a high-Z first wall. The confinement improvement is based on an increased edge pedestal pressure and reduced core transport. In terms of the scenario recipe a flat central q-profile with $q \approx 1$ is favourable with clamping of the current profile provided by either fishbones (higher performance) or central higher (m,n) NTMs.

For anomalous transport (energy, particles, toroidal momentum) a multi-faceted picture of mode dominance in different plasma parameter regimes of ITG, TEM and ETG turbulence is evolving based on detailed measurements including fluctuation reflectometry and gyrokinetic calculations (section 3). In ITER modestly peaked density profiles and benign high-Z impurity accumulation are to be expected. Similar structures were found for natural and pellet induced mitigated type I ELMs. They develop to outward drifting helical filaments which are seen as footprints on plasma facing structures (section 6).
New insights were gained on the interaction of energetic particles (driven by NBI and ICRH) with large scale instabilities (TAEs, NTMs, ELMs) based on new diagnostic and theoretical tools (section 4). The unexpected broadening of NBI driven currents beyond a certain heating power can be explained by a fast particle diffusion driven by small-scale turbulence. Off-axis NBI current drive above a certain turbulence level is questionable. The active control of MHD instabilities (sawteeth, NTMs) concentrates on ECCD as proposed for ITER. NTMs were completely stabilized, with very localized deposition of DC ECCD in improved H-modes, while for the deposition widths larger than the marginal island size as in ITER modulated injection phased with the island O-point was demonstrated to be advantageous (section 5).
The tungsten wall programme is as important for DEMO as the erosion of low-Z material and the destruction of graphite under neutron bombardment will be unacceptable there. The main result was the high W erosion rate at the LFS poloidal limiters, where it is dominated by ICRF accelerated impurities and fast particles from NBI. The W concentration could be kept at an acceptable level by ELM pace-making (using pellets) and by tailored central heating using NBI and ECRF enhancing the turbulent impurity transport. With increasing tungsten coverage the carbon concentration was clearly reduced, where the outer divertor target remained as the carbon source. We should get rid of carbon in the next campaign with full W covering of the divertor and we expect decisive answers for high-Z operation.

1.3 Technical Enhancements and Programme in 2007

In order to achieve the consolidation of the ITER design and its base line scenario and the exploration of new improved scenarios, it is necessary to successively upgrade the AUG technical systems. The step-by-step transition from graphite to an all-tungsten device will soon be completed, including the W coated target plates of the bottom divertor. One ICRH antenna is now equipped with a closed Faraday screen to test the ELM influence on the voltage stand-off. The new blower gun extends the pellet ELM-triggering capability to frequencies of 140 Hz and the use of smaller pellets is under development. Our ECRF system is presently being upgraded in power (4 MW provided by 4 gyrotrons), pulse length (10 s) and deposition variability (tuneable frequency 105-140 GHz, toroidally and real-time poloidally steerable mirrors).

The first 2-frequency gyrotron is currently being commissioned at IPP. The status of the AUG technical, heating and CODAC systems is given in section 7.

The restart of AUG as a full tungsten machine is planned for the end of March 2007 with main emphasis on the operation in an all-metal machine. Accordingly the proposals were prioritized into W compatibility of ITER scenarios, extension of the working space with metal wall and other ITER related physics investigations compatible with the generator restrictions. Out of the 178 submitted proposals 59 were from 14 EURATOM Associates, the US and Japan. The programme will be executed in cooperation with the EU Associations and in close connection with the ITPA joint experiments.

In the mid term range we will focus even more on advanced tokamak operation as the hybrid scenario of the improved H-mode and the ITB discharges with reversed magnetic shear. Reliable creation and sustainment of optimal shear profiles requires an additional current profile control method such as LHCD with about 5 MW installed power at AUG. In order to overcome the lower ideal MHD limits of reversed shear plasmas we have to rely on wall stabilization, which needs a stabilising shell at the low field side much closer to the plasma than the present walls. This shell has to be combined with internal coils to actively control the MHD instabilities growing on the resistive time scale of the shell (RWMs). As such internal coils have several other interesting applications, such as rotation control, ELM tailoring and tearing mode control, their installation as a first step of the package is planned.

In this annual report, besides sections 2-7 mentioned above, we describe in section 8 core plasma physics, as transport, turbulence and radial electric field measurements. Section 9 covers edge and divertor physics, as edge transport, plasma flows in the SOL, tungsten erosion and material migration, heat and particle flux profiles in SOL and divertor. Section 10 covers the contributions from Stuttgart University and section 11 describes the international cooperations.

2 Improved H-modes: Physics, operational range and extrapolation to ITER

Since the mid-1980's H-modes have been developed as the standard scenario, allowing a robust extrapolation to "pulsed" operation in next step experiments such as ITER. Since 1998 ASDEX Upgrade has developed stationary H-modes that routinely obtain confinement enhancement factors $H_{98}(y,2)>1$ and normalised β_N=2-3. These discharges are characterized by a q-profile with low magnetic shear in the centre and q(0)~1. Further development of this scenario in recent years by ASDEX Upgrade and other experiments indicate that improved H-modes are a candidate for an ITER hybrid scenario or could extend ITER operation beyond what is currently foreseen using standard H-modes.

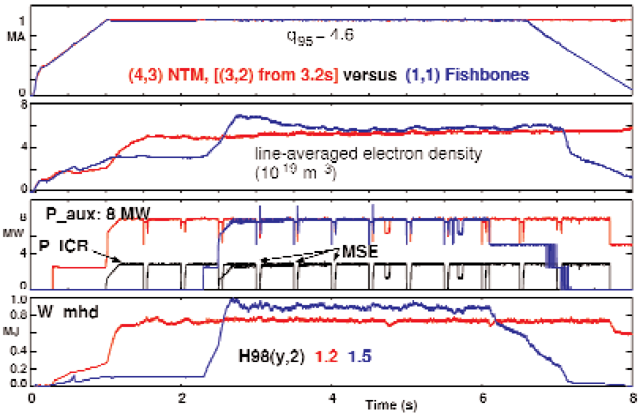

Figure 1: Comparison of a discharge with (early) heating during the ramp-up (red curves) and a discharge with (late) heating during the flat top ramp-up (blue curves). The stored energy is significantly higher for the late-heating case. Since operational parameters are almost identical this shows up directly in the H-factors, which are 1.2 and 1.5 respectively, using the IPB-H_{98}(y,2) scaling.

Key to the improved H-mode scenario is to obtain a stationary q-profile with q(0) near 1 and with low magnetic shear. This specific q-profile is obtained by heating during the current rise phase of the discharge, at moderate neutral beam power. In the subsequent main heating phase the plasma pressure can be increased to reach β_N~3.

Recent studies at ASDEX Upgrade aim to further characterise and understand the physics of the improved H-mode scenario. The main focus is on the influence of the ramp-up phase for plasma current and heating on energy confinement and MHD-activity during the subsequent flat-top phase. Depending on the ramp-up scenario two different stationary plasmas can be generated, although external control parameters are similar for the flat-top phase (figure 1).

The MHD-modes observed during the flat-top phase are different in the cases shown in figure 1. For the early-heating a (4,3)-NTM is observed at 1.8 s which changes to a (3,2)+(5,4) NTM at 3.2 sec. The late-heating case shows (1,1)-fishbones

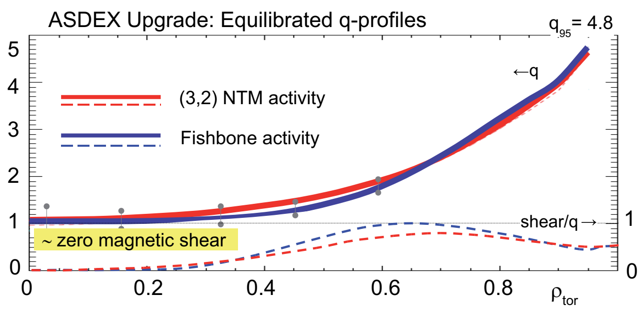

Figure 2: Typical q-profiles in improved H-modes for two types of discharges. These q-profiles are obtained during the flat top phase of the pulse. One discharge with NTM activity (red curve) is compared to one discharge with fishbone activity in the centre (blue curve). The magnetic shear s=(r/q)dq/dr is also shown, normalised to the local q value for these two cases.

during the whole phase with full heating power. The equilibrated q-profiles are shown in figure 2; these are obtained using MSE data to constrain the CLISTE reconstruction.
The differences between the current profiles in the flat-top phase appear to be due to different MHD modes. These MHD modes set in during relaxation of the current profile, which itself depends on the ramp-up scenario. Also the stored energy is different in the two cases, as well as the peaking of the temperature profiles. Three mechanisms seem to play a role in linking the observed changes in MHD-behaviour and current profile to the changes of the kinetic profiles: the increased transport due to the MHD modes themselves, the variation of the ratio of magnetic shear to safety factor, which modifies the critical temperature gradient-length for the onset of ITGs and effects on the H-mode pedestal pressure. Also the latter shows remarkable differences as analysed on the basis of high-resolution Thomson-Scattering measurements at the plasma edge.

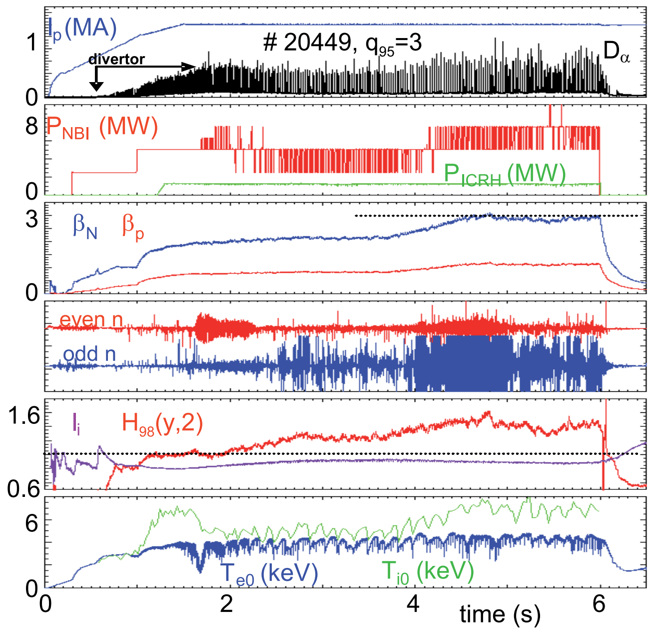

Figure 3: An improved H-mode at q_{95}=3.17 (1.2MA/2.0T, #20449), achieving H_{98}(y,2)=1.4 at β_N=2.9, with fishbone activity in the centre keeping the q-profile stationary.

The central tungsten concentration can be kept at acceptable levels ($<10^{-4}$) in improved H-mode experiments by using RF heating in addition to the NBI heating. Operation at high density with $\langle n_e\rangle=1.1\times10^{20}$ m^{-3} ($\langle n_e\rangle/n_{GW}$=0.85-0.9) is demonstrated. However, the highest H_{98}(y,2) values are achieved at ITER relevant ν* (operation at low $\langle n_e\rangle$). New experiments at q_{95}=3.1 achieve H_{98}(y,2)=1.4 at β_N=2.9, with fishbone activity in the centre keeping the q-profile stationary (figure 3). ECCD can be used to stabilize (3,2) NTM activity during the low β_N~2 phase of these discharges at low q_{95}~3. This (3,2) NTM activity can be seen around t=2 seconds in figure 3. The kinetic profile shapes are scaled to ITER, setting $\langle n_e\rangle=0.85n_{GW}$ and keeping $\beta_{N,th}$. This predicts (figure 4) high fusion power for improved H-mode discharges at q_{95}=3.1 (P_{fus}=1070 MW, Q=∞). In these conditions, the density and temperature at the edge are within ITER design parameters. At lower I_p in ITER (9.5 MA-13 MA), significant fusion power can be achieved ($P_{fus}\geq$400 MW, Q=6-15). However, using the IPB_{98}(y,2) scaling expression, the auxiliary power requirements at high β_N>2.5 and at I_p<11 MA may exceed the maximum P_{aux} planned for the first stage of ITER (73 MW).

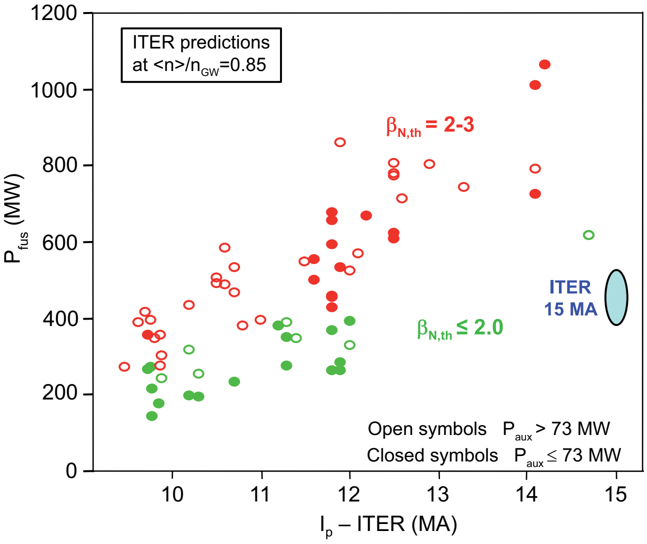

Figure 4: The fusion power in ITER is predicted by scaling the kinetic profile data from ASDEX Upgrade. The dependence on the plasma current used (I_p-ITER) is shown.

3 Turbulence and zonal flow physics

3.1 Core ITG & TEM turbulence transitions

Changes in the behaviour of core density peaking with variations in plasma collisionality have been attributed to transitions from trapped electron mode (TEM) to ion temperature gradient (ITG) dominated turbulence. This hypothesis was tested by measuring changes directly in the turbulence velocity using Doppler reflectometry. Doppler reflectometry measures the propagation velocity $u_\perp=v_{E\times B}+v_{ph}$ of the turbulence moving in the plasma. The magnitude and direction of $u_\perp$ depends on the plasma scenario, particularly on the momentum driven rotation by neutral beam injection. However, in non-NBI heated discharges $u_\perp$ drops to a few km s^{-1} and becomes comparable to the expected turbulence phase and $E_r\times B$ velocities, e.g. $v_{E\times B}\approx v_{ph}$. Radial profiles of $u_\perp$ in ohmic diverted discharges with various densities and plasma currents show a positive and negative peak structure associated with the SOL and edge ∇P regions – which is notably invariant – due to the high collisionality (above banana limit) in this region which affects the dominant drift wave turbulence only marginally. However, in the core, $u_\perp$ reverses from the ion to the electron drift direction with increasing collisionality ν*, as shown in figure 5 at normalized radius ρ_{pol}=0.7, together with an additional jump from one linear branch to another around the cross-over.

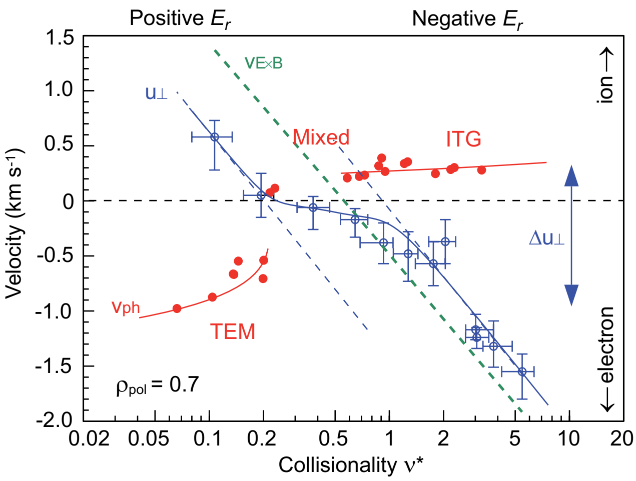

Figure 5: Core $u_\perp$ velocity from Doppler reflectometry for ohmic shots with computed phase velocity (GS2) and E×B velocity (dashed-line) vs collisionality

Also shown are the corresponding phase velocities computed for these discharges using the GS2 linear gyro-kinetic code ($v_{ph}=\omega_r/k_\theta$ real part of the dominant instability frequency corresponding to the poloidal wavenumber at which the growth rate $\gamma/k_\perp^2$ is maximum). The phase velocity shows an abrupt reversal from the electron to ion drift directions indicating the transition in the dominant core turbulence from TEM to ITG. For this data the probed $k_\perp$=10-12 cm^{-1}which straddles the expected ITG and TEM wavelength range. The magnitude of the jump in the phase velocity matches that in $u_\perp$ across the transition. This essentially validates the GS2 code for these conditions and suggests a smooth linear variation in the resultant $u_\perp$ against log(ν*), and hence a core E_r which changes sign with the dominant turbulence. At high collisionality TEM turbulence is predicted to be linearly stable leaving the predominant ITG, while at low ν* TEM dominates. However, in between, simulations predict similar growth rates for TEM and ITG, creating a transition region with mixed turbulence nature. (Note that the GS2 code tracks the dominant mode and does not resolve sub-modes.) The $u_\perp$ curve indeed suggests that the density structures move with a resultant velocity between TEM and ITG. Attempts to identify two separate modes in the Doppler spectrum corresponding to $v_{E\times B}=v_{ph(ITG/TEM)}$, so-called line-splitting, have not revealed convincing double peaks or discernible modulation in $u_\perp$. In addition to density scans (within and from shot-to-shot) the collisionality has also been perturbed via the electron temperature by applying up to 800 kW of on-axis electron cyclotron heating in various power steps. Similar $u_\perp$ behaviour is obtained, although, the transition from ITG to TEM tends to be sharper. Also, at high densities (the ITG range) the turbulence spectra are significantly wider – beyond that due to rotational broadening alone, suggesting a change in the underlying turbulence k-spectrum.

3.2 Zonal flows and GAMs

Turbulence theory and numerical simulations predict that zonal flows and associated geodesic acoustic modes – GAMs (radially localized oscillating E×B flows with an m=n=0 mode structure but finite radial extent generated by non-linear turbulence interactions) are important in moderating the turbulence amplitude via shear de-correlation. Continuing investigation of GAM behaviour using Doppler reflectometry shows coherent $v_{E\times B}$ modes across the edge confinement region. The mode frequency is typically between 5 to 25 kHz and scales linearly as $\omega=G\,c_s/R$ (sound speed over major radius with a scale factor G of the order of 1) over a wide range of ohmic and L-mode conditions. GAMs, however, have not been observed in H-modes, possibly due to reduced zonal flow drive resulting from the lower turbulence levels, or due to the higher rotational shear in the edge. The GAM frequency shows the appropriate variation with ion mass for Hydrogen, Deuterium and Helium plasmas, but with a strong inverse dependence on plasma elongation κ and a weak direct dependence on the local q. Figure 6 shows the variation of the GAM frequency vs $\sqrt{(T_e+T_i)}$ for various plasma elongations κ at a fixed q_{95}. A series of dedicated κ and q scans were performed resulting in a best-fit frequency scaling of $\omega\approx4\pi\, c_s/R\, [(1+\kappa)^{-1}\text{-}q^{-1}]$. There is some variation in the 4π factor with radial position which may indicate additional parameter dependence. In fact the GAM frequency is not a smooth monotonic function of radius but shows distinct plateaus a few cm wide which is indicative of several zonal flow layers. Typically the GAM is observed in the edge density gradient region up to the pedestal radius (i.e. r/a>0.92), but at high q_{95} and low elongation the density pedestal is less pronounced and the GAM can be seen as far in as r/a≈0.75. This points to a link with the high turbulence drive and the large vorticity and E_r shear present in the edge. GAMs are not seen in the open-field SOL region (1/f spectra), nor inside of the density pedestal region / core (flat spectra). The q dependence in the above equation predicts a lower q limit for which the GAM can exist. Experimentally this is observed in the low κ discharges where as the q profile falls, the innermost GAM position is pushed progressively outward, i.e. the GAM is bounded by both the q and density profile. GAMs are also absent at high collisionality. The zonal flow m=n=0 mode structure is still to be confirmed, but there is indirect evidence of the GAM m=1 pressure side-band mode from non-diverted (low elongation) plasmas where the reflectometer line-of-sight is closer to the m=1 mode maxima. High κ diverted plasmas show no corresponding density oscillation.

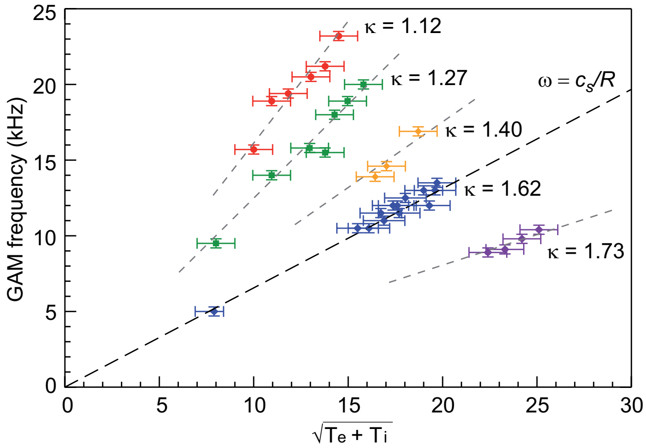

Figure 6: GAM frequency vs $\sqrt{(T_i+T_e)}$ for ohmic plasmas with increasing plasma elongation κ at fixed q_{95}=3.85

4 Loss of fast ions due to MHD modes

4.1 Fast particles physics: a keyword in the AUG programme

One of the crucial aspects of fusion research is fast particle physics. AUG has unique capabilities to contribute to this subject, thanks to a powerful and flexible heating system, to innovative diagnostics and to a strong integration between experiments and theory. Fast particle physics has become therefore an important element of the AUG experimental portfolio and many experiments were carried out in 2006.
The AUG heating system, with 20 MW of NBI at 60/93 keV, 7 MW of ICRH and 2 MW of ECRH, allows for a variety of scenarios, where the fast ion population can be finely tuned and decoupled from the bulk plasma. In addition, the ICRH launchers can be slightly detuned to produce a beatwave, with carrier frequency variable from a few kHz to approx 400 kHz. This provides a tool for testing the resonant response of the plasma.
An important diagnostic like the fast ion losses detector (FILD), which was initially tested in 2005, has been optimised and provided a large set of experimental data during the 2006 campaign. The FILD (its principle is illustrated in last year's report) measures fast ion losses resolved both in energy and pitch angle. The sampling rate of 2 MHz allows all the fast particles' dynamics up to Alfvén modes and beyond to be observed. In addition, the 148 SXR channel tomography and the reflectometry have provided crucial elements for the reconstruction of fast particles driven mode eigenfunctions.

4.2 Fast particles losses driven by Neoclassical Tearing Modes (NTM)

The impact on the global confinement of NTMs has been broadly studied, but less is known on how they influence energetic particles. To this purpose, experiments have been performed in 0.8 MA plasmas with NBI as the main heating and fast particle source. Fast particle losses are observed in the presence of both 2/1 and 3/2 islands. Lost fast particles are mostly passing and are produced by the NBI. When they leave the plasma they have energy close to the value they had when they were injected. Their transit frequency (~200 kHz) is higher than the mode frequency (~5 kHz for 2/1, ~15 kHz for 3/2). A coincidence between the frequency and phase of the mode and those of the losses is observed, as well as a strong correlation between the NTM amplitude and the amount of particle losses. An example is shown in figure 7, which reports the Fourier spectrograms vs. time for one of the FILD channels (#7, corresponding to particles with pitch angle ≈70° and energy ≈90 keV) and for a magnetic pick-up probe, for a time lag where a (2,1) NTM and its harmonics are present. Preliminary experiments, where the NTM amplitude has been reduced by means of ECCD stabilization, have also been realized. Experiments with modulated NBI give information on time scales of the losses: a fraction of particles are lost within a few toroidal transit periods (5 µs for 93 keV deuterons), but there is also evidence of slower losses, with loss times up to a few ms.

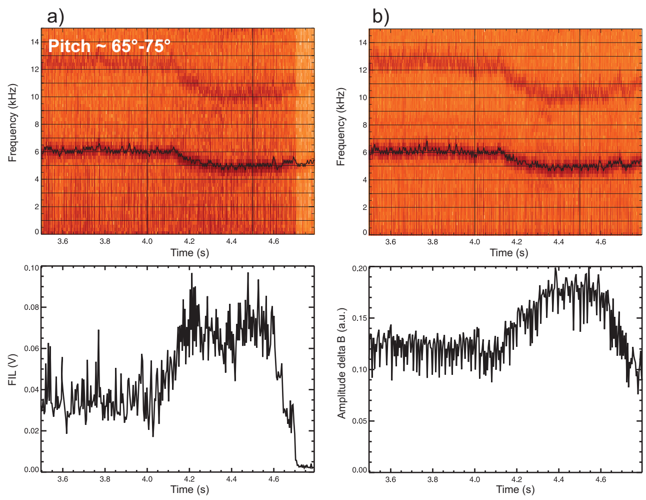

Figure 7: (a) Fourier spectrogram and amplitude of the dominant harmonic vs. time for a FILD signal; (b) the same for a magnetic pick-up coil signal (see text).

The experimental findings have been interpreted in the framework of a mechanism, which involves drift islands in the fast particle orbit space. This mechanism is the result of the interaction of energetic ion motion with a magnetic equilibrium perturbed by a long-wavelength mode. For example, a (2,1) magnetic island does not cause significant ergodicity of magnetic field lines (followed by the guiding centres of thermal particles). The situation for fast particles is different: the coupling between their guiding centre motion in the perturbed magnetic field and the orbit shift due to the drifts (which has a (m=1, n=0) character) results in several chains of drift islands (with (1,1), (2,1), (3,1) and (4,1) helicities) in fast particle phase space. Depending on the shape of the q-profile, on the location of the q=2 resonance and on the amplitude of the original (2,1) mode, these islands may or may not overlap. In both cases they may drive fast particle losses. Simulations of this mechanism performed with the Hamiltonian guiding centre code ORBIT and with the GOURDON code give results, which are consistent with experimental data. An example is shown in figure 8: it can be seen that losses are restricted to a limited region of the ions phase space. Preliminary calculations predict that only a few % of the fast ions are lost due to this mechanism.

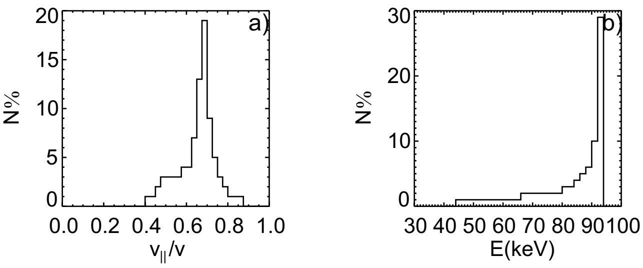

Figure 8: Histograms of the pitch-angles a) and of the energies b) of the particles lost during an ORBIT simulation

4.3 Fast particle losses due to TAE and other high frequency modes

Experiments with constant total heating power, but with a different mix of E- and I-CRH, have allowed the fast particle fraction to be modified, while keeping approximately the same background kinetic profiles. As ICRH power is increased, spontaneous excitation of several TAEs is observed, together with fast particle losses. A resonant interaction between the energetic ions and the magnetic perturbation leads to loss of trapped ions, which have energies up to several hundreds keV and pitch angle $\sin^{-1}(v_{//}/v)$~70-80º. Losses are highly correlated with the MHD activity, in terms of both amplitude and frequency, as shown in figure 9. The wave-particle resonance condition in the plasma frame has been studied using the HAGIS code.

The ICRH beatwave also allows for interaction with TAEs at power levels where they are not excited by the fast particle population. A reduction in the effective damping rate is observed as a function of the increasing fast particle content. Besides TAE, a new MHD perturbation called *Sierpes* mode (due to the shape of its frequency pattern in the Fourier spectrogram, see figure 9), observed for the first time in AUG, has a strong influence on the energetic deuterium ion population. This core-localized mode has a frequency of ≈80 kHz and dominates the transport of fast ions in ICRH heated discharges. Fast hydrogen ions are redistributed from the core toward the edge while deuterium ions are directly ejected to the wall due to their larger banana width. More studies are underway.

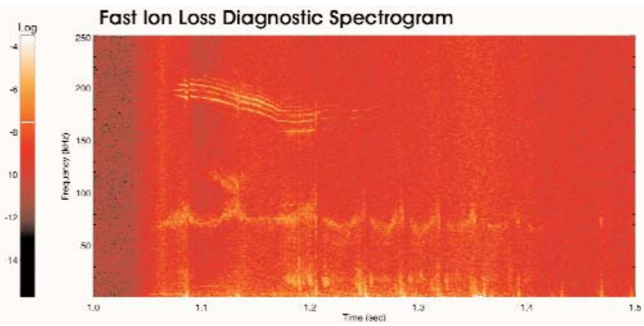

Figure 9: Spectrogram of the FILD channel #13, showing fast ion losses correlated with various types of MHD activitiy: TAEs, sawteeth, fishbones and the Sierpes mode

5 Stabilization of MHD modes by ECCD

Core MHD instabilities limit performance and operational space of tokamaks. Their control is therefore of great importance for present and future devices, such as ITER. ECCD is an ideal tool for this purpose and it is also foreseen for ITER. Therefore work is being concentrated in this area in ASDEX Upgrade.

For sawtooth control, the width of the EC driven current is a key parameter. Previous experiments in plasmas with dominant NBI heating were performed with a broad ECCD deposition of d/a=0.05 (a is the plasma minor radius). In co-ECCD experiments, stabilization (i.e. longer sawtooth period τ_{ST}) was found with the CD just outside q=1 and destabilization with the CD just inside, consistent with changes in the shear at q=1. However, ctr-ECCD was less effective due to the opposite signs of the contribution from heating versus ctr-CD. A comparison between the previous findings and more recent experiments using narrow deposition (d/a=0.02) is shown in figure 10.

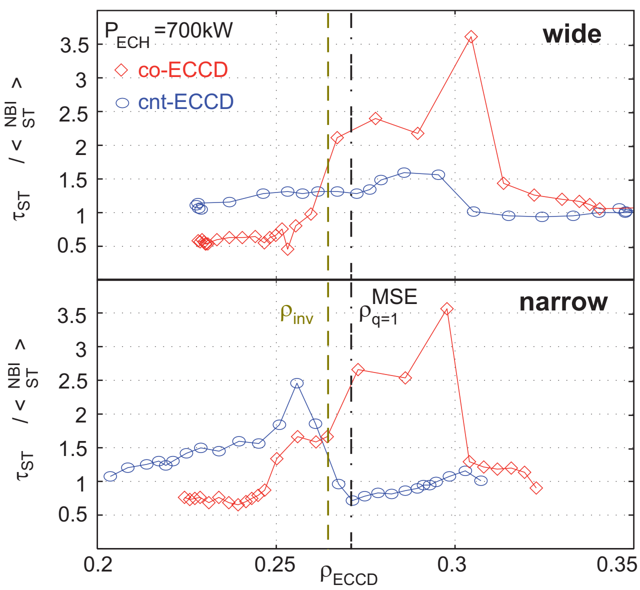

Figure 10: Co- and ctr-ECCD effects for (a) broad and (b) narrow CD deposition

While the heating power is constant, the CD density with narrow width is doubled; hence the CD contribution dominates over the heating. This is drawn from figure 10 (b), where we observe clear ctr-CD stabilizing effects inside q=1 and destabilizing outside. The predicted increase in stabilization efficiency by a factor of 4 is not visible. The CD deposition is varied by a B_T ramp and is moved by ~3.5 cm/s, i.e. the maximum moves by a half width in 300 ms. Hence, at the longest sawtooth periods (~200 ms), quasi-static conditions for the corresponding data point are not reached and further experiments with a discharge-to-discharge variation of B_T will be performed to clarify this point. To isolate the pure heating effects, an additional narrow ECCD experiment has been made in which two gyrotrons at half power have been used, one in co- and the other in ctr-ECCD at the same location. By placing the two CD sources in opposite directions, but with the same total power as for the pure co- and ctr-ECCD, the current drive effects cancel out leaving the heating effects only. By assuming linear superposition of the effects of co- and ctr-CD, we compared the heating effects on τ_{ST} from the ECRH experiment, with the ones calculated from co- and ctr-ECCD. The calculated period is obtained from $\tau_{ST,calc}=(\tau_{ST,co}+\tau_{ST,ctr})/2$. Figure 11 shows such a comparison, with τ_{ST} normalised to the period without ECCD. The measured and calculated curves are in very good agreement and support previous modelling results.

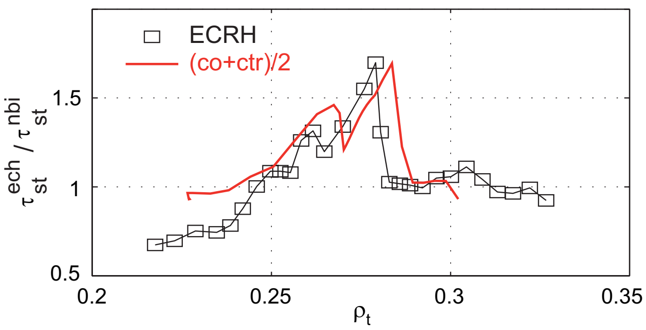

Figure 11: Comparison between experimental and calculated heating effects

For the stabilization of NTMs, the beneficial effects of the narrow deposition have already been documented in 2005. These experiments were made with a deposition width d smaller than the marginal island size W_{marg} ($d<W=W_{marg}$) below which the island decays on its own. However, if the island size W is smaller than d, while still being larger than W_{marg} (i.e. if $d>W>W_{marg}$), theory predicts that the required power can be substantially higher. As for ITER W_{marg} might be smaller compared to present experiments and modulated ECCD will be required in order to deposit power only in the island O-point. To validate the theoretical predictions, a series of experiments with broad ECCD deposition have been performed, once with non-modulated (DC-ECCD, for which the mode is not stabilized) and once with modulated ECCD.

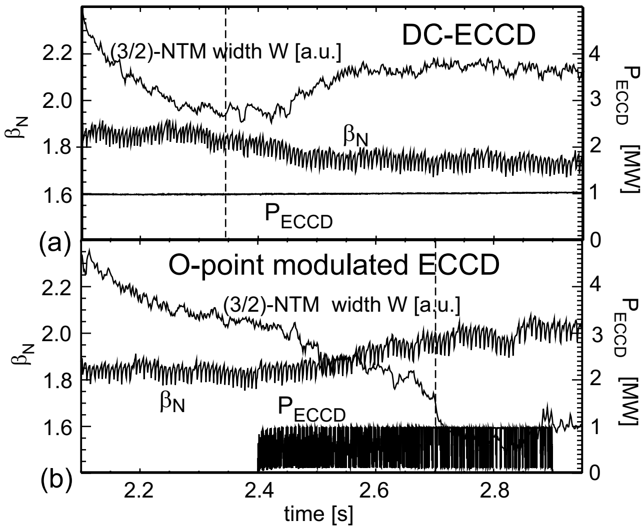

Figure 12: NTM stabilization experiment comparison between (a) DC and (b) modulated broad ECCD deposition

For the modulated case, it is essential to inject the ECCD in phase with the island O-point. To achieve this requirement, the ECCD has been feedback modulated using the magnetic pick-up coils. The phase shift between the mode and the ECCD has been set up in order to inject the ECCD in the island O-point and X-point as well as at different phases between them. Figure 12 shows the comparison of NTM stabilization for the cases of (a) DC-ECCD and (b) modulated ECCD. Comparing the (3/2)-NTM amplitude, it is clearly seen that DC-ECCD reduces the island only partly, while modulated ECCD fully stabilizes the mode. It is important to underline that for a same discharge, performed with narrow DC-ECCD width, the NTM is regularly stabilized at higher β_N. Figure 13 shows the achieved reduction of the island size as a function of α_{exp}, the phase difference between island O-point and ECCD power deposition. Although the predicted destablizing effect for pure X-point modulation could not be found, the figure clearly shows that by modulating in phase with the island O-point the stabilization efficiency is maximized and the NTM completely suppressed.

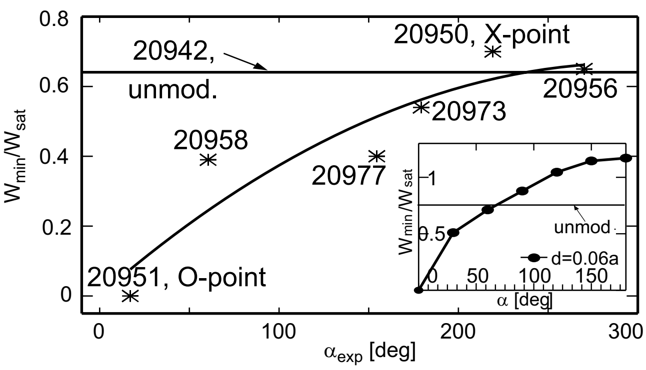

Figure 13: Island size reduction versus phase difference between mode O-point and ECCD power

6 Filamentary transport

Present ELM models and simulations, e.g. MHD and/or turbulence codes, show that the release of the ELM energy is not axially symmetric but localized in the outer mid-plane. The localized helical loss of particles and energy from the hot pedestal appears in the scrape-off layer in the form of magnetic field aligned filament-like plasma structures. Footprints of these structures have been detected as spiral power deposition structures on the upper divertor targets, as D_α light in the outer mid-plane, as density and temperature blobs by the Thomson scattering system, and as heat and particle load to probes exposed to the far SOL plasma. The strength and the movement of such filaments in the far SOL (near to the low field side inner wall) were investigated by combined measurements with different Langmuir and magnetic pick-up probes and with thermography of the probe heads. The Thomson scattering system was used to investigate blobby transport during ELMs but also for inter-ELM phases.

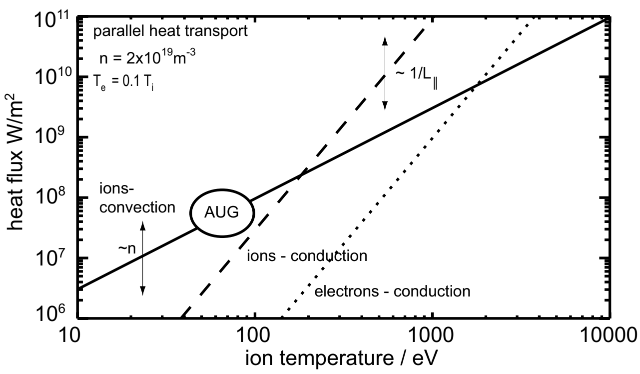

Figure 14: Comparison of parallel energy loss channels in the SOL in dependence on the ion temperature

The Langmuir probe measurements show a burst like structure of the ion saturation current during type-I ELMs with a width of a few microseconds and a period of a few hundred microseconds (figure 15). Each burst is attributed to a single filament. The temporal evolution of a burst is characterized by a steep increase and a slower decrease on a time scale of tens of microseconds.

The e-folding lengths of the ion saturation currents measured with the two different Langmuir probes and that of the heat flux are comparable. This is a typical feature for all the discharges under investigation and implies that the e-folding length for particle and heat flux is dominated by the density e-folding length. It follows from this that the reduction of the energy content in the filament is rather a loss of particles than a cooling of ions or electrons. This requires that the heat conduction ($\sim T_e^{7/2}$) has to be small compared to convective losses ($\sim n_e T_i^{3/2}$) as expected for cold electrons (<10 eV) and marginally collisional ions (see figure 14) in the far SOL.

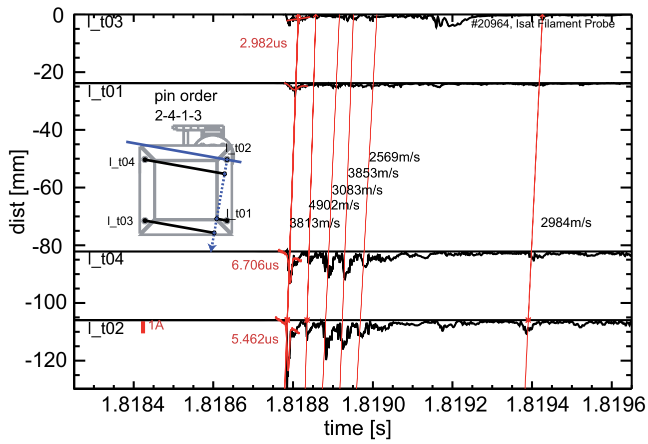

Figure 15: Measurement of the filament poloidal rotation speed during a single type-I ELM. The geometry of the filament probe is shown as insert.

This is consistent with the estimations for the ion temperature of about 30-60 eV by comparing heat load and particle flux.

A magnetically driven filament probe which was recently installed allows us to deduce the rotation velocities of filaments perpendicular to the direction of the magnetic field at the radial position of the protection limiter in the SOL. Four Langmuir pins are arranged at the corners of a rectangle, surrounding a magnetic pick up coil. For a given local field line inclination angle, the position of these Langmuir pins can be mapped along field lines to the same toroidal position. The time delay of the signals (ion saturation current, j_{sat}) allows us to deduce the rotation speed, as shown in figure 15. From the time delay a rotation downwards, i.e. toroidally in co-current direction, with a velocity of about 4 km/s can be estimated. The rotation velocity becomes slower in later phases of an ELM (see figure 15). No significant dependence of the rotation velocity on the distance to the separatrix was detected.

The signal measured by the magnetic pick up coils could be modelled by assuming a field aligned current rotating in front of the pick up coils. Two main cases were investigated. A filament rotating slowly (v_{pol}=3.5 km/s) in the SOL and a fast (v_{pol}=20 km/s) rotating filament inside the separatrix. The required current densities are about 600 A/cm² for the filament in the SOL and 12 A/cm² inside the separatrix, respectively. This has to be compared to the maximum ion saturation current of about 15 A/cm² that was measured by Langmuir probes inside the SOL, i.e. the signal of the magnetic pick-up coils is caused by remote filaments of the separatrix region in contact with the core plasma.

Large scale inter-ELM fluctuations are measured in the hot and steep plasma edge H-mode profiles of electron density and temperature by high precision, high resolution Thomson scattering. These large scale fluctuations are also observed by Electron Cyclotron Emission. Fluctuations with a quasi-periodic structure were found in a 2D snapshot with a frequency of about 61 %. When interpreted as field-aligned helical structures toroidal quasi-mode numbers of 6 to 48 were found. The amplitudes of the fluctuations decrease with increasing quasi-mode number and edge profile gradient lengths. In the SOL also large-scale fluctuations in the electron density are observed in the 2D poloidal snapshots (see figure 16). The number of electrons confined in these filaments in the near SOL decays exponentially with increasing distance from the separatrix. This confirms the results obtained by Langmuir probes and Thermography in the far SOL: it was found that the particle loss during an ELM is at least to a significant fraction due to the electron density ‘blobs’ as observed in the SOL by Thomson scattering.

In the 2D poloidal snapshots of electron density and temperature both quasi-periodic and non-periodic large scale fluctuations with relative fluctuation amplitudes up to 100 % are found. In the middle of the steep gradient region the perturbations are symmetric, but asymmetric both further inside (more minima), and further outside (more maxima).

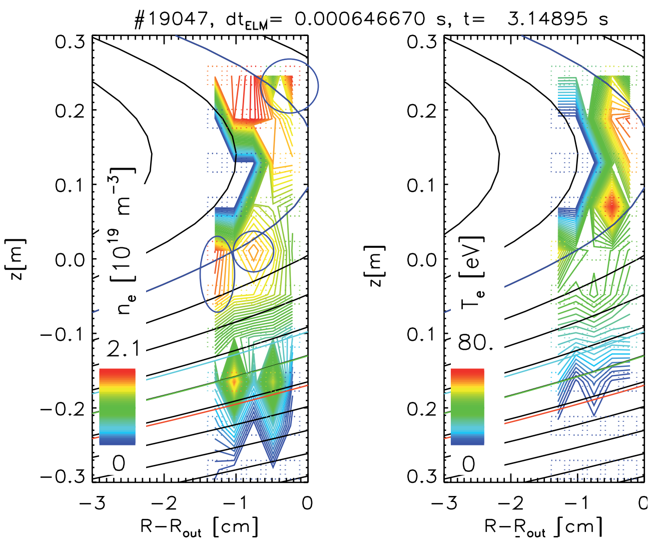

Figure 16: Filaments during an ELM. The position of the separatrix is marked in blue.

7 Technical systems

In 2006, the experiment was in operation for 40 days performing 710 shots in total with 520 shots useful to the physics programme. There was an incident with the flywheel generator EZ4, on April 27th which terminated the experimental programme for 2006. This unscheduled opening was used for extensive cleaning of tungsten surfaces that were installed during the last years, to improve the in vessel fore-vacuum system and additionally to install non-scheduled diagnostics. As a last step towards a full tungsten experiment, the strike point modules in the lower divertor are now covered by tungsten (see figure 18). The structure and the shape of the inner divertor were modified to allow easy replacement of target tiles.

7.1 Machine core

The operation in 2006 was dominated by the incident with the flywheel generator. Details are given below. In addition the improvements to the gas feeding system and the vacuum vessel are described. The cryogenic system was operated without problems and was not modified in 2006.

Power Supply: On 27th April there was an incident involving the flywheel generator EZ4. Due to a combination of failures in power supply and control circuits, neither the braking system nor the pumps for the lubrication worked, so the bearings ran hot. Strong vibrations occurred that broke the oil supply lines. In the bearings, material melted, ablated and the shaft dropped down. Finally the rotor touched the stator; this caused irreparable damage to the isolation of the stator winding. The rest of the 2006 campaign was cancelled. The main consequence of this was that an additional independent ohmic breaking system for EZ2 will be installed by March 2007. After these changes to the generator the next campaign will start. EZ4 is planned to be available again in 2008. Without EZ4, less than half of the energy and power for the poloidal field coils and additional heating is available. Investigations to optimize the configuration of the power converters without EZ4 have been made, using a new configuration of the power supplies. Successful tests in July 2006 of operation with EZ3 alone proved the feasibility of this new configuration, which is mainly based on lower maximum voltages and therefore slowing down the current changes in the coils. Operation at a plasma current of, e.g. 0.8 MA with additional heating up to 10 MW will be possible with a flat top time of 4-5 seconds. In 2007 the thyristor converter groups 8 and 9 for torsional damping will be installed. Furthermore the first of at least 5 units of EZ5 will be tested and installed.

Vacuum Vessel: The carbon remaining in the vessel during the step by step transition to a full tungsten first wall led to a re-deposition of C on the W surfaces. These tiles had to be taken out and cleaned by an ultrasonic water bath to achieve a first wall free of carbon layers. The design of the inner divertor has been changed to allow a replacement of the strike point tiles without dismounting the base structure, and increasing the effective pumping speed. The alignment of in vessel components has been adjusted using a FAROArm®.

Torus Pumping and Gas inlet system: For the torus pumping system (TPS) a new cooling water control has been installed. The exhaust line was improved to avoid explosive gases by flushing it with pure nitrogen. Three turbo pumps crashed in 2006 because the bearings reached the end of their lifetime. Due to the modular design of the TPS, these crashes did not influence the plasma operation. Two types of new turbo pumps have been tested during operation.

The main effort was focused on the Gas Inlet System (GES). The old gas feeding system consists of 20 piezo valves, which were fed by 4 common lines and individual gas bottles inside the torus hall. For safety reasons the gas bottles were

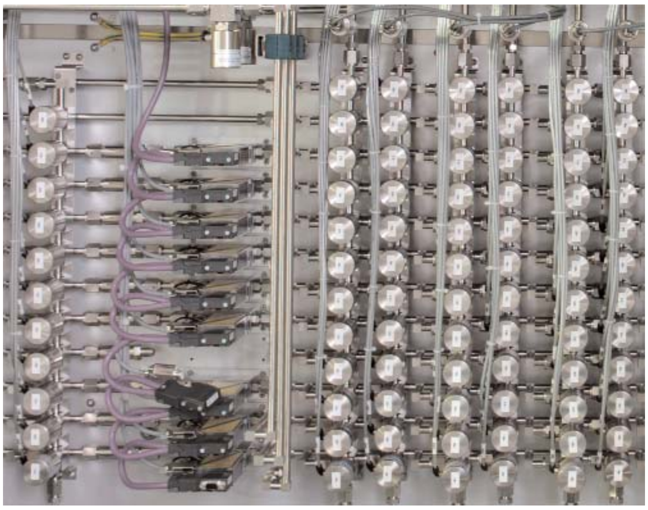

Figure 17: Part of the new gas inlet matrix

Figure 18: View of the new full W divertor

moved to an outside cubicle. To gain more flexibility and to allow a complete remote change of the gas species a switching matrix has been installed (see figure 17).

Ten gas stations for different gases have been built up outside the torus hall. All stations are metal sealed. The gas is fed via stainless steel tubes into the matrix. This allows switching the gas to 20 different stainless steel tubes, which feed a valve installed at the vessel. The pressure at the matrix is controlled to allow an accurate calibration of the gas valves, which is essential for gas balance investigations. The gas species for each valve can be changed in-between shots. The matrix is fully controlled by a SIMATIC PLC system. As at the TPS, the different parts are operated via a local PROFI-BUS. The components are linked by fiber optics on the PLC. The first 4 valves have been operated by the gas matrix. This will allow a remote change of the gas species by the fast shot control system.

7.2 Preparation of an all W first wall

The area covered by W-PFCs has been increased steadily since 1999 reaching 100 % for the 2007 campaign (see table 1). The configurations chosen are W coatings on graphite in order to reduce mechanical loads which could arise from eddy and halo currents due to the higher conductivity of W compared to C. The different PFCs are subject to different power loads and erosion yields. This is taken into account by selecting appropriate different thicknesses of the W-coatings produced either by physical vapour deposition (PVD) or vacuum plasma spraying (VPS). Although ‘thick’ VPS coatings have already been used during the 1995/1996 W divertor experiment it became evident that laboratory tests are necessary in order to provide reliable solutions for the coating of the divertor. Additionally, the geometry of the strikepoint tiles was adjusted (see figure 18) and the CFC substrate of the inner strikepoint module was exchanged for graphite in order to optimise the conditions for the application of and the operation with the W coatings.

VPS coatings from two suppliers (Plansee AG and Sulzer Metco AG) were tested at the ion beam facility GLADIS in thermal screening tests up to 23.5 MW/m² as well as under cyclic loading for 200 pulses at 10.5 MW/m² on tiles with a specific test geometry and two graphite substrates (SGL R6710 and Schunk FP479) without any failure. Finally, three divertor strike point tiles from the production process (Plansse AG) passed the cyclic loading as well. The Langmuir probes are produced from bulk W material (Negele, Plansee AG).

Campaign	Location (incremental)	Coating (µm)	Area (m²)	Remark
2002/2003	central column upper PSL inner baffle low. divertor	1 PVD	14.6	all new W coatings, erosion meas. at central column
2003/2004	upper divertor outer baffle low. divertor 1 guard limiter	4 PVD	24.8	test of guard limiters, erosion meas. at limiter and divertor
2004/2005	upper aux. limiters horiz. plate low. divertor 1 ICRH limiter	4 PVD 200 VPS	28.0	test of VPS coatings for limiter and divertor applications
2005/2006	all poloidal LFS limiters roof baffle lower PSL	3 PVD	35.9	VPS coatings removed, lab. tests of VPS coatings
2007	lower outer divertor lower inner divertor all toroidal LFS limiters diagnostic armours	200 VPS 3 PVD	40.8	complete W coverage of all PFCs

Table 1: W coatings applied since 2002. The coatings were produced either by Plasma Vapour Deposition (PVD) or Vacuum Plasma Spray (VPS).

7.3 Control, data acquisition and computer infrastructure

The new real-time plasma control showed remarkably stable operation and excellent performance characteristics. Further

enhancements were prepared for machine protection, instability handling and feedback control but could not be tested because of the experiment shut-down. We made best use of the unwanted situation with renewal of control IO: many out-dated IO modules were replaced (higher bandwidth, lower latency, strongly reduced number of modules), and connectivity to new real-time diagnostics improved (to give free access to all plasma control information). To facilitate plasma control development when experimenting restarts a second (reduced scale) plasma control was installed as a lab test bed, supporting discharge replay with input data from previous discharges or with artificial data. A new experiment supervision system was commissioned to support the chief operator. The system co-ordinates plasma control, data acquisition, and plant systems for heating, fuelling, magnetics and power supplies. It assists the operator to select among discharges or various test cases and select parameters. With this it manages case-specific preparation, execution and post-execution activities and exchange and conversion of information among systems, and provides execution state information back to the operator. Finally it logs all information for performance analysis, failure tracing and the archive.
By replacing an old "Black Diamond" network backbone switch with a new "eXtreme 8810" model, the first step was made in enhancing the backbone speed from 1Gb to 10Gb. This has become mandatory in order to react to the soaring amount of data handled for data acquisition, data analysis, and cross server traffic in the AUG network.
The AUG file systems have been extended by new RAID arrays and file servers (partly organised in high availability clusters). Disk space has been extended to 2.5 TB for users, 16 TB for on-line "normal" shot files, and 1.2 TB for MR-AFS staging space. The shot file archive is backed up by the mass storage facilities of the RZG. Two thirds of the "normal" shot files now reside on disk. This reduces the access time to only fractions of a second and is a great advantage to the data analysis.
Renovating 60 more offices with thin Sun-Ray desktop appliances carried forward the transition from separate computer workstations into a new world of client/server computing. In total now 180 thin clients are utterly quiet providing computing power to users in the AUG IT environment.

7.4 Neutral beam heating

After extended maintenance work during the previous summer shut-down, both injectors had been recommissioned in time for the 2006 operation period. The modified gas inlet system with the gas bottles moved to an outdoor cubicle for safety reasons worked without any problems. The injection system was reliably available for plasma heating at maximum parameters (20 MW D^0 from eight beams) under full control of the new CODAC system, and individual beams were routinely used as diagnostic beams for the MSE and CXRS diagnostics.
After roughly three months of operation, however, two water leaks in injector-1, one occurring shortly after the other, resulted first in a loss of one beam and finally in the loss of the whole injector. The first leak was due to melting of the back plate in ion source #3, a source that had been in operation since the beginning of the injection experiments some 13 years ago. The reason for this was identified as a failure of an electronic device responsible for the transmission of the set points from the injector control to source power supplies. As a consequence, the load onto the back plate due to back streaming electrons became intolerably high leading to melting of this plate after two seconds of a shot onto the calorimeter. An interlock was implemented into the control system to prevent similar failures in the future.
During the re-commission of the injector one of the calorimeter plates developed a water leak. This plate, together with a few others, was installed during the previous maintenance period. Those have been produced by applying a modified production technique: electron beam welding was used instead of brazing. Inspection of the damaged plate revealed that broken welding seams were responsible for the failure. In addition, further examination of the new plates showed that all newly procured plates suffered from cracking of some welding seams after a short period of operation. They are being replaced by spare plates from the original production series. Methods of improving the design of the new plates are presently being discussed with industry. Since the flywheel generator accident, neutral beam operation has stopped. During the subsequent shut-down inspection and maintenance work was carried out and recommissioning will start as soon as the generators are available again.

7.5 Ion Cyclotron Resonance heating

The ICRF system was ready for operation at the restart after the summer opening in 2005. It operated reliably during the whole campaign. Substantial maintenance work, improvements, and new installations were made to the ICRF system and related supporting equipment in parallel to operation during the experimental campaign but more specifically in the present, somewhat longer opening. On the generator side, the final stage of two of the four generators underwent a thorough check-up including complete dismantling, cleaning and refurbishing of worn-out or broken components. Additional diagnostics were added to all generators allowing faster detection of the cause in case of a fault. As the vacuum transmission line, feeding antenna 3, had shown an increasingly degrading power handling capability in the last few years, we had made provisions to dismantle it and to replace components with newly designed and improved versions. The vacuum transmission line is in the immediate vicinity of the machine, completely surrounded and built-in by many other apparatus that have first to be removed. The intricate work took a long time but was worth it in the end; the cryogenic vacuum system of the same line was refurbished and we are confident that the improvements will restore the power handling capability of system 3. The C limiters at the corners and at the top and bottom of the antenna have been replaced with W-coated limiters. All antenna limiters have now been W-coated, as the

other (side) limiters had already been replaced in 2005. One antenna will be fitted with an optically closed Faraday screen to investigate the influence of shielding the antenna from plasma, possibly coming through ELMs into the antenna, on its voltage stand-off capability.
The cooling of the data acquisition racks was improved, which will increase the reliability and lifetime of the electronic components. An extension of our test facility allows a better follow- up of the tests of the manipulator where, in cooperation with Kharkov University, different materials are being investigated with respect to their voltage stand-off capability. A simplified model of an antenna whose design would be compatible with a stabilising wall was built, and the location of a new test facility for it was secured.

7.6 Electron Cyclotron Resonance Heating

The construction of the new ECRH-2 system with 105-140 GHz/ 4× 1 MW/10 sec is ongoing. Plasma test shots with the first installed gyrotron Odissey-1 were performed up to 820 kW/0.8 sec at 140 GHz. No arcing in the transmission line was observed. The measured transmission losses are 10 % at 140 GHz and 12 % at 105 GHz. The tests had to be stopped because the gyrotron cavity was damaged due to a failure of the superconducting magnet. The gyrotron was sent back to GYCOM for repair. It was replaced by the second gyrotron Odissey-2 which will also work as a two-frequency gyrotron. The extension of the system to four gyrotrons is subject to a European preferential support project. The gyrotrons have been ordered at GYCOM. Construction of the first frequency-tunable double-disc torus window was completed at FZK Karlsruhe. The low power reflection measurements which were performed are in good agreement with theory (figure 19). Since arcing in the high-power long-pulse load was one of the main obstacles in the tests with gyrotron Odissey-1, this load will be replaced by a larger version, already successfully tested at GYCOM. A second long-pulse load provided by CNR Milan is also available.
To prepare the feedback-controlled ECRH deposition for NTM stabilization, detailed tests of the dynamic behaviour of the fast-steerable launchers have been performed in collaboration with CNR Milan using a mockup system. The installation of the fast launchers in the ECRH port has been completed with the mounting of systems 3 and 4. In the old ECRH-1 system, a broken gyrotron was replaced by a similar tube, formerly used at W7-AS. This will bring the system back to its original performance of 2 MW/2 sec for the next experimental campaign.

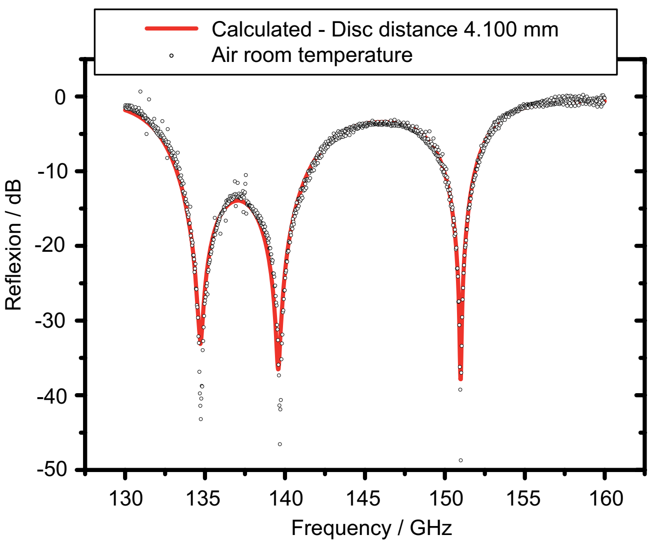

Figure 19: Calculated and measured reflection of the double disc torus window tuned to 135 GHz

8 Core Plasma Physics

8.1 Reconstruction of the internal loop voltage profile

As reported in the Annual Report 2005, discrepancies have been found between the predicted and observed current profile modifications due to off-axis NBI, correlated with the increase of heating power and of turbulent energy losses. It has therefore been surmised that small scale turbulence, driven by gradients in the thermal plasma profiles, might also act on suprathermal particles. To gain direct information on the radial distribution of the NBI driven currents and their temporal behaviour, the radial profiles of the parallel electric field have been investigated.
The latter follow from equilibrium reconstructions, using time dependent measurements of MSE angles and loop voltage. For the loop voltage profiles shown in figure 20, a procedure has been applied using equilibrium reconstruction procedures in the CLISTE code. Immediately after switching from on-axis to off-axis beams (and back), the profiles show the expected behaviour: the loop voltage decreases at the radial location of the respective beam deposition. Within a time much shorter than the current redistribution time however, the loop voltage flattens again. As no strong MHD activity is present in the discharge (except for small fishbones in the very centre of the plasma), current redistribution cannot have been completed within this time. Within this time only the source of the current, the fast particles, can be redistributed.

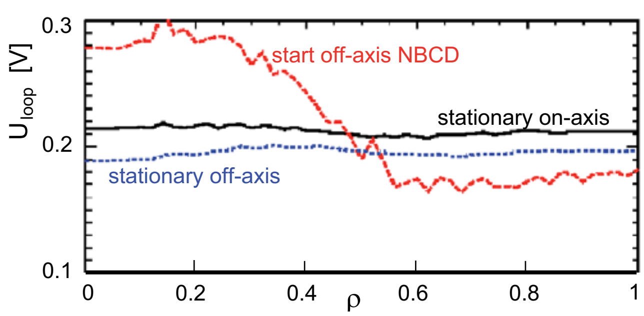

Figure 20: The difference in the stationary U_{loop} demonstrates the larger current drive capability by the off-axis beam. The total heating power is 5 MW in a low triangularity discharge. The off-axis beams are reduced in voltage to restrict the fast ion velocity below $v_A/3$.

8.2 Effect of density peaking on Z_{eff} profiles

During several identical and consecutive H-mode discharges the densities of typical impurities were measured. Their summed contribution to Z_{eff} was compared to the value derived from bremsstrahlung measurements and matched well within the uncertainties (figure 21).

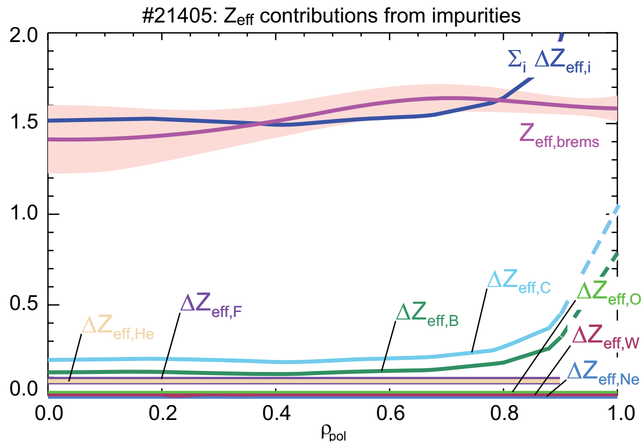

Figure 21: Comparison of Z_{eff} deduced from bremsstrahlung with individual contributions from typical impurities

With peaked density profiles a neoclassical pinch should lead to peaked Z_{eff} profiles. Using on- and off-axis ICRH heating the expected effect was not observed in every case. Plotting the peaking factor of Z_{eff} vs. the one for n_e as in figure 22 revealed that both discharges show the same behaviour but one reached peaking factors of n_e above which the impurity accumulation terminated the discharge, whereas in the other case the discharge was switched to another scenario before n_e-peaking could lead to any significant effect in the Z_{eff} profile.

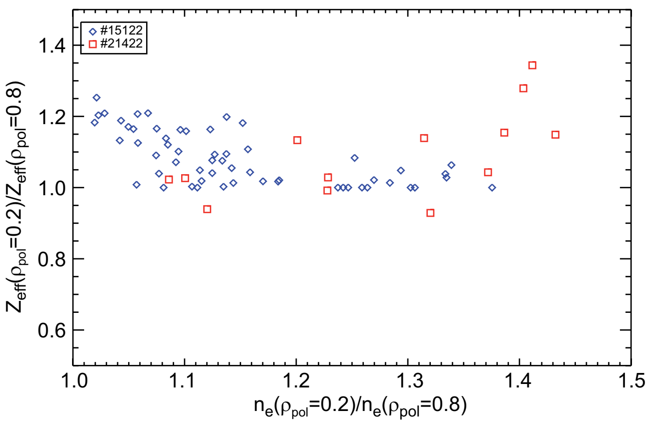

Figure 22: Z_{eff} peaking vs. n_e peaking for ICRH off-axis heated discharges

8.3 Radial Correlation Lengths of the Turbulence

The technique of correlation Doppler reflectometry was employed for measuring radial correlation lengths of the turbulence, L_r. The experimental measurements agree well with theory and with L_r measured on other fusion devices using different diagnostic techniques. A strong link between L_r and plasma confinement was observed. From L to H-mode, an increase in the absolute value of the E_r shear was measured coinciding with a decrease in L_r. This observation is in agreement with theoretical models which predict that an increase in the absolute shear suppresses turbulent fluctuations in the plasma, leading to a reduction in L_r. Further, L_r is seen to decrease from plasma core to edge and to decrease with increasing plasma triangularity δ, indicating plasma confinement improvement with triangularity. The experimental results have been extensively modelled using a 2-dimensional finite difference time domain (FDTD) code. The simulations confirm that correlation Doppler reflectometry measures a consistent and robust L_r, which agrees with the modelled turbulence correlation length. L_r was found to scale inversely with the radial wavenumber, with little dependence on the poloidal wavenumber and fluctuation level. In comparison, the correlation lengths from standard reflectometry overestimate L_r at low fluctuation levels and underestimates L_r at high levels. It appears that an introduction of a tilt angle which removes the specular component in the reflected spectrum improves the L_r measurement in both the linear and nonlinear turbulence regimes.

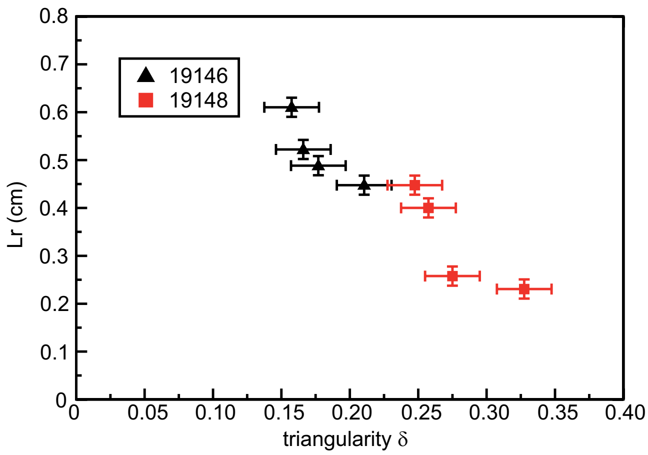

Figure 23: Radial correlation lengths as a function of plasma triangularity

8.4 Non-parametric profile gradient estimation

Reliable profile and profile gradient estimates are of utmost importance for many different physical models in fusion science, e.g. transport modelling or mode stabilization. Fitting profiles to a collection of results from different diagnostics defines basic work in plasma physics. The fitting results often crucially depend on the functional representation of the profile. In particular, the estimated uncertainty of the profile and, even worse, the estimation of the profile gradient and its uncertainty are closely coupled with profile flexibility. This is one reason why profile gradient uncertainties are usually not provided. Profile flexibility to allow for a form-free description of the data often competes with profile reliability.

The estimation reliability decreases with the increasing number of degrees of freedom. The problem of the proper choice of the functional representation of the profile is hampered by measurement errors and by lack of information in profile segments. Severe complications arise from systematic deviations due to inconsistent diagnostics.
The aim is to have a robust technique to allow for a reasonable balance between flexibility and reliability. Flexibility is obtained by using non-parametric profile functionals, e.g. linear interpolation between pointwise estimations or cubic or B-splines. Reliability is frequently obtained by either providing a family of tailored parametric functionals or piecewise polynomial functions combined with modified hyperbolic tangent functions (tanh) at the plasma edge. The uncertainty of profile estimates is determined by measurement errors as well as the supported degrees of freedom (DOF). The balance between fitting the significant information content in the data and avoiding noise fitting poses a major problem. In the framework of Bayesian probability theory the competition between flexibility and reliability is tackled in a natural way by marginalizing all model parameters including the DOF implicitly providing penalization of the DOF. For a reasonable balance between flexibility and reliability an approach using exponential splines was developed and applied to estimate ion and electron temperature and density profiles and profile gradients including reliability measures. An Integrated Data Analysis (IDA) concept allows the combination of sets of diagnostics employing a comprehensive physical and statistical (including systematic errors!) description.

8.5 β_N dependence of heat transport

In the scale invariance approach, the normalised energy confinement time $B\tau$ can be described by a set of dimensionless parameters, such as the normalised Larmor radius ρ^*, the normalised collisionality ν^* and the normalised plasma pressure β_N. There is a great economic interest in operating fusion reactors at high β_N. Therefore knowing the β dependence of confinement and transport is important in extrapolating present day discharge scenarios to ITER plasmas. So far, the experimental studies on this subject have yielded contradictory results. The confinement empirical scaling law for H-mode plasmas exhibits strong negative β_N dependence such as $\beta_N^{-0.9}$, while dedicated experiments performed on DIII-D and JET show no β_N dependence of global confinement time and transport. In order to clarify these discrepancies, first β_N scaling experiments have been performed in ASDEX Upgrade in H-mode with type-I ELMs. In two sets of discharges, performed in different density ranges, β_N has been varied from β_N=1.4 to 2.2 while the other dimensionless parameters were kept constant. The global analysis of these experiments exhibits a strong unfavourable β_N scaling, $B\tau \propto \beta_N^{-0.9}$. This result is confirmed by the local analysis which shows an increase of the thermal heat diffusivity with increasing β_N,$\chi_{eff}/B \propto \beta_N^{0.65}$.

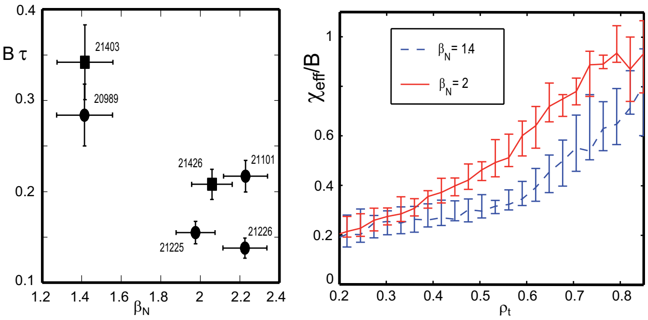

Figure 24: Normalised confinement and diffusivities as described in the text

This is in disagreement with DIII-D and JET results. Two main differences can be identified: in comparison to JET and DIII-D, in ASDEX Upgrade the collisionality is higher by a factor of 5 and the upper triangularity is somewhat lower. To investigate the question of the role played by plasma shape in β_N scaling, new β_N scans, in which the plasma shape will be changed are planned for 2007 in ASDEX Upgrade and DIII-D.

8.6 Stochasticity during MHD mode interactions

The role of stochastization of magnetic field lines is analysed in fast reconnection phenomena occurring in AUG plasmas during various conditions. The mapping technique is applied to trace the field lines of toroidally confined plasma where perturbation parameters are expressed in terms of experimental perturbation amplitudes determined from measurements (magnetics, ECE, SXR). It is known that a stochastic region can be created if the two conditions are fulfilled: (i) amplitude of the perturbations must be sufficiently large (ii) all the modes have to be locked simultaneously. It was shown that these conditions are fulfilled for two completely different MHD events: frequently interrupted regime of neoclassical tearing mode (coupling of (3,2), (4,3)

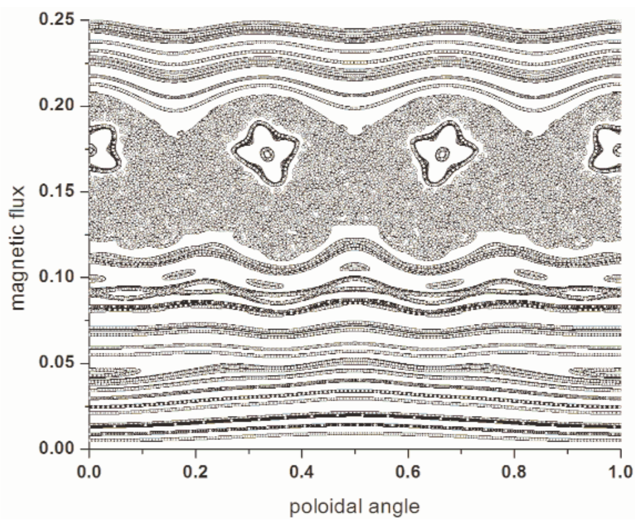

Figure 25: Poincare plots for interaction of (3,2) tearing mode, (4,3) ideal mode and (1,1) ideal modes. Stochastic region is clearly seen in figure for experimental perturbations.

and (1,1) modes, see figure 25) and minor disruption due to interaction of the (2,1) and (3,1) mode. In the first example, stochastization plays a positive role and reduces influence of the (3,2) NTM on the plasma confinement.

In the second case, stochastization destroys the confinement between the corresponding resonant surfaces which leads to a strong reduction of the plasma confinement and minor disruption. In this example stochastization plays a negative role. Our investigations demonstrate that stochastization can play an important role for completely different MHD phenomena in tokamaks.

8.7 Tungsten proves compatible with ITER-relevant plasma edge

In 2006, the evolution of tungsten concentrations (c_W) during the last ~5 years has been reviewed. The findings fit well into the framework of results, which have been found earlier. In figure 26, the measured c_W is plotted versus the shot number.

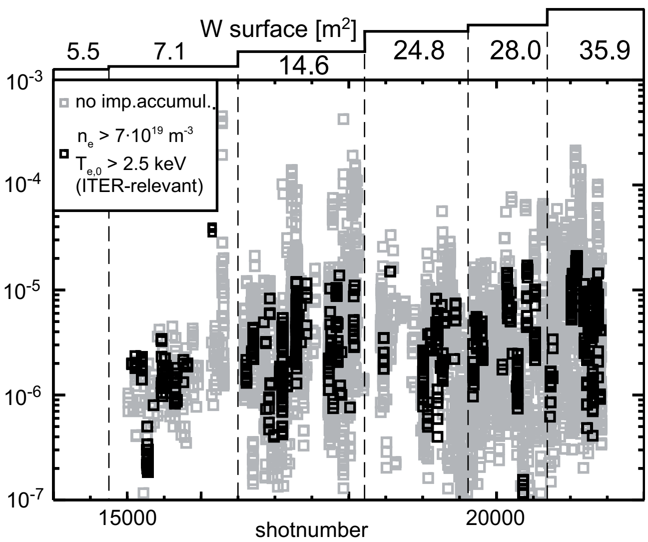

Figure 26: Tungsten concentrations from 2001 to 2006

On top of figure 26 the coverage of the first wall with tungsten is indicated, while the full area of the first wall is 40.8 m^2. The grey data points denote the c_W for all plasmas without impurity accumulation – a state which must be avoided in ITER and a reactor by, for example, intrinsic or external heating of the plasma core. The presented data points are extracted from plasma phases which do not exhibit strong variations in stored energy. These data points range between 10^{-7} and 10^{-3}, with low density plasmas exhibiting the highest c_W. For plasmas with very low or no additional heating power, the lowest c_W is found. However, in ITER-relevant discharges with high heating powers (i.e. central temperatures above 2.5 keV) and high edge densities, c_W is typically below 1-2·10^{-5} (black data points). This value yields negligible influence on the performance of ITER and a reactor.

It could be demonstrated that these low values for c_W are also achievable more than 100 discharges after a boronization. At this point the boron layers have been removed from the dominant part of plasma facing surfaces, at which the plasma-wall interaction takes place.

8.8 Scaled ITER performance

Scaling laws have been developed and refined for decades to extrapolate the plasma performance in present day tokamaks to ITER. With this work we aim to retain some additional information coming from the profiles shape, in order to evaluate present day discharges with figures of merits as possible ignition or fusion relevant as possible. In particular existing figures of merit or parametric dependences of the fusion performance can be validated. Moreover, we can project the performance of new scenarios or new parameter ranges to ITER, although these discharges are not taken into account in the established databases leading to the scaling laws, such as the widely acknowledged IPB98$_{(y,2)}$, the gyrobohm scaling and the Cordey scaling (2005). Thereby the assumptions are that the T_i, T_e, n_e profile shapes are like those in AUG, as well as the H-factor (confinement improvement), q_{95} and the normalised thermal $\beta_{N,th}$. Plasma geometry, impurity content and toroidal field are taken from the ITER design. The density is scaled to yield a Greenwald fraction of 0.85.

In this work we show that under the assumptions all considered scaling laws predict the ITER target to be reached in terms of fusion power and fusion gain Q (see figure 27). Ignition is possible according to all scaling laws. IPB98$_{(y,2)}$ gives the most pessimistic prediction, in particular a very unfavourable scaling of Q with $\beta_{N,th}$. At constant $\beta_{N,th}$, IPB98$_{(y,2)}$ scales favourably with density. One can push this work to estimate a prediction of the current drive required to sustain a given scenario, and thus the discharge duration, keeping in mind that this is just an extrapolation and is not based on any dimensionless physics model. A flexible tool is now available such that different assumptions or different scaling laws can be easily implemented for further investigations.

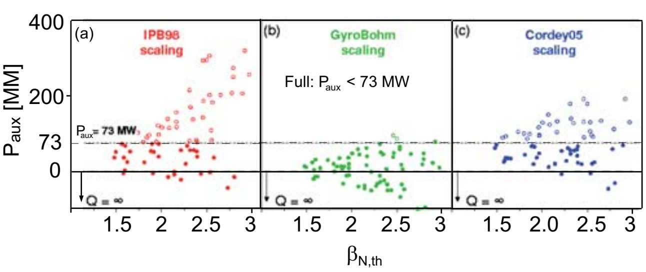

Figure 27: Auxiliary heating power as a function of $\beta_{N,th}$ according to the IPB98$_{(y,2)}$ (a), GyroBohm (b) and Cordey05 (c) scaling laws. Open points represent discharges with auxiliary power above the 73 MW (dashed line) scheduled to be available for ITER. Points below the continuous line correspond to igniting discharges.

9 Edge and Divertor Physics

9.1 Deconvolution of D_α emission profiles and penetration of neutrals

A complete description of the plasma density profile shape in the edge and scrape off layer (SOL) region requires the knowledge of transport parameters as well as the plasma source strength determined by the influx of neutral particles from the vessel wall. In order to examine the impact of neutrals in terms of influx density distribution and penetration depth a pair of cameras have been installed to record the D_α emissivity with high spatial and dynamic resolution. The deconvolution has been performed using a tomographic reconstruction algorithm and a ray-tracing-fit to analyse dedicated regions in more detail while the complex mechanism of neutral penetration – basically molecule dissociation, atom ion charge exchange, atomic ionisation – is reconstructed by the Monte Carlo Code KN1D. Given the experimental plasma profiles, a match of experimental and modelled D_α emissivity profile is obtained by adjusting the neutral influx density at the grid boundary. At similar core density ($n_e \approx 5 \cdot 10^{19}$ m^{-3}) the low field side recycling is much higher in L-mode (typical ion source strength at separatrix ten times higher) than in H-mode and the maximum of the ion source is outside the separatrix in the L-mode case and inside for the H-mode case (1-2 cm in both directions, z≈-45 cm, lower single null (LSN)).

9.2 Target power and current asymmetries during type-I ELMs

For a physics based extrapolation of target power load characteristics it is necessary to understand the ELM related SOL transport physics. Dedicated discharges for optimised infrared measurements have been performed in upper single null (USN) geometry with both normal and reversed field direction, i.e. with the ion $B \times \nabla B$ drift direction pointing towards and away from the active X-point, respectively. These measurements are complemented by an analysis of currents flowing through the inner and outer target plates. The experiments show that the ELM power load towards the inner target plate is larger than towards the outer target with normal field direction but vice versa with reversed field. The current measurements also reveal that a net negative charge flows into the outer target and a net positive charge into the inner target during the ELM in normal field and also vice versa for discharges with reversed field. The absolute value of the ELM target energy difference between inner and outer target is strongly correlated with the corresponding charge difference in both targets. This strong correlation confirms the correct analysis of the target surface temperature when calculating the corresponding power fluxes to the target tiles and is found to be consistent to recent studies at JET, where target current measurements are missing.

9.3 Modelling of divertor detachment

Divertor detachment is a fundamental prerequisite for burning plasma operation and the complexity of the underlying mechanisms necessitates complex numerical code packages such as SOLPS5.0 for interpreting the experimental observations. SOLPS5.0 combines the fluid code B2.5 and the Monte Carlo neutrals code EIRENE and uses a grid based on the magnetic reconstruction of experimental discharges. Despite being used for predicting the divertor performance in all operational regimes of ITER, it has not been fully validated against experimental observations from current tokamaks, in particular at high densities. The gradual change from a carbon dominated machine to a full tungsten machine, has provided a unique opportunity in helping to understand the role of intrinsic carbon impurities for the onset of divertor detachment. A series of well diagnosed ohmic lower single null discharges was performed at various flat top densities, covering the entire range of regimes at the outer divertor from low recycling, to high recycling and the detached regime. At any line average density the inner target was found to be detached. The discharges were undertaken in such a way as to provide as close as possible configurations to those previously used at DIII-D, with the aim of being able to do comparative studies between the two machines.

9.4 Plasma flow in the far SOL

A fast reciprocating probe system in Mach configuration is used to study the plasma flow parallel to the magnetic field in the SOL. It is located outboard about 30 cm above the torus midplane. The experiments were focused on H-mode discharges in USN configuration, which allow for a reversal of the toroidal magnetic field B_t and helicity on a shot to shot basis. All discharges were performed with I_P=0.8 MA, $|B_t|$=2T and a total heating power in the range of 7-7.5 MW. The electron density was at a Greenwald fraction f_{GW} of 0.65 or 0.8. In standard configuration with ion $\nabla B \times B$ drift towards the active divertor (B_t>0) the plasma flow is for f_{GW}=0.65 in co-current direction away from the active upper outer divertor towards the lower divertor and inboard side. Mach numbers (M) increasing from outside towards the separatrix are detected with maximum values of 0.5 (distance $R-R_{sep} \geq 2$ cm). Increasing the density in this configuration to f_{GW}=0.8 the flow pattern changed. In 2 cm distance to the separatrix M is about 0.1, decreasing further with larger distances. Some discharges even show a flow reversal with a plasma flow in counter-current direction (towards the upper outer divertor) over the first 1-2 cm in front of the limiter. With reversed magnetic field there is a strong plasma flow towards the upper outer divertor (co-current direction). M is increasing from the limiter towards the separatrix and maximum values of about 0.4 were reached at the innermost position of the measurement for both densities.

9.5 Impurity fluxes in the Scrape Off Layer

Impurity fluxes in the SOL can be measured by exposing collector probes at the outer midplane manipulator. Discharge- and even time-resolved measurements within one discharge can be carried out employing rotating cylindrical samples shielded by a 6mm slit aperture. The samples are analysed ex-situ by ion beam analysis methods. Time-resolved measurements allow correlating impurity fluxes with well defined discharge conditions. Increased deposition is observed within the low density start-up phase as well as in configurations with small separatrix-sample distance and increased ICR heating. Apart from deuterium and the dominant first wall element W, impurities like Ca and Fe, as well as traces of other elements are also detected. $c_{Fe}\approx 10^{-3}$ and $c_W \approx 10^{-5}$ are found at the plasma edge, in good agreement with spectroscopic findings. The exponential fall-off length of the deposition varies between ≈2 mm (Fe) and ≈6-10 mm (D), depending on the discharge conditions. Furthermore the degradation of the effect of boronization and the related increase of impurity content were monitored. While the amount of deposited boron decreases slowly, the impurity concentration of most elements increases slowly and continuously – except for Ca and Fe. The origin of Ca was identified to be the isolation of electrical cables which are nearly unaffected by the boronization, resulting in a rapid increase of Ca to 'unboronized' levels after only ≈5 discharges.

9.6 ^{13}C migration

The interpretation of long term studies on carbon deposition at plasma facing components is hampered by varying plasma scenarios during a campaign. Puffing of marker gases before the opening of the vessel allows only one scenario to be studied. Experiments puffing $^{13}CH_4$ were performed in H-mode in LSN (2003) and USN (2004) as well as in L-mode in the lower divertor (2005). For the 2005 investigations 80 samples from the lower divertor and the main chamber have been analysed using SIMS by the Helsinki group. In total, 55.4 % of the injected gas has been found and the strongest deposition (28.5 % of the puffed ^{13}C) was observed at the limiters close to the puffing location. Deposition at the strike points was quite low and almost balanced (2.8 % at the inner, 2.9 % at the outer divertor), indicating a penetration probability for puffed gases of about 6 %. This value is in close agreement to theoretical expectations. In contrast, long term studies show strong deposition at the inner and erosion at the outer divertor. Obviously, material deposited at the outer divertor is eroded again in subsequent shots. DIVIMP calculations were performed to simulate the deposition pattern for the L-mode. The amount of deposition at the inner and outer divertor could be reproduced, however the calculations show the strongest deposition at the SOL close to the separatrix, whereas the maximum of the ^{13}C deposition is found in the private flux region.

9.7 Tungsten erosion during ICRH operation

All poloidal limiters have been W-coated since the 2006 campaign and they are a significant source of the W during ICRF operation. It is mainly attributed to the sputtering by impurities accelerated in the rectified sheath. Already about 20 shots after boronization, the effective W sputtering yields (Y_{eff}) at the limiters of the active ICRF antennas rise to the values well above 10^{-4}, indicating a fast erosion of the boron layers. At the same time the W densities in the confined plasma grow considerably such that the access to H-mode with ICRF is affected. The yields at the auxiliary limiters away from the antennas increase more slowly because the particle fluxes are lower and the RF fields are localized at the antenna region in the conditions of good ICRF absorption. Among the main parameters affecting the W source at the antenna limiters during ICRF, are plasma shape, antenna-separatrix distance (strongest effect) and gas puffing rate since these affect the local temperature and density at the edge. T_{edge} and the Y_{eff} can be decreased by gas puff, but the increase of the primary particle fluxes results in about constant W influx. For H-mode discharges as compared to L-modes, W yields and fluxes are generally higher, due to the hotter plasma edge and ELMs. Plasma shapes with high δ are often characterized by higher W yields and fluxes compared to low δ shapes. Under special conditions like (0π) antenna phasing, the difference in shapes becomes even stronger.

9.8 Tungsten erosion during ELMs

The W influx Γ_W from the low field side limiters was monitored in a few discharges with high time resolution of 253 µs to resolve the influx peaks during single type-I ELMs. The ELM frequency varied from 46 to 175 Hz and the ELM energy W_{ELM} decreased from 25 to 6.7 kJ with approximate $1/f_{ELM}$ dependence. Each ELM causes a drastic increase of Γ_W by more than an order of magnitude. In figure 28(a), the tungsten fluency during an ELM is seen to rise approximately linearly with W_{ELM} for a set of purely NBI heated plasmas (5-7.5 MW) and with a 3 times larger slope for a set with additional ICRH heating of 0.7 MW per antenna. The increased W influx during ELMs is mainly due to a strong increase of the effective sputtering yield Y_{eff} as can be seen in figure 28(b). Here Y_{eff} is shown for the phases in-between ELMs and during ELMs. Y_{eff} rises by about a factor of 10 during the ELMs for pure NBI heating and less for the few points with ICRH, which have higher Y_{eff} between ELMs. This rise reflects an increased mean energy of the ions hitting the W-surface, pointing to an increase of T_{edge} as well as an increase of the fast ion load onto the limiters. For the whole data set including the ICRH points, the fraction of the W fluence during ELMs to the total W fluence does not depend on the ELM size and is (70±10) %. The effect of ELMs was also measured for the influx of the low-Z elements boron and carbon. The influx during ELMs changes much less and the ELM contribution to the total influx is only (45±5) %. It has to be noted, that this data gives only the local behaviour at one position in the middle of the ICRH limiter.

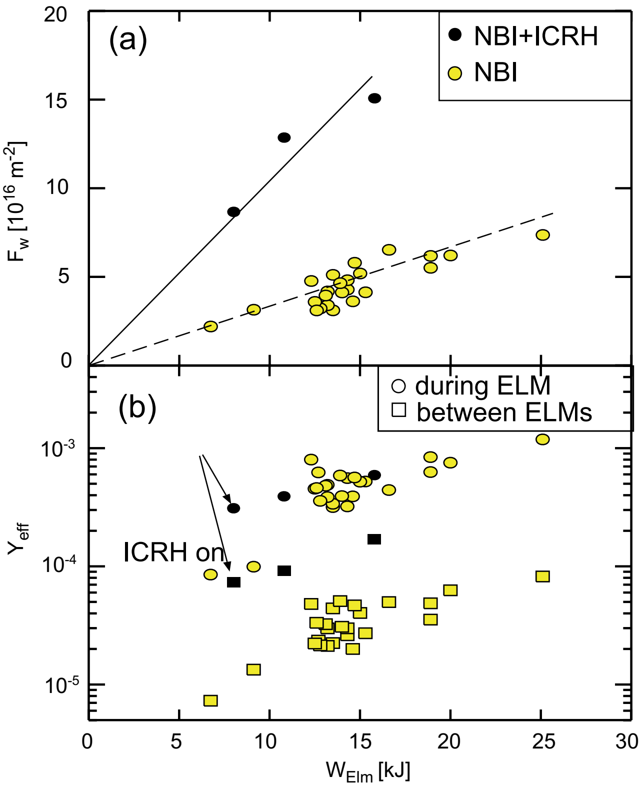

Figure 28: (a) Tungsten fluence F_W during type-I ELMs at an ICRH limiter versus the ELM energy loss of the plasma W_{ELM} for discharges with NBI and ICRH heating. (b) Effective tungsten yield during and in-between ELMs.

9.9 Long term evolution of carbon with increasing tungsten coverage of PFCs

The increasing W coating of plasma facing components (PFC) has led only to a slow reduction of the plasma carbon content. Figure 29(a) shows the development of the core C concentration C_C during the high density phase of the standard H-mode over the last years. It decays much slower than the carbon PFC fraction. A numerical code has been set up to describe the carbon particle transport and migration pattern for realistic tokamak conditions. Radial particle transport of D and C ions in the core and SOL plasma is treated by a diffusive/convective ansatz, parallel transport and drifts in the SOL are introduced as simple loss times which are expressed by Mach numbers M and connection lengths. ELMs are treated by repetitive enhancement of the diffusion coefficient. The transport coefficients and M are adjusted using spectroscopic and plasma profile measurements. It is assumed that the C sputtering yield on the tungsten surfaces follows a linear dependence on deposition thickness for thin layers, turning into a constant value above a critical thickness related to the penetration depth of the deuterium projectiles. A specified C erosion flux Γ_C from the outer divertor is fed to the upstream separatrix to simulate the effect of a net outer divertor carbon source. Carbon entrained in the D flux builds up a thin layer on the W surface, reaching equilibrium between deposition and erosion after several seconds. Results of the particle transport calculations are shown in figure 29(b) for different C PFC fractions and the corresponding components indicated on top. Diamonds denote core C concentrations without divertor source, crosses with a net C source of $2 \cdot 10^{19}$ ions/s. A typical concentration measured by charge exchange spectroscopy is indicated by a circle.

The trend of C reduction compares well with figure 29(a) for a net $\Gamma_C \approx 10^{19}$ atoms/s from the outer divertor, becoming the dominant carbon source for the core plasma. The modelling reproduces nicely the observation that W coating of the inner heat shield, where 2/3 of the main chamber recycling occurs, only slightly decreases the C_C.

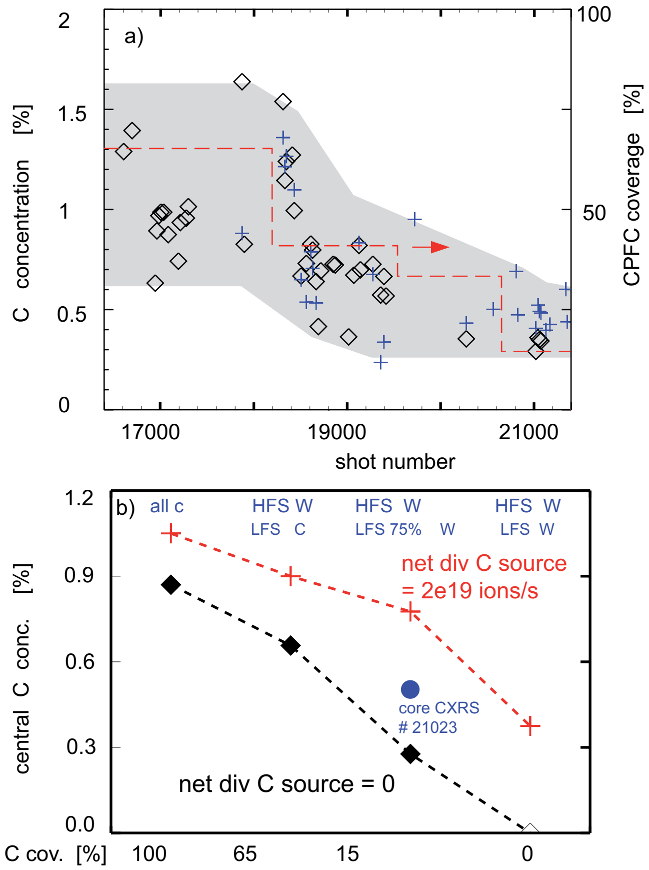

Figure 29: a) Carbon PFC coverage fraction and long term development of the C concentration in the core plasma. b) Modelling of the C concentration with increasing W PFC surface fraction with and without net C ion influx from the divertor.

9.10 Oxygen wall cleaning

Oxygen discharge cleaning is one of the candidate techniques for the removal of re-deposited carbon layers in ITER. Accompanied by promising laboratory studies, the technique was tested in ASDEX Upgrade after the 2004/2005 campaign. During 49 h of helium glow discharge with an admixture of 2 % oxygen a total of 25 g of carbon was removed from the vessel. Investigation of a total of 48 a-C:H film samples, which had been mounted in various locations prior to the cleaning experiment as erosion monitors, showed that in principal all plasma facing surfaces could be accessed by the glow discharge, only hidden places such as gaps or locations deep in the divertor could not.
In contrast, a before-and-after comparison of selected tiles with clearly visible layers on top of their tungsten coating showed no effect. Analysis of the layers indicated, however, that they consisted mainly of boron with C/(C+B) ratios between 0 and 0.4. The effect of B on the erosion rate was studied in a laboratory experiment in more detail; a-B:C:H layers with B/(B+C) ratios between 0 and 1 were eroded in an ECR oxygen discharge. The total erosion rate dropped by almost two orders of magnitude from pure a-C:H to pure a-B:H films. It is interesting to note that the B erosion rate stays constant and C is eroded with it according to the film stoichiometry (see figure 30).

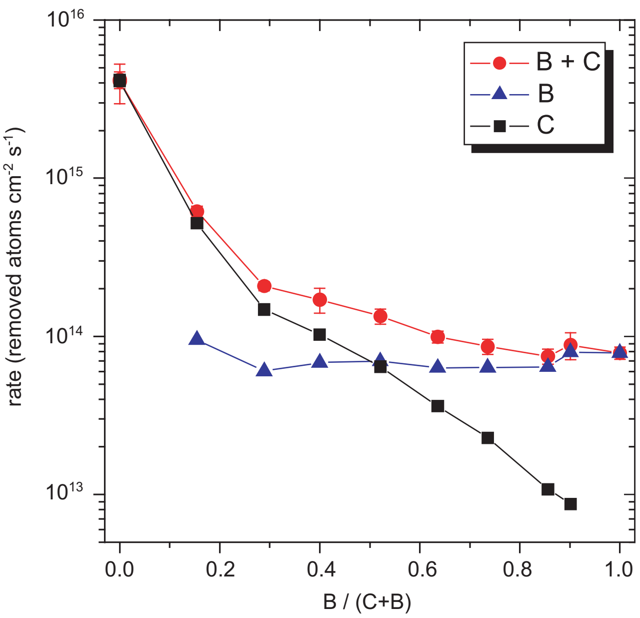

Figure 30: Removal rate of B and C from layers with different B/(B+C) ratio

9.11 Development of a fast pellet gun for ELM pacemaking

So far, investigations on ELM triggering by pellet injection have relied upon systems developed for fuelling purposes. Consequently, pacing experiments were hampered by insufficiently well adapted pellet parameters causing, e.g. too strong fuelling and a lack of repetition rate. Also, pellets crossed the pedestal region too fast for a dedicated investigation of the ELM trigger dynamics. Therefore, a novel system was developed under the premise of maximum suitability for ELM pacing. It is based on the blower gun principle and thus capable of combining high repetition rates up to 143 Hz with low pellet velocities. The new system adds two different injection lines from the low field side (LFS) to the existing one on the high field side and allows different poloidal launch positions to be compared. One LFS line forms a straight injection path, dedicated to operational use aiming at simplicity and hence high reliability. The other one has a tilted path optimised for dedicated physics investigations. It relies on an extremely shallow particle deposition and vanishing radial pellet velocity at the plasma flux surfaces in the edge region or the SOL. By varying driver gas pressure and/or species, pellet speed values ranging from 100 m/s to 350 m/s can be achieved. During test bed operation, pellet delivery reliability beyond 90 % for rates up to 100 Hz could be achieved. First injection attempts into plasma discharges proved successful operation of the entire system but did not reach the full test bed performance. After additional in-situ optimisation the system is now expected to be fully operational.

10 Stuttgart University

10.1 High-power microwave technology

As in the past years, IPF has contributed to the technology for ECRH on AUG (see section 7.6 "Technical Systems"). In the context of the replacement of a gyrotron in the old ECRH-1 system, the matching optic was modified according to the beam parameters. For the new multi-frequency system ECRH-2, a transmission line was designed which connects the gyrotrons to the new dummy load. Also, the matching mirrors of a damaged tube were retrofitted to a gyrotron which was delivered in 2006. To obtain the thermal load for the launcher mirrors, the ohmic loss of the surface of a sample was measured, giving absorption of 0.12 % and 0.24 % for H-plane and E-plane, respectively, at an angle of incidence of 45°. The mirror was also tested in the transmission duct of the W7-X ECRH system with a power of 700 kW and pulses up to 20 s. No damage was detected, which shows that the launcher mirrors are well suited to the conditions in AUG.

10.2 Conformal gratings for multi-pass ECRH with 2nd harmonic O_2-mode or 3rd harmonic X_3 mode

For high-density plasmas, ECRH in the O_2 mode is an option to exceed the cut-off density of the conventional X_2-mode by a factor of 2. The injection of the power in the X_3 mode allows ECRH experiments at a different magnetic field. Thus, both modes could increase the flexibility of the ECRH systems; however they suffer from incomplete single-pass absorption. Therefore in-vessel reflectors have been designed to allow 2-pass (or multi-pass) transmission with controlled polarisation and beam parameters. These reflectors employ polarization independent holographic phase gratings conformal to the inner vessel surface. For the 2006 experimental campaign, a grating had been installed at the inner wall to perform 2-pass absorption experiments; however, due to the early shut-down, no results could be obtained. In parallel, the investigation of various gratings continued. High performance could be obtained in first as well as in higher diffractive orders. The results confirm the possibility to design and manufacture conformal holographic gratings which show high efficiency in both polarizations as well as low polarization change of the reflected beam.

10.3 Turbulence studies in the scrape-off layer

As a new activity, a programme for the investigation of the turbulent transport in the scrape-off layer of AUG has been set up. Two Langmuir-probe systems, a fixed reference probe and a reciprocating probe array, will be used to measure the spatiotemporal structure of the fluctuations in the L-mode and in quiescent phases of the H-mode. Emphasis will be put on the cross-phase between density and potential fluctuations, which is a fingerprint of the underlying instability, and on the propagation of dominant structures like blobs. The results are to be compared with data from the dimensionally similar TJ-K plasma.

11 International & European Cooperations

ASDEX Upgrade cooperations are organised under IEA Implementing Agreements (IA), the International Tokamak Physics Activity (ITPA), bilateral contracts and by providing support and an open structure at IPP in particular for the participation of EURATOM Associations in the AUG scientific programme.

11.1 IEA Implementing Agreement

In view of the new ITER era and the upcoming contributions from new superconducting devices in Asia, the collaboration under the umbrella of IEA IAs has been enlarged by inviting China (EAST) and India (SST1) to participate. The full participation of China and India in this agreement will be very beneficial for all involved parties. Both EAST and SST1 are supposed to extend, together with KSTAR (Korea), the present results obtained at AUG and DIII-D to more reactor relevant pulse lengths.

A one year study on erosion/deposition of the carbon-beryllium-tungsten system at the University of California ended in 2006. The aim of the study has been the characterisation of this material mix under conditions similar to those expected in JET and ITER. In particular, heat pulses associated with ELMs have been simulated by a transient application of a positive voltage bias to a graphite target during deuterium plasma exposure in the PISCES-B linear device. Power transients with sample peak temperatures between 800 and 1400 °C were obtained, with and without beryllium impurity seeding. The power transients accelerate the formation of the Be_2C layer and hence strongly reduce the chemical erosion of carbon. No indication for removal of these protective layers was found in the present temperature range. At the Be_2C decomposing temperature (2100 °C), however, a different behaviour could arise.

11.2 AUG contributions to joint experiments under ITPA

The critical physics issues concerning ITER operation are identified by the ITPA, which proposes joint experiments (JE) involving several research facilities on an international level. AUG is represented in all ITPA topical groups (TG) and their meetings have been attended throughout 2006. The 'Steady State Operation' – TG is chaired by an IPP scientist. In the following all ITPA JE with significant AUG contributions in 2006 are listed.

- CDB-2 Confinement scaling in ELMy H-modes: β degradation
- CDB-9 Density profiles at low collisionality
- TP-3 Determine transport dependence on T_i/T_e ratio with high confinement operation
- TP-7 Measure ITG/TEM line splitting and compare to codes
- PEP-10 The radial efflux at the mid-plane and the structure of ELMs (AUG & MAST)
- DSOL-2 Injection to quantify chemical erosion
- DSOL-9 ^{13}C injection experiments to understand C migration
- DSOL-11 Disruption mitigation experiments
- DSOL-12 Oxygen Wall Cleaning
- DSOL-13 Hydrogen/Deuterium co-deposition in gaps of plasma facing components
- DSOL-14 Multi-code, multi-machine edge modelling and code benchmarking
- DSOL-16 Determination of the poloidal fuelling profile
- DSOL-17 Cross-machine comparisons of pulse-by-pulse deposition
- MDC-3 Joint experiments on neoclassical tearing modes (including error field effects)
- MDC-5 Comparison of sawtooth control methods for neoclassical tearing mode suppression
- MDC-8 Current drive prevention/stabilization of NTMs
- MDC-9 Fast ion redistribution by beam driven Alfvén modes and excitation threshold for Alfvén cascades
- SSO-2.1 Complete mapping of hybrid scenario
- SSO-2.2 MHD effects on q-profile for hybrid scenarios

11.3 EURATOM Associations

The participation of scientists from EURATOM Associations remained at a high level as in previous years. The AUG Programme Committee had meetings in June and December. Besides IPP ten Associations are represented in this body. In the following the most important contributions from Associations are summarized.

DCU – University College Cork: Progress made during 2006 in the context of the ongoing collaboration between IPP and University College Cork is summarized as follows:

(i) Loop voltage profile reconstruction based on a solution to the time derivative of the Grad-Shafranov equation constrained by time derivative data from magnetic and MSE signals has been added to the interpretive equilibrium code CLISTE.

(ii) CLISTE has been extended to interpret thermal and fast pressure profiles across the full plasma radius. Work is in progress to allow for the effects of plasma rotation on force balance.

(iii) A study of internal transport barriers on ASDEX Upgrade, the subject of a PhD thesis, was successfully completed.

(iv) Over the course of the 2006 experimental campaign, TAE discharges were performed to study TAE seen at ASDEX Upgrade in a broad range of relevant parameters to document the behaviour and effects of these modes. It has been demonstrated that q-profiles obtained using the information extracted from these modes agrees with q-profiles reconstructed using only MSE data. Improved q-profile reconstruction was also possible for many standard ICRF and tangential NBI heated plasmas with TAE present. Both fixed and sweeping frequency ICRF beatwave experiments were successful in exciting TAE. This has established the first step in using sweeping frequency ICRF beatwaves to scan the q-profile by exciting several TAE at different locations along the minor radius.

ENEA - Consorzio RFX, Padova: A scientist from Consorzio RFX continued to manage the AUG Task Force IV ‘MHD Stability & Control’. In addition, contributions to the interpretation of fast ion losses driven by MHD instabilities and to the study of the internal structure of Toroidicity-induced Alfvén Eigenmodes (TAE) were made.

Numerical studies on the role of NTMs in fast particle transport have been performed with a test particle approach using the Hamiltonian guiding centre code ORBIT. Orbits of NBI fast particles have been computed in a circular cross section tokamak equilibrium perturbed by an NTM eigenfunction, including interaction with the background plasma. Estimates about loss times, amount of lost fast particles and spatial localization of the losses have been obtained and are consistent with experimental measurements. The proposed mechanism is based on the presence of several drift islands in the fast particles’ orbit space.

TAE eigenfunctions were investigated with the upgraded AUG soft x-ray (SXR) tomography. Thanks to its 30 channels with 2 MHz sampling rate, SXR fluctuation profiles due to high-frequency MHD modes have been investigated. By modelling of the SXR data with the MHD-IC code, significant information has been extracted from these line-integrated measurements. In particular, the radial displacement eigenfunctions of several simultaneously unstable TAE modes could be reconstructed in various plasma conditions. Preliminary results are consistent with predictions from the CASTOR code.

FZ Jülich: Experiments in the frame of the IPTA DSOL-2 focused on the determination of the chemical erosion yield under detached conditions. A discharge scenario was developed to detach the outer divertor in L-mode. Strong reduction of the intrinsic CH Gerö band emission was observed. Injection of methane or ethane leads to a significant extrinsic Gerö band photon flux. The corresponding inverse photon efficiencies are larger than theoretically predicted ones (HYDKIN) and slightly larger than the ones with attached divertor. The intrinsic hydrocarbon flux was reduced by one order of magnitude in comparison to the attached case. However, this strong reduction is partially compensated by the reduction of the impinging ion flux. The erosion yield itself is only reduced, if the particle flux of neutrals to the target is taken into account. These experiments confirm the Roth formula for the detached plasma conditions if atoms and ions are considered.

HAS – KFKI Budapest: Pellets injected into type-I ELMy H-mode discharges are known to trigger ELMs. The triggering mechanism was investigated in detail by linking the dynamics of the triggered ELMs to the time history of the pellet position in the plasma. According to our observations ELMs can be triggered either by the cooling of the pedestal region causing a sudden increase of the pedestal plasma pressure gradient driving the plasma to the unstable region of the ballooning mode, or by the strong MHD perturbation developing into an ELM.

In order to support the understanding of experimental observations, the radiation of doped pellets was studied by the hybrid code and the transition between the spherically and linearly expanding regions of the pellet cloud by the Q2D code.

In the framework of a JET EP-2 project for upgrading the JET Li-beam diagnostic a new type of ion source is being developed. The aim is to increase the beam current into the 3-5 mA range at beam energies around 45 keV. The same source could be used on JET, AUG and TEXTOR. In 2006 the required intensity has been reached, but a long-term reliable operation of the source could not be achieved yet. A further collaboration has been started to prepare an IDL version of the Li-beam code package in order to make calculations on different fusion devices more straightforward.

Hellas: The reciprocating probe system positioned in the lower divertor of AUG and operated by the Greek team was used in conjunction with a fast data acquisition system to investigate fast flow fluctuations and in-out divertor flow asymmetries during type I ELMs in low-power H-mode discharges. Measurements were carried out both in the divertor SOL and in the private flux region. Transient flow enhancement was observed during ELMs in the HFS SOL, while in the LFS SOL the flow was seen to reverse direction and move locally away from the target plates. Inside the private flux region a more complicated flow pattern was observed, with the plasma moving in the counter-current direction during the initial phase of the ELM, and then reversing to a co-current direction.

IST – Centro de Fusão Nuclear: In 2006 there have been no major hardware changes to the multichannel FMCW density profile and dual-channel stepped frequency fluctuation reflectometers operated by CFN, although design studies for new bistatic oversized transmission lines have been undertaken. In addition, there has been progress on several software topics. A new code has been developed for extracting the density pedestal parameters directly from the group delay data – final testing and implementation in the shotfiles is planned for the next campaign. There has been further development in the use of neural networks for fast plasma position monitoring. Future development will aim for a demonstration of a real-time radial position control system. In 2005 a new collaboration was begun on the development of a probabilistic data analysis technique for density profile extraction. Significant progress has also been made in various physics topics where reflectometry forms the primary diagnostic, notably on the localization of core fast particle modes, such as TAEs and Alfvén cascades, and in particular the measurement of radial eigen-functions for core TAEs and edge MHD modes and their comparison with theory and numerical simulations. On the theory side, the modelling of turbulence on open and closed field lines has progressed. The effect of curvature on the structure of high and low-field-side scrape-off layer fluctuations has been investigated using simulations with limiters to mimic single and double null configurations.

RISØ: Collective Thomson scattering (CTS) provides spatially and temporally resolved measurements of the 1-D fast ion velocity distribution. The upcoming experiments in 2007 will demonstrate the feasibility of the measurements and provide a wealth of new data on spatially localized ion velocity distributions. There was significant understanding of the frequency behaviour of high power gyrotrons from experiments done in early 2006 in collaboration with IPP, Risø and MIT. Measurements of the beam pattern in the AUG vacuum vessel have been carried out to further understand and improve the CTS transmission line. The new gyrotron in tandem to the CTS receiver have the potential to be used as an NTM real-time stabilization system with no need for equilibrium information. The NTM signature at about 17-20 kHz has already been observed from preliminary measurements of the CTS receiver viewing the plasma at 105 GHz.

TEKES: The fast particle flux onto the material surfaces and the fast ion edge distribution were compared for co- and counter-injected NBI in the presence of toroidal magnetic ripple and radial electric field E_r by using the orbit-following Monte Carlo code ASCOT. The fast ion density and its gradient in the pedestal region are higher for counter-injected than for co-injected particles, which might play a role in the edge stability, suppression of ELMs, and transition to quiescent H-mode (QHM). The ripple decreases the density gradient in both cases. With counter-injection (QHM case), the wall load is substantial even without the ripple. The ripple always increases the wall load, but the divertor load is either decreased or is unchanged. The effect of E_r alone is small.

The ASCOT neutral particle analyser (NPA) model was refined to more accurately model the six dedicated discharges with varying NBI-sources and NPA sightlines carried out in 2005. The measured and simulated fluxes are now of the same order of magnitude.

The deposition profile of 1 MeV tritons, born in D-D fusion reactions between the NBI-injected fuel ions and bulk plasma, was simulated with ASCOT including the toroidal ripple. The results are in quite good agreement with the measurements even though the measured tritium had been cumulating over the entire experimental campaign while only one (most typical) discharge was simulated.

The first SIMS results on the C-13 puffing experiments were published. The migration of C-13 was simulated for a 'canonical' L-mode background calculated by SOLPS, and the results were surprisingly similar to the deposition profiles measured earlier for a set of H-mode discharges.

Kinetic electrons were simulated in the AUG scrape-off-layer to determine their energy distribution on the divertor targets. The results indicate a sufficient non-thermal contribution which might explain some of the discrepancies in divertor measurements.

The design work for upgrading the NPA was carried out. The upgrade will allow time-resolving of individual counting events, thus making it possible to resolve the NPA signal during sporadic events, such as ELMs. The upgrade of the NPA system will take place in 2007.

Fast ion losses due to fast ion driven Alfvén eigenmodes in the presence of ICRF and a new Sierpes mode were analysed.

UKAEA: The results of studies of the influence of magnetic configuration on H-mode access in near double null plasmas in MAST and AUG have been published.

The radial efflux due to ELMs has been measured on AUG and MAST at various values of I_p, B_T, n_e and P_{NBI}. Preliminary results on the effect of these parameters on the radial fall-off length of the efflux and radial velocity of the filaments have been obtained. Although the e-folding length is larger on MAST (λ~5 cm) than on AUG (λ~ 2.5 cm), for a given machine the e-folding length is similar at the ELM and inter-ELM. Furthermore it is independent of magnetic field or other parameters that we have adjusted to date. Similarly, although the radial velocity V_r is twice as large on MAST as on AUG, to date no parameter has been found that can affect V_r. The e-folding lengths of particle flux (j_{sat}) and heat flux are comparable for the investigated parameter set at AUG. This points to a convection dominated transport with a collisional far SOL.

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JET Cooperation

Head: Dr. Josef Schweinzer

JET suffered from a series of technical problems in the first half of 2006, but has been able to overcome them and achieved significant performance leading to a variety of new results. In addition, the enhancement programme made a huge step forward with the final approval of the budget.

Results

JET concluded a major shutdown and launched the C15 campaign on 24th April. After unplanned intervention in the summer due to a vacuum leak, the C16 campaign started on 25th Sept., followed by C17. Both recent campaigns obtained good results due to high availability and performance of auxiliary heating and diagnostics systems. During C17, the number (132) of pulses with Neutral Beam (NB) power above 20 MW significantly exceeded that in previous years. Together with the LHCD and ICRH systems a maximum power around 32 MW was coupled to the plasma. 19 IPP scientists participated in campaigns C15-C17, conducted experiments, operated diagnostics or contributed to JET research activities with theoretical studies and surface analysis.

Hybrid Mode

As part of a study for the ITPA pedestal and edge physics topical group, the H-mode pedestal of conventional H-modes was compared to the one of improved confinement scenarios such as the hybrid mode. For JET, the analysis was based on the 2003/4 hybrid experiments. In those discharges the β-limit was not reached and no significant improvement in confinement factor was observed compared to conventional H-modes. Also the pedestal performance of those hybrid discharges was similar to that in standard H-modes, with a similar correlation between total stored energy and pedestal stored energy. The 2006 programme on hybrid discharges aimed to characterise this scenario on JET and to qualify it for ITER by accessing a wider operational space than in previous campaigns. A comparison to H-mode discharges without target q-profile modification has been carried out and showed that without NTMs similar (or higher) performance is achieved with the hybrid discharges. This comparison has been done at different q_{95} values (2.7, 3,4 and 5) and was fully integrated in the successful widening of the operational space in terms of q_{95}. In addition, it has been attempted to reach the β-limit. Good MHD stability up to a β_N=3.6 has been confirmed.
Also the operational space in terms of density has been extended to the Greenwald density limit in high triangularity discharges up to β_N=2.6. Following ASDEX Upgrade (AUG), an attempt has been made to reproduce a high density, high β plasma in a near double null configuration with small ELMs. In order to show how divertor damage in ITER could be avoided an experiment with different levels of N_2 and D_2 gas fuelling with and without feedback control on the radiative fraction was done. A type III ELMy H-mode with hybrid recipe has successfully been obtained, where the edge plasma radiated 75-85 % of the input power. Advanced plasma control was also extensively used for generating hybrid discharges lasting up to 20 s, thus demonstrating the stationary nature of this regime. These experiments were accompanied by studies on coupling of LH power to high edge density hybrid discharges at low magnetic field, transport studies using a ^{3}He resonance for electron heating and hybrid discharges at higher magnetic field with dominant electron heating by high power ICRH using a hydrogen minority scheme.

Marginal β of NTMs

The JET part of the ITPA joint experiment MDC-3, involving also AUG and DIII-D, for the (2/1)-NTM marginal β_{pol} scaling has started. A reliable scenario for triggering (2/1) and also (3/2)-NTMs at different plasma currents (I_p=1.0-2.0 MA) has been established. The key element is the achievement of large sawteeth as a seed for NTMs by application of early central deposited ICRH. A power variation of the ICRH allows switching between the two modes. The NTM is finally triggered by a stepwise increase of the NBI power up to 20 MW. After that a slow power ramp-down is performed in order to accurately measure the marginal β_{pol} value, where the mode becomes intrinsically stable again. First preliminary data analysis together with data taken in 2003/4 have revealed a scaling law which is consistent with previous experiments and theoretical expectations. Further analysis is ongoing and additional experimental time has been allocated for 2007 to complete the JET part of this scaling by a full scan of I_p.

Transport

Ion temperature modulation experiments aim at determining properties of the ion thermal conductivity, in particular the stiffness factor. Experiments have already been performed in two previous JET campaigns. Those carried out in 2006 take advantage of recent diagnostic improvements, including a higher time resolution (10 ms instead of 50 ms) which allows the variation in modulation frequency to be significantly extended. In L-modes heated by 5 to 10 MW of NBI the temperature perturbation has been excited by ICRF ^{3}He minority, at modulation frequencies between 4 Hz and 20 Hz. The analysis of the heat pulse propagation yields the expected behaviour: amplitude and damping respond to frequency as predicted. In agreement with theory, the stiffness factor is not very high, but larger than that usually found for electron heat transport. Experiments with modulation of Neutral Beam (NB) sources have been performed to study transient transport of toroidal momentum in the plasma. This method is expected to bring evidence of possible pinch-like terms, if any, and of the predicted coupling of toroidal momentum transport with ion heat transport. The experiments were technically successful, but the localisation of the perturbative part of the torque was not achieved, due to a NBI hardware limit. Preliminary transport analysis has been performed, including FFT analysis of the torque and toroidal velocity.

Particle transport has been studied by means of an empirical statistical approach applied to a combined JET/AUG database (see section "Theoretical Plasma Physics").

A comparison between the experimental observations of impurity transport and the predictions of linear gyrokinetic theory with the code GS2 has been carried out. This work focused on the effects of radio frequency electron and ion heating and on the charge dependence of impurity transport. Transport mechanisms have been investigated, which could account for the outward pinch observed in JET with ICRH in mode conversion scheme to provide electron heating. It has been found that parallel compression of parallel velocity fluctuation provides a convective velocity of the impurities, which is directed outwards in the case of instabilities propagating in the electron drift direction. By such a mechanism, a qualitative agreement between the experimental results and theoretically predicted behaviour was found. The dependence of impurity transport on the impurity charge Z was studied experimentally and turned out to be weak. In contrast with predictions of neoclassical transport, for anomalous transport the diffusion and the pinch are found to depend only weakly on the impurity charge, particularly for Z larger than 10. These experimental results are in agreement with the Z-dependence predicted for ITG and TEM. The value of Z where the impurity transport becomes independent of Z for usual JET H-mode plasmas is found to be between 10 and 20.

ELM analysis and mitigation

Software for Kl3b (infra-red thermograghy) was adapted to the new JET MKII LBP divertor. In addition, spatial alignment and temperature calibration checks were done. Possibilities to recalibrate the Kl3b time traces to permit an exact comparison with other high sampling signals on a 50 μs timescale have been evaluated and software development has started.

Mitigation of type-I ELMs has been observed on DIII-D, without degradation of pedestal profiles or core confinement, when a resonant n=3 magnetic perturbation was applied. On JET the Error Field Correction Coils capable of producing an n=1 or n=2 magnetic perturbation, were used for similar studies. The power load characteristics under such conditions were measured and the effect of different phase shifts (0, 90, 180, 270) of the perturbation relative to the location of the infra-red observation was studied. Detailed investigations of ELM induced in/out target energy splitting and comparison to pedestal top parameters were done as well.

Analysis for ELM pacing by magnetic triggering (plasma kicking) and a comparison with similar experiments performed at TCV and AUG was done. JET results show a similar behaviour as on AUG. ELM frequency control by such magnetic triggering requires a slow ramping of coil currents and is restricted to moderate values of 20 to 60 Hz.

A study of pellet data compiled from fuelling experiments analysed with respect to ELM pacing physics proved that every pellet injected from different locations (LFS, HFS, top) during type-I ELMy phases triggered an ELM, because of the locally imposed perturbation. ELM onset was already detected when only a minor part of the pellet mass (less than 1 % of initially 3.8 10^{21} D) was ablated. The study shows, that ELM pacing can be achieved with negligible impact on initial plasma parameters when the pellet just penetrates about 2 cm beyond the separatrix.

ICRF heating

JET was given support for the maximization of ICRF power in ELMy H-modes using the 3 dB coupler network. In particular, the analysis of reactions of the ICRF system to ELMs was performed, and recommendations on the settings of the arc detection system were given. Support on the asymmetric feeding of antenna straps connected to 3 dB couplers was also provided to study the compatibility of the ICRF antenna operation with the operation of the LH system. Special emphasis was put on the analysis of the arcing events during and after ELMs for different settings of the arc detection system. ELMs have proved (in agreement with the experience at AUG) to initiate special conditions for arcing inside the antennas and possibly in the vacuum transmission lines.

Tungsten spectroscopy

An understanding of the spectral emissions of tungsten (W) is necessary to improve the W-diagnostic. Earlier studies at AUG enabled insight of spectral emissions and abundances of the different ionization states up to electron temperatures of about 5 keV. Experiments at JET have been performed in C15-C17 to get measurements of the spectral emissions of W for higher electron temperatures. During several discharges with central temperatures up to 10 keV, W-ablations were done. However, the spectral emissions around 3 nm, which have been predicted by calculations of atomic structure codes and by related plasma modelling, could not be observed. The observation of weak, well-known lines of W, suggests that the intensity has been too weak for detection by about a factor of three, while uncertainties like the spectral shape of the calibration and the accuracy of the atomic data exist.

Erosion & impurity migration

The erosion of beryllium, carbon, nickel and tungsten was determined at the inner main chamber wall of JET during the 2001-2004 campaigns with long-term samples. The erosion of W was between 1.3×10^{17} and 1.9×10^{17} atoms/cm^2 (about 22 nm), corresponding to a mean erosion of only 3×10^{-4} nm/s. The inner wall erosion was homogeneous in poloidal and toroidal directions. The erosion of Be was about 60 times, and the erosion of C about 500 times larger than the erosion of W. The erosion of the long-term samples is predominantly due to sputtering during plasma operation and not due to erosion during helium glow discharge conditioning, as could be proven with samples protected with a magnetically operated flap, which was only open during plasma discharges.

Eroded material migrates mainly to the inner divertor target tiles. Such migration is of particular significance with a Be first wall due to possible detrimental effects by material mixing at divertor surfaces and formation of co-deposited T inventories. Time scales of the corresponding erosion/redeposition processes are essential for the assessment of their consequences. In 2006 these were studied in a series of identical discharges directly after a Be evaporation by spectroscopic measurement of Be and C sources at the main chamber wall and in the divertor, respectively. The experiment used 2 MW NBI heated L-mode discharges with large wall clearance to avoid excessive erosion by direct wall contact in the main chamber. Both at the outer wall and at the outer divertor plate one finds a steep decrease of the Be source in the first three discharges with a corresponding increase of the C source. This is followed by a slower decrease of the Be source within the following 30 discharges. In the inner divertor the Be source does not vary significantly after Be evaporation. These findings serve as experimental input for the benchmarking of impurity transport simulations, which will allow the understanding of the observed migration patterns to be improved.

Plasma edge and divertor modelling

A very successful Edge Modelling Campaign took place at JET, with 15-20 participants from across Europe, four of which were from IPP. Amongst the work performed/continued/ started were:

As part of a larger modelling effort of the TF-E at JET and as a continuation of a similar study at AUG, a variety of disruptions have been simulated for JET H-mode plasmas. The aim of this analysis is to study the power fluxes to the plasma facing components of JET and the time scale of the thermal quench phase of a disruption and to compare the results with those of the companion study at AUG. For this purpose, suitable JET discharges have been identified and modelled in detail with the B2 SOLPS code based on JETTO transport results. By varying the gas-puffing rate, the pre-disruptive equilibrium conditions, especially for the divertors, have been screened through a range of parameters. The resulting equilibria have been subjected to a simulated thermal quench. The analysis of these simulations and their comparison with the AUG results is currently being carried out.

The benchmarking of the 2D comprehensive edge codes was continued, with comparisons of: SOLPS5-EDGE2D, SOLPS5-SOLPS6, SOLPS5/SOLPS4 and (in a visit to ORNL and LLNL) of SOLPS5/UEDGE. This work is expected to continue in the coming year(s) and is performed together with a number of collaborators.

A good match of the inter-ELM state of an H-mode shot using EDGE2D-NIMBUS in preparation for examining the effect of drifts was established. A working group on comparing the physics in the various edge-codes was setup.

Previous SOLPS simulations of ^{13}C gas puff experiments on JET had been targeted at trying to identify trends, and this work switched to using the experimental equilibrium, densities and powers associated with the actual experiments. The work has shown that including the full CH_4 break-up chain does not significantly change the results of the simulations and has confirmed the key role played by the separatrix density as the main control parameter for in/out deposition.

Bayesian reconstruction of magnetic geometry

A new 3D magnetic field code MAG3D was developed which allows modelling the relationship of PF currents, iron core, and plasma currents with magnetic diagnostic data (pickup coils, saddle coils and full flux loops). Based on this development, a novel Bayesian method "Current Tomography" has been developed and implemented. This method orders all possible plasma current distributions that are compatible with the magnetic diagnostic data according to their probability (a probability measure over all possible current configurations is defined). Therefore, also the uncertainty of the reconstructed 2D current distribution and corresponding flux surface geometry is regularly obtained providing error bars on flux surfaces (including LCFS, magnetic axis position, X-points, strike points etc) and the underlying current profile. As a next step, polarimetry data will be included in the reconstruction. This new method of magnetic geometry reconstruction is meant to form the centre part of a future integrated diagnostic analysis tool, which will utilise raw data from as many diagnostics as possible to achieve a high level of consistency between them.

Enhancements

The IPP has almost finished its two JET-EP diagnostic projects KB5 bolometer and KA3 fast ion loss scintillator probe. Both systems are delivering high quality data (see below) and have significantly contributed to the scientific success of campaigns C15-C17.

The ICRH group has provided support in the definition of the arc detection systems of the new ITER-like ICRF antenna, and has regularly attended the project board meetings.

The decision for the next major enhancement of JET (JET-EP2), including the ITER-like wall installation and a further neutral beam heating upgrade, was finalised and the procurement of the major items was started. IPP contributes to various JET-EP2 projects with a different level of involvement. In support of the ITER-like Wall project IPP leads a diagnostic project (DIR project) to improve the resolution of the divertor infra-red measurement. The new system will be able to measure the power deposition on the outboard divertor target during type-I ELMs and should resolve the ELM filamentary structure.

In 2006, the call-for-tender evaluation was finished and the signature process for purchasing such a high resolution IR-camera has started. The commissioning of this diagnostic is planned for autumn 2007. Another important IPP task in support of the ITER-like wall is the supervision of the production of all required tungsten coated tiles for the JET divertor (see below).

IPP also supports the upgrade of the JET neutral beam system to a total injected power of 35 MW. IPP experts were involved in the design review of the actively cooled duct protection. For the upgrade of the JET lithium beam IPP has given advice for the design of new components of the ion source and has provided a beam test facility in Garching.

The plasma control upgrade (PCU) aims to harness vertical instability control against huge ELMs at high plasma current. Failure of the vertical stabilisation in such cases would lead to intolerable disruptions. IPP is assisting in the development of an upgrade as a member of the project board. The first important step for designing a new power supply with improved output voltage was successfully completed with a call for tender. In 2007, launching a separate group for power supply build-up and commissioning restructures the PCU project. Thus, the PCU will contain two activities, the new power supply upgrade and the controller redesign. IPP will be involved in the latter.

Bolometer – KB5

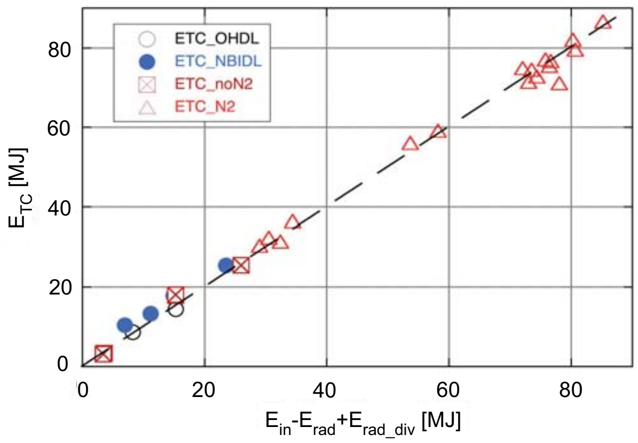

Figure 1: Energy detected by thermocouples in divertor target tiles E_{TC} vs. the prediction from E_{in}-E_{rad}+E_{rad_div} (input energy, total radiated energy & radiated energy deposited on target tiles as deduced from tomography). OHDL=OH density limit, NBIDL=NBI density limit, N2/noN2=discharges with or without N_2 puffing to enhance radiation. The good agreement between E_{TC} and prediction is an attest to both the absolute radiation values as well as their spatial distribution as derived from tomography.

Fast Ion Loss Scintillator probe – KA3

A diagnostic for the detection of energetic particle losses was built by IPP and put into operation. The diagnostic meets its design criteria (5 % pitch angle ξ, 15 % Larmor radius r_L resolution) and allows time resolved measurements of particle losses (E>250 keV, 4 cm<r_L<14 cm, 35 °<ξ<85 °) to be taken. It has been operating since campaign C15 with fully automated data acquisition. For the evaluation of image data collected by a frame-transfer CCD camera (25 Hz), coordinates of the phase space mapped onto the scintillator plate are required. A full 3D model of the probe geometry is used for identification of grid points indicating ξ and r_L.

The results are exceeding expectations. It is possible to identify prompt losses of products of DD beam target fusion in discharges with low to medium density and heating power above 15 MW NBI. In plasmas with substantial ICRH power, particle losses are found in the whole detectable range. During monster sawteeth events, large loss signals are seen which are much more localized in phase-space. Losses triggered by other MHD activity, like tornado modes, fishbone and NTM activity, have also been observed. Thus, the KA3 diagnostic has produced valuable input for many MHD experiments and physics studies. The interpretation of results and comparison with theoretical expectations for fast particle losses has just started.

ITER-like Wall

In the frame of the ITER-like Wall JET-EP2 project IPP continued the tungsten coating task started in 2005. Conducting low-cycle fatigue tests on the most promising samples selected on the basis of the 2005 thermal screening tests completed the investigation of tungsten coatings on bi-directionally fibre-reinforced carbon substrates. A total of 12 samples were subjected to cyclic high heat flux loading in the GLADIS facility at 10.5 MW/m² for 5 seconds with 200 repetitions. A report was issued with this completed set of GLADIS results together with additional investigations including metallography and electron microscopy. This formed the basis for the decision of the ITER-like Wall Project Board which types of coatings will be employed in the JET vessel.

Up to the end of 2008 IPP will support the production of tungsten-coated tiles by providing GLADIS tests and surface analysis tools.

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Stellarator Research

Wendelstein 7-X

Heads: Dr. Remmelt Haange, Prof. Thomas Klinger

In 2006, construction of Wendelstein 7-X has further progressed. Although further technical problems considerably delayed the delivery of the non-planar coils and thus the device assembly, there was great progress in manufacturing and delivery of components to Greifswald. In the autumn of 2006, the parallel assembly of the second half-module of the magnet system has started.

1 Introduction

The construction of Wendelstein 7-X, a large-scale first-of-a-kind device, is an enormous challenge. It requires all available resources of the Greifswald site of IPP and also significant contributions from the Garching site. In addition, the fusion research centers at Karlsruhe and Jülich are strongly involved in the Project Wendelstein 7-X. On the management side, the introduction of a new project structure as of January 2004 has meanwhile proven to be appropriate. However, the change of priorities makes adjustments necessary. In particular, the strong emphasis on the manufacturing and repair of the coils and the manufacturing of the device structure and cryostat made it necessary to set up a new sub-division in 2006. As of now, the six sub-divisions of the Project Wendelstein 7-X are: (1) Project Coordination, (2) Magnets and Cryostat, (3) Supply Systems and Divertor, (4) System Engineering, (5) Assembly and (6) Physics (see figure 1). In addition, the position of an Associate Director Coordination was created at the director level. During 2006 the urgently required engineering capacity was further increased. As of December 2006 about 260 engineers, technicians, scientists and support staff work in Greifswald on the Project Wendelstein 7-X. About 20 more positions are to be filled in 2007. The increase of engineering personnel requires a very aggressive recruitment on a difficult labour market.

In 2006 the final design and manufacturing of a large number of device components has considerably progressed. They are described in chapter 2 with emphasis on the key components, namely the superconducting magnets and the device structure. Design and industrial manufacturing are accompanied by an ongoing strong engineering effort, conducted by the System Engineering subdivision (chapter 3). Global finite element models of the magnet system and of the cryostat were developed for detailed structural analysis of the critical components. The recent results have shown that only a few additional reinforcement modifications were necessary. The basic design of the Wendelstein 7-X now seems to be sound, also from the structural point of view. The goal for 2007 is the design freeze of the major components.

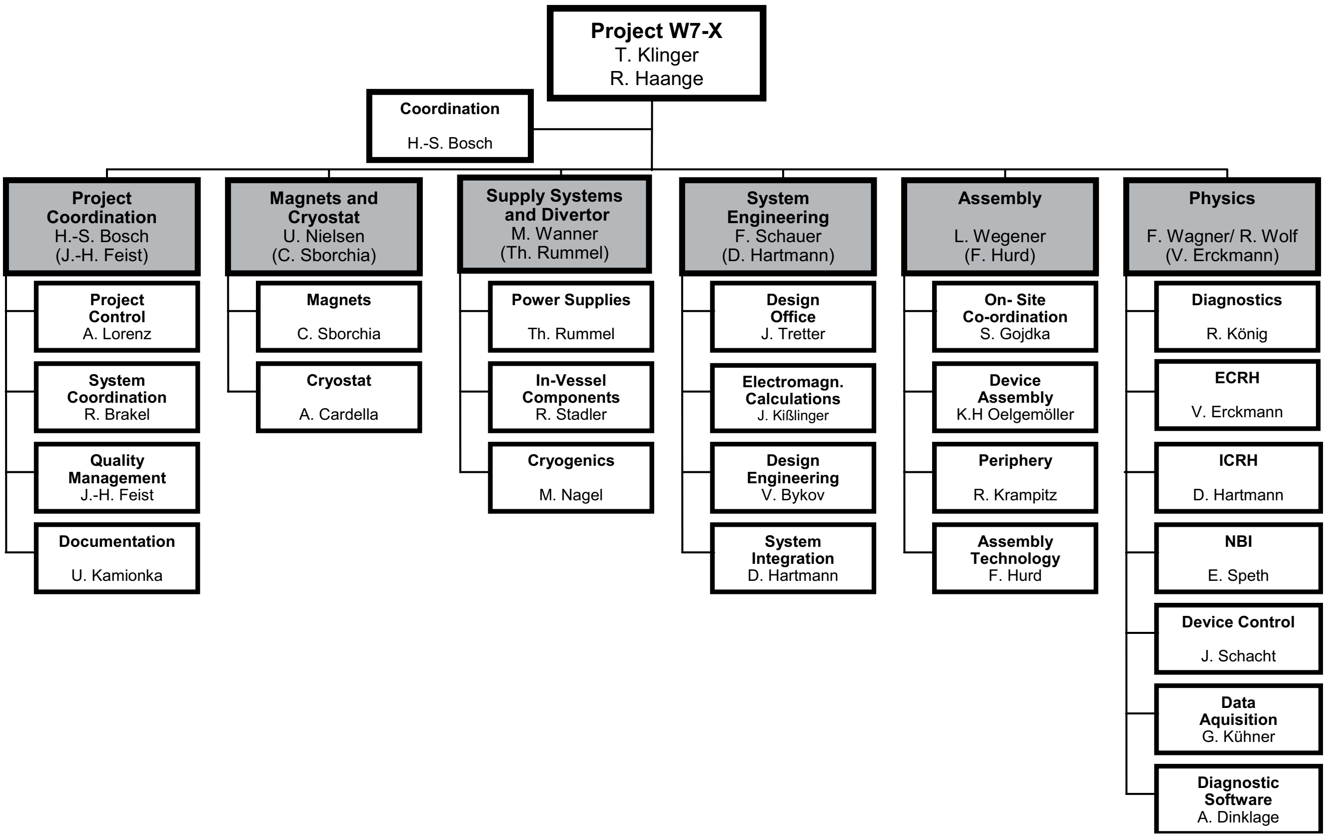


Figure 1: Structure of the Project Wendelstein 7-X as of 31 December, 2006

In parallel the assembly technologies and procedures have been further developed and the actual device assembly has continued, as is described in chapter 4. Last but not least the development of the plasma diagnostics (chapter 5), the heating systems (chapter 6) and the control system has been driven forward.

1.1 Project Coordination

This subdivision comprises four departments dealing with coordination activities for the project Wendelstein 7-X:

- Project Control is responsible for the financial planning of the project and for control of the expenditures, time planning of all the activities in the project as well as of the external contracts. It supports the component responsible officers in handling their industry contracts as well as in organisational aspects of the project and in the reporting to all external supervising bodies, especially the Projektrat, the body of the financing institutions.
- System Coordination coordinates the general technical aspects such as interface control, configuration management, technical specifications (of the device as such as well as of its components), safety aspects and materials issues. In addition a safety analysis of the device has been started. Development of the ring book as an update of the Wendelstein 7-X technical specification is under way.
- Quality Management (QM) is organising the QM system within the project W7-X and supports all external contracts concerning QM aspects. This department in 2006 has continued its preparation for quality assurance during the assembly phase of Wendelstein 7-X. In addition, audits of all departments within the project Wendelstein 7-X have been performed to improve the awareness towards QM and to receive suggestions for further improvements of the QM system.
- The Documentation department is responsible for an independent check of all technical drawings and CAD-models and for archiving all documents relevant to the project (i.e. MS-Office documents as well as all CAD-models and drawings). Meanwhile, a commercial electronic documentation system, the Agile PLM System has become operational for Office documents as well as for the archiving of the CAD models (in CADDS5-format). Further improvements are implemented to improve the use of the system. Especially, an Internet interface was introduced to allow also the external partners within the project to use this documentation system.

1.2 Schedule

Further delays in the delivery of the coils resulted in an interruption of the device assembly in Greifswald. In parallel to this, a thorough review of the assembly steps and of newly developed assembly technologies revealed that the complete assembly of Wendelstein 7-X would take longer than originally estimated. Both these effects and the inclusion of some contingency would, in total, result in a further delay of about two years. As such a delay was considered not acceptable by IPP, means were discussed to shorten this schedule. One measure to shorten the assembly time is the set-up of a second assembly line for the magnet half-modules and the magnet modules. This is still under discussion and has not yet been approved by the Projektrat. A prerequisite for this is accelerate the cold testing of the coils by the introduction of a second cryotest facilty. This has been agreed and FZK has started to reactivate its test facility TOSKA in cooperation with IPP (see 2.1.4).

2 Magnets and Cryostat

2.1 Magnet System

2.1.1 Superconductor

The coils are wound by a cable-in-conduit superconductor which is composed of 243 NbTi strands wound to a cable and enclosed by an aluminium jacket. The void within the cable is used for the helium coolant. The production of the superconductor for the 70 superconducting magnets and the spare lengths has been completed in June 2006.

2.1.2 Non-planar Coils

The non-planar coils have been contracted to a consortium formed by Babcock Noell GmbH and ASG Superconductors (Italy). At the end of 2006, all 50 winding packages have been delivered for coil assembly. 19 non-planar coils have been completed until the end of 2006. Ten of them are accepted to be assembled at IPP Greifswald, two coils are being tested and 7 coils are waiting to be tested in the cold test facility at CEA Saclay. The other coils are at different assembly stages. BNG fulfilled the aim to reach a series production of the coils with a delivery of at least two coils per month in the last quarter of 2006. The non-planar coil production is now concentrated on finishing the coil assembly at the BNG production site in Zeitz. The winding pack production was shared between ABB Augsburg (Germany) working as BNG subcontractor and ASG. After winding the geometry, mass flow rate, high voltage insulation and He-tightness are checked on every double layer. Following a careful quality inspection by ABB as well as by IPP and during the acceptance tests at CEA, winding packs and coils with short circuits and insulation defects in the connection area were identified. Due to the concern about the quality and integrity of the insulation system in the terminal area an additional HV test in Paschen-minimum conditions (reduced pressures) was implemented during the work acceptance tests of coils. These tests are carried out in a vacuum tank up to 9.1 kV at different pressure levels starting from 10^{-4} mbar to 100 mbar. During the test a camera system observes the header region and allows to pinpoint the location of the discharges. These tests turned out to be particularly useful and sensitive to check the insulation quality. A detailed analysis and qualification program for the necessary insulation repairs was done. The repair actions are not yet completed. All winding packs met the stringent geometrical accuracy requirements of typically 2 mm. The winding packs are embedded in a steel case. The stainless steel casings for the non-planar coils are cast as half-shells at Österby Gjuteri AB in Sweden. For each casing the material properties, the geometrical shape and casting defects are checked. The applied X-ray system to check for defects was limited to a material thickness of 70 mm. For areas with larger thickness BNG has launched a campaign of inspections with high energy LINAC testing equipment. Several casting defects have been found, especially in the regions of the reinforcing ribs and at the corners of the winding pack. In terms of castability and weldability, mechanical properties at cryogenic temperatures and geometrical tolerances the quality of the castings is very good.

Foto A. Künzelmann

Figure 2: Non-planar coil assembly at BNG site in Zeitz

The coil assembly is structured roughly in the following production steps: embedding of the winding packs into the casings with the final closure weld of the half shells; final milling process of the casings; preparation of the cooling shield on the casing surface; instrumentation of the coil with temperature sensors and strain gauges. The requirements for the position accuracy of threads, fit holes and machined surfaces are very strong with typically 0.4 mm tolerance. This requirement is particular challenging since all interfaces are defined in three dimensions. The experience shows that the tight requirements could be fulfilled in most cases. Minor deviations were checked whether they could be accepted or whether a re-work had to be performed. Recently, some design changes have been implemented into the production resulting in the reinforcement of some supports. The final acceptance test of each coil is performed at nominal working conditions in the cryogenic test facility of CEA in Saclay. 10 non planar coils have been successfully tested with a very good performance and a slightly higher safety margin against a quench than expected.

Figure 3: Planar coil during assembly trials at IPP

2.1.3 Planar Coils

Manufacture of the 20 planar coils at Tesla Engineering is well advanced. The production of winding packages has been finished. The production line of coil winding was dismantled. 17 of 20 winding packages are embedded. All 20 coil cases are manufactured. The last three remaining coil cases are prepared for embedding. The manufacturing tools for the casings and the windings were disassembled and sent to IPP for long term storage. The assembly of cooling cladding is ongoing and the revised soldering procedure of cooling tubes is working well. 10 of 20 planar coils are delivered and five of them are already successfully tested at cryogenic conditions. High voltage tests were performed under vacuum at various pressure levels (so called Paschen test) after the cold tests. These Paschen tests have shown the proper manufacturing of the insulation system, one coil needs a repair of the quench detection wire connector. The important remaining manufacturing steps of planar coils are the machining of coil cases and the assembly of the cooling system including the leak check using SF_6 gas. These manufacturing steps are now part of the series production. The contract of planar coils is scheduled to be finished in 2007.

2.1.4 Coil Tests

As in the years before, all coils delivered by the manufacturers are thoroughly tested in the low temperature laboratory of the Commissariat à L'Énergie Atomique (CEA) in Saclay. In the year 2006 eight non-planar and four planar coils were tested. As the quench behaviour of the superconducting cables and all formerly tested coils in fully consistent with the specified requirements, the quench tests were omitted. Instead, only a fast current discharge is performed on each tested coil. In order to speed up the test procedure, several particular investigations on the coils were dropped if on all earlier coils no problems could be detected during these investigations. Four months of delay were caused for the tests by damages of the turbines in the cold-box of the facility. Compressor oil residuals were found to be responsible for the turbine failures. This oil penetrated a damaged non-return valve located in the input tube of the helium compressor. After that problem could be localised, the non-return valve was immediately replaced, all helium tubes of the cold facility were thoroughly cleaned with iso-propanol, and the damaged turbines were repaired. To assure the delivery schedule of the coils as well as to have a fall-back system in case of another breakdown of the main test-facility (CEA) it was decided to set-up a second one. After the signing of the memorandum of understanding between IPP and Forschungszentrum Karlsruhe (FZK) to refurbish their (FZK) facility, called TOSKA, for these needs, IPP started with its work-packages (support structures and bus-bars), FZK with the other tasks of refurbishment (cryo-supply, data handling-system etc.). The recruitment of personnel for the test-crew has started. The site is planned to be operational early 2008 with the test-capacity of at least nine non-planar coils per year at least.

2.1.5 Bus-Bar System

During the year 2006 the design of the bus-bars of the first module was finished and the manufacturing has been started. The engineering drawings and documents are completely available and approved by IPP. The first six bus-bars are available for delivery. The next bus-bars are being prepared for manufacturing at present. To avoid unforeseen problems at the assembly of the bus-bars in Greifswald, FZJ will realise additionally to the manufacturing a test assembly of the bus-bars with the available 1:1-model. The manufacturing and assembly plans will be arranged in a such way that the additional test assembly can be carried out without any loss of time.

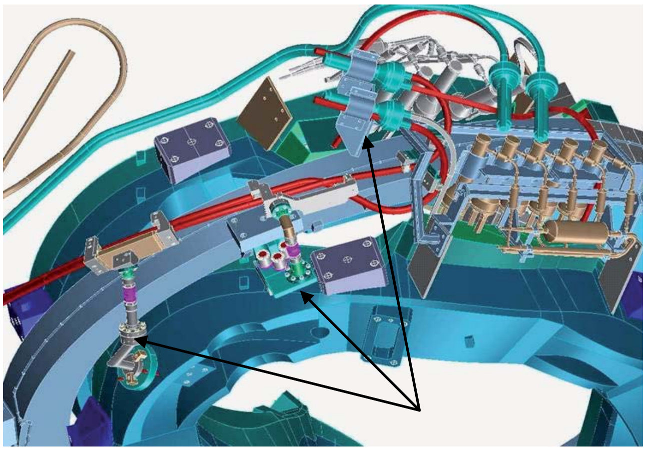
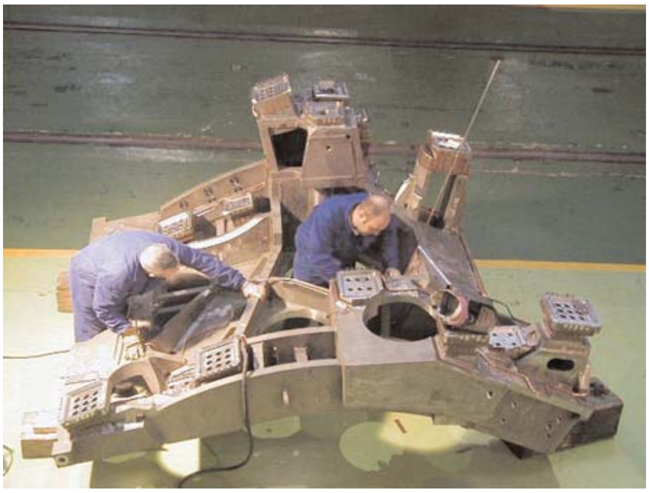


Figure 4: Mechanical supporting bearing for fixing the bus-bars on the magnet system

The engineering data of the first module are available at FZJ. IPP and FZJ together carried out extensive calculations of the basic design of all support of the first module in 2006. Due to small changes, three supports have to be recalculated at the detail design. The start of the manufacturing of the support is affected by the long delivery times of steel. Additionally to the present contract volume, the design and the manufacturing of the bus supports on module separation flanges has been agreed. The technological procedure of the bus assembly was completely optimised, updated and integrated within the assembly process. Preliminary planning and tests were carried out. The installation of the preparation area is planned for 2007. The qualification of the lip weld on joint casings by FZJ is unexpected time-consuming. Added support by IPP is being planned at present. This problem is time-critical for the manufacturing start of the joint casings. The delivery of the T&C transition pieces for the bus system was finished in 2006. The procedure of welding of the transition pieces with the aluminium jacket of the superconductor has been improved. Since the supplier bound by contract has not yet delivered a successful qualification of the insulation caps of the transition pieces, IPP had to find an alternative supplier. The design, the specification and the tender of all further insulation pieces are finished. The new order to a competent supplier will be placed soon. The work procedures for the assembly of these insulation pieces were completely qualified. The prototype test of the optimised joint in the Efremov Institute confirmed the present design values. The alternating field tests, which are a part of this test contract, are still outstanding because the test equipment has not worked as required.

2.1.6 Coil Support Structure

The coil support structure is being manufactured by the Spanish contractor Equipos Nucleares, S.A. (ENSA). It consists of ten identical sectors with a total weight of 72 t made from steel plates and cast extensions. The first module (#5) had to be further modified last year during manufacturing due to design changes necessary to reinforce the structure, following new structural analyses results or as a consequence of collision studies with other components. Finally module #5 has been precisely machined (e.g. precision within 0.1 mm for the extension blocks, where the coils are attached) at the Italian subcontractor Rovera and a full laser scanning of the entire component has shown no non-conformities. After installing the helium cooling tubes and the instrumentation the first half-module has now been completed (figures 5 and 6). It has passed the pressure tests and the leak tests have shown very good leak rates (5×10^{-9} mbar/l/sec). A very good progress has been achieved also for the second half module, which is being sent to Rovera for the final machining.



Figures 5 and 6: Installation of the cooling tubes and front view of module 5.0

2.2 Vessel and Cryostat

The plasma is surrounded by the plasma vessel, which follows the plasma contour and constitutes the first ultra-high-vacuum barrier. The entire superconducting coil system is assembled between the plasma vessel and the outer vessel, which function as a cryostat keeping the magnet system at cryogenic temperature and constitute the boundary between W7-X main device and the external environment. 299 ports give access to the plasma vessel for diagnostics, additional heating and supply lines. The MAN DWE is responsible for manufacturing the plasma vessel, the outer vessel, the thermal insulation, and the machine base. The Swiss company Romabau Gerinox is manufactured the ports.

2.2.1 Plasma Vessel

The plasma vessel (PV) is composed of ten half-modules which are divided into two sectors to allow stringing of the innermost coil during assembly. Construction of the plasma vessel required 200 steel rings to be bent to the designed shape and carefully welded to represent the changing cross-section of the vessel with an accuracy of 3 to 7 mm. Vacuum tightness of the welds was checked by an integral helium leak test of the vessel segments prior to cutting the holes for the ports. Water pipes around the vessel allow control of its temperature during plasma operation and for bake-out at 150 °C. Manufacture of all ten half-modules has been completed in 2005 and installation of the thermal insulation has started. Rogowski and saddle coils which are used for the magnetic diagnostics have been mounted on the outside of the first vessel sector during assembly preparation. Each of the first two half-modules (ABB50 and ABB51) has been integrated with the non-planar coils type 3. The two sectors forming the two half-modules were then welded. In both cases the welding was achieved with very low shrinkage. A R&D action has been performed with MAN DWE in order to develop the weld procedure for the welding of the half-modules. The weld between the PV half-modules can only be accessed from inside and on the outer part the vessel will then already be covered by the thermal insulation. A special design has been developed and successfully tested in order to perform the weld providing enough shield gas to the root weld, avoid the burning of the thermal insulation, perform a suitable leak test and finally minimize the component distortion.

2.2.2 Outer Vessel

The outer vessel is assembled from five lower and five upper half-shells and will have 524 domes for ports, supply lines, access ports, instrumentation feedthroughs and magnetic diagnostics. All upper and lower main bodies of the half-shells of the outer vessel have been manufactured. Cutting of all the openings in all the modules is finished. The details of the design of the vessel support to the machine bed have been finalised. The main workshop domes of modules 5 and 1 and the supporting legs have been welded. Module 5 has been pre-assembled (figure 8) and all the workshop domes at interfaces have been welded.

2.2.3 Thermal Insulation

Efficient protection of the cold components against thermal radiation is achieved by actively cooled shields, high vacuum, and 20 layers of reflecting foils. The fabrication of the panels for the plasma vessel used a novel, patented technology to achieve the narrow required tolerance of ±2 mm. Epoxy impregnated glass fibre mats were joined with segmented copper meshes to achieve panels with good lateral heat conductivity while keeping eddy currents low. Fabrication of all panels for the cryostat has been completed. Prior to assembly all holes for the ports and the fixation holes for the mechanical supports on the plasma vessel have to be integrated and the copper braids for the thermal connection to the cooling tubes have to be fixed. Three quarters of the panels for the first half-module of the plasma vessel and one quarter of the panels for the second half module have been mounted (see figure 7). The panels are kept at temperatures between 50 K and 80 K by cold helium gas. The design of the panels for the ports and the outer vessel has been continued. The section of the panels closer to the plasma vessel will be made from brass to limit eddy currents. The section of the shield closer to the outer vessel will be made from sheet copper. Integration of the port insulation has to be performed simultaneously with the port assembly. During integration of the insulation special care has to be taken to avoid gaps for heat radiation between neighbouring panels. To gain experience in mounting the thermal insulation a dedicated test has been performed at IPP.

Figure 7: Mounting of the thermal insulation panel

In a further test it was demonstrated that the multilayer insulation packages can be joined properly at the half-module joint of the plasma vessel under the restricted accessibility conditions during assembly. The test also confirmed that the multilayer insulation was not overheated and damaged during welding of the half module sectors.

2.2.4 Ports

A total of 299 ports are used to evacuate the plasma vessel, for plasma diagnostics and heating, as well as for supply lines and sensor cables. The cross sections of the ports range between 100 mm circular up to 400×1000 mm^2 square and are equipped with bellows to compensate deformations and displacements of the plasma vessel with respect to the outer vessel. All ports are surrounded by water pipes to control their temperature. By the end of 2006, 297 of the 299 ports have been completed and delivered to IPP. The last two ports are planned to arrive in Greifswald in the spring of 2007.

Figure 8: Pre-assembled lower and upper shells of module 5

3 Supply System and Divertor

3.1 Magnet Power Supply

The five types of non-planar and two types of planar coils are energised by power supplies providing direct currents of up to 20 kA at voltages of up to 30 V. Fast and reliable discharge of the superconducting magnets in case of quenching is realised by fast circuits which short-circuit the coils and dump the magnetic energy to nickel resistors The Swiss contractor, ABB, has successfully tested all seven units and demonstrated that the current can be stabilised to an accuracy of 2×10^{-3}. The quench detection system is developed in cooperation with FZK. The system consists of some 400 quench detection units which permanently check the differential voltages across the double layers of the coils, all sectors of the bus system and the superconducting part of the current leads. The system has to reliably detect millivolt signals in a broadband noise environment and operate at high voltages during a rapid shutdown of the magnets.

In order to allow continuous operation of the magnet system for several days some remote check-out and control features were added to the electronic units. The prototype quench detection unit was finished according to schedule and successfully tested by FZK and IPP. To simulate actual operating conditions transient broadband quench signals were taken during a coil test at Saclay and used as input signals for the quench detection unit. Electromagnetic compatibility was verified at the University of Applied Science in Stralsund. Operation in the projected stray fields was verified in the magnet test stand at IPP.

3.2 Current Leads

Fourteen current leads able to carry 18 kA each connect the seven groups of superconducting coils to the corresponding power supplies. Forschungszentrum Karlsruhe (FZK) is developing, designing, manufacturing and testing the current leads. The leads contain high temperature superconducting material in order to keep the refrigeration requirements small. A particular feature of the leads is that they are operated upside down, e.g. with the cold end on top. Therefore the design of the heat exchanger has to avoid free convection within the flow channels. Free convection would short-circuit the temperature gradient between inlet and outlet and degrade performance particularly at small flow velocities. First tests by FZK with a heat exchanger operated in upside down position showed that the degradation is acceptable. Since the new current leads will require helium cooling between 50 K and 300 K, the cooling concept of the helium refrigeration plant had to be adopted (see chapter 3.4). The design of the current leads and their supports has further to consider the very limited space during assembly, thermal shrinkage of the magnet system during cool-down, deformations of the coil support structure and the bus lines during ramp-up of the coils. Similar to the coils, the current leads have to be able to withstand high voltages under degraded vacuum conditions.

3.3 In-Vessel Components

The in-vessel components comprise divertor target plates and baffles for energy and particle control, panels and heat shields to protect the wall against plasma radiation, control coils to modify the magnetic configuration at the plasma boundary, cryo-pumps to control the neutral gas density during high-density plasma operation and supply lines for heat removal. Several areas with different heat loads can be distinguished. The divertor horizontal and vertical target modules will experience power fluxes up to 10 MW/m^2. The baffles, which prevent the neutrals from re-entering the main plasma chamber, receive power fluxes of up to 0.5 MW/m^2. The wall is subject to neutral particles and plasma radiation in the range up to 0.3 MW/m^2.

To keep the reflux of impurities to the plasma within acceptable limits all plasma-facing surfaces will be covered with low-Z material. The target plates are armoured by CFC tiles, the baffles are covered by graphite tiles and the wall protection shall be coated later with boron carbide. In spring 2006 a design review was held in Garching to check all subystems and components of the in-vessel components prior to fabrication. As a consequence it was decided to test all 980 target elements of W7-X at a limited number of load cycles at nominal heat load.
The company Plansee AG, Austria is manufacturing the target elements, MAN DWE the wall protection panels and BNG the control coils. Assembly of the target modules from target elements as well as fabrication of the baffles, the heat shields, the cryo-pumps and of the supply lines is performed by the central technical services of IPP in Garching.

3.3.1 Target Modules

Ten divertor targets with surfaces of 1.9 m^2 each are composed of 890 segments which closely follow the 3-D shape of the plasma boundary. For these areas 6-8 mm thick CFC tiles made of SEPCARB® NB31 from SNECMA Propulsion Solide, France are joined with the water-cooled CuCrZr heat sink either by electron beam welding or hot isostatic pressing (HIP). Since the SEPCARB® NB31 material did not meet the specified structural and thermal requirements additional series of prototypes were manufactured by Plansee to check whether the degraded material can still be used. High heat load tests on the first series of prototypes in the GLADIS facility revealed an unacceptable failure rate of the interface between the CFC and the CuCrZr heat sink. Following a detailed analysis it was decided to manufacture another series of 18 prototypes based on different design solutions. These prototypes were delivered and checked for mechanical defects of the bond in the SATIR faciltity of CEA/Cadarache. Meanwhile the target plates are being prepared for tests in the GLADIS facility. The results shall be completed in February 2007 to allow releasing series fabrication and fixing the acceptance criteria. One target module is composed of six to twelve target elements which are fixed on a common frame. The supports of these modules are adjustable within a range of a few millimetres to allow compensation of manufacturing tolerances and assembly tolerances of the plasma vessel or uneven loading during plasma operation. The frame design is rather advanced and is regularly checked with the assembly technology division. Hydraulic tests on one target module are being conducted to check that the water flow is distributed evenly between the different target elements and that no vibrations are caused by the high flow velocity which could damage the bellows. First tests were successful.

3.3.2 Baffle Modules

The baffle modules shall prevent back streaming of the neutralised gas from the target plates. Due to the lower heat load these areas are protected by graphite tiles which are screwed to CuCrZr heat sinks. The first lot of graphite tiles has been delivered. Stainless steel water lines are brazed to the heat sinks for heat removal. Two companies have meanwhile been qualified for the complicated brazing of the stainless steel pipes to the CuCrZr heat sinks. A first lot of baffles has been manufactured by the IPP workshops in Garching. The fixing screws for the graphite tiles are made from titanium zirconium molybdenum (TZM) alloy. To avoid high-Z impurities from entering the plasma the screws shall be covered with a layer of B_4C or CVD carbon. To test the bonding stability of the coating under assembly conditions some samples of coated screws were ordered.

3.3.3 Wall Protection

About 70 m^2 of the plasma vessel surface is covered by double-walled stainless steel panels with integrated water-cooling. These panels shall be coated at a later stage with B_4C to keep impurities from the wall at an acceptable level. The first series of 90 panels has been delivered by MAN DWE. The channels within the panels are formed by hydraulic pressing with approx. 100 bar. Infrared mapping demonstrated that some channels had insufficient flow and need to be enlarged by re-pressurisation at approx. 130 bar. The inner wall of the plasma vessel, which is only a few centimetres away from the plasma is protected by graphite tiles using the baffle design principle. Design of the inner wall protection has to integrate also several plasma diagnostic components as well as a NBI beam stopper and a mirror for ECR heating. By end of 2006 some 550 wall protection tiles have been fabricated in the IPP workshops. During steady state and full power plasma operation the inner surfaces of the ports need to protected in the same way as the plasma vessel. For cost saving reasons manufacture of the port protection panels has been postponed to a later date. Nevertheless the design of these areas had to be continued to fix the interfaces and the routing of the cooling water lines. At a later stage would be accessible only with great difficulties. The NBI ports need to be protected against energetic particles by graphite tiles. Due to the spatial constraints the design of the protection is supported by detailed heat load calculations.

3.3.4 Cryo-Pumps

Ten cryo-pumps are located behind the target plates and allow increasing the pumping capacity for hydrogen and deuterium to 75 m^3/s during high-density plasma discharges. The cryo-pumps are composed of a cryo-panel cooled with single phase helium, a Chevron baffle cooled with liquid nitrogen and an additional water cooled baffle. Fabrication of the helium and the Chevron baffles has been completed for all cryo-pumps by the IPP workshops. The manifolds for the cryogen supplies as well as the interfaces to the transfer lines are being designed.

3.3.5 Control Coils

Ten control coils will be installed behind the baffle plates. These coils will be used to correct small field errors at the plasma edge, to optimize the position and extent of the islands and, if necessary, dynamically sweep the power across the target plate. The coils are supplied by the company BNG. Each coil is made of eight turns of a hollow copper conductor and is water cooled. By the end of 2006 three coils have been delivered. Minor manufacturing errors which have been observed during integration and testing of the first coil have meanwhile been fixed. The adjustment of the current leads with regard to the coil has been facilitated by a dedicated mounting tool. The double O-ring sealing between the water cooled plug-in and the insulating vacuum space has been improved.

3.3.6 Supply Lines inside the Plasma Vessel

Cooling of the in-vessel components requires routing of a network of supply lines with some 3800 connections which have to be connected to the interfaces of the supply lines at the outer vessel flanges. Design of the water lines inside the plasma vessel has to consider the restricted space behind the wall panels, different pressure drops and simultaneous routing of several pipes through narrow ports. Connection to the supply lines to the interfaces at the outer vessel is realised by plug-ins. The plug-ins are pre-fabricated and will be welded from inside to the adjacent pipes applying orbital welding. First tools have been developed in cooperation with industry and tested successfully.

3.4 Refrigeration System

The refrigeration system has an equivalent capacity of 7 kW at 4.5 K to supply the magnet system, the thermal shields, the current leads, and the cryo-pumps with helium at different temperatures and pressures. Linde Kryotechnik AG, Switzerland is in charge of the delivery of the helium refrigerator. Originally the refrigeration system was designed for an operation scheme where the superconducting coils were energised at nominal current only during 80 days per year. Over night and during the remaining days the plant would have run in different standby modes. To allow economic operation the excess plant capacity during standby modes (e. g. overnight) would have been used to liquefy helium into a 10,000 l storage tank. During W7-X operation helium would have taken from the storage tank to boost the refrigeration power. Following a decision of the project to reduce the number of load cycles of the superconducting coils the magnet system need to be supplied with helium continuously for approx. 5 days. This reduces considerably the helium rate which can be withdrawn from the storage tank since no helium will be re-liquefied overnight. Re-calculation of the refrigeration process by Linde Kryotechnik AG showed that the reduced cooling demand of the high-T_c current lead reduces the helium withdrawal from the storage tank such that continuous operation during four to five days is feasible. In 2006 the process heat exchangers of the refrigerator were manufactured and integrated into the cold box and the subcooler. Manufacture of the magnet distribution box started. The compressor units, their electro motors and the helium transfer lines are being manufactured and first works test have been passed successfully. The liquid nitrogen system of the branch institute consists of a 30,000 l tank and a distribution system. In 2006 approx. 68,000 l of liquid nitrogen were provided for the ECRH system, the cryo-laboratory and other users within the institute.

4 System Engineering

The subdivision System Engineering (SE) provides the engineering support to the Wendelstein 7-X project. It is organized in four departments: Design Office, Design Engineering, Electromagnetic Calculations and System Integration.

4.1 Structural Analyses

4.1.1 Finite Element Models

In 2006 SE continued to investigate the stress levels and deformations of structural components of W7-X during various modes of operation mainly by the finite element (FE) method. Since the whole structure is by far too complex to be described in a single model, it is necessary to use global (coarse) models, and local (detailed) models that are analysed independently with boundary conditions extracted from the global models. Two separate global models (GM) are applied: the magnet system global model and the cryostat global model. The global models include elastic materials only. The magnet system GM encompasses the non-planar and planar coils, the central support structure (CSS) including the extensions for the coil supports, and the inter-coil support structures. The latter consist of the "narrow support elements" (NSE) on the high field side between non-planar coils, the "lateral support elements" (LSE) on the low field side between non-planar coils, the "contact elements" (CTE) between the half-modules and modules, and the "planar support elements" (PSE) between planar and non-planar coils. The narrow and part of the planar support elements basically consist of pads held by pad frames that in turn are inserted into the coils. These pads slide on the adjacent coils. The magnet global model behaves nonlinear and is very sensitive to the variations of initial parameters and boundary conditions. The magnet system GM is being implemented now in three commercial FE packages: ADINA, ANSYS, and ABAQUS, the two latter with support from the Efremov Institute (St. Petersburg) and the company LTC (Italy). The ANSYS GM was extended from simulating a half module with corresponding symmetric boundary conditions (so called 36° model) to simulating a full module (so called 72° model) in order to include the cryolegs and analyse in addition influence of dead weight and module supports (figure 9).

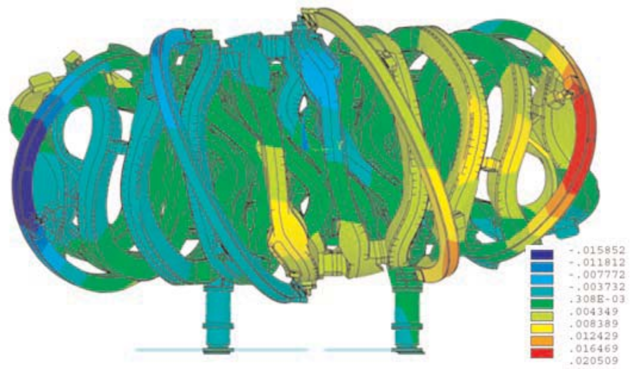
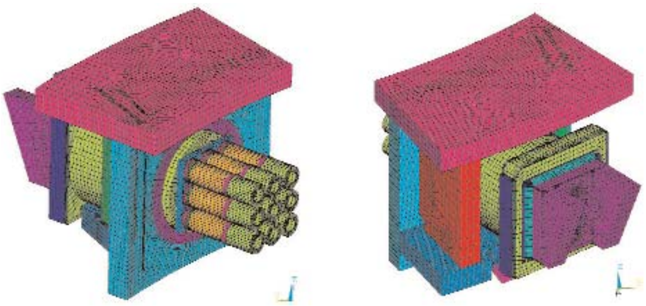


Figure 9: 72° ANSYS FE global model of magnet system with cryolegs (Efremov Inst., Russia; IPP)

The ANSYS GM is the workhorse which is heavily used for all kind of magnet system analyses. The ABAQUS GM was mainly developed as an independent tool to confirm the ANSYS results. This was achieved successfully with the 36° model to within about 10 % for critical components. The ABAQUS GM is now being extended also to 72° and will be finished in the middle of the year 2007. The ADINA GM which is recreated completely from scratch in cooperation with IBK company (Germany) suffered some heavy delays and will also be finished before summer 2007. As soon as these models are fully available at IPP they will not only be used for benchmarking, but in particular each one will be used for the application it is best suited for. The ANSYS GM is widely known and much experience is available within IPP and elsewhere, ABAQUS is well suited for dynamic analyses and strength limit analysis, whereas from ADINA it is expected to be faster and better suited for analysis of non-conformities. The main GM applications are calculation of stresses and deformations occurring during different modes of operation such as cooling of the structure and magnets to cryogenic temperatures, and applying the electromagnetic forces of different magnetic configurations. Also the influences of the winding pack embedding and bolt preloads between coils and the CSS, between CSS modules, and of LSE as well as PSE variations can be simulated. The GM is used also for predicting handling deformations during assembly. In particular, the 72° GM is used for load cases which break the stellarator symmetry, for instance for investigating the influence of dead weight, support forces and buckling of the magnet system. Using input data from the global model, a number of local FE models have been developed that scrutinize in detail the behaviour of the selected components.

These local models are generated and investigated by System Engineering and by other institutes in the framework of international contracts:
Forschungszentrum Jülich: bus system (ongoing);
Warsaw Technical University: central support elements (ongoing); figure 10 and figure 11;
CEA/CRIL Technology: central support ring (close to completion);
ENEA: lateral supports between coils 5-5 and 1-1, resp.; (contract closed in 2006);
Efremov Institute: contact supports (figures 12 and 13), etc (contract is to be closed in May 2007);
Ljubljana Univ.: narrow support parametric studies (contract closed in 2006).



Figures 10 (left) and 11 (right) : Central Support Element analysis, WUT, Poland. Example: FE sub-model of NPC type 4, connection Z1

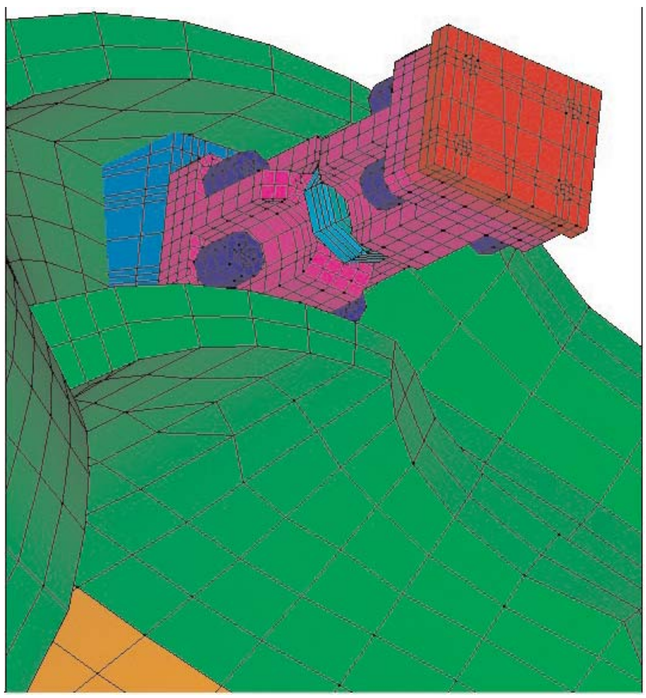


Figure 12: Fragment of Global FE model with Contact Element, Efremov Inst., Russia

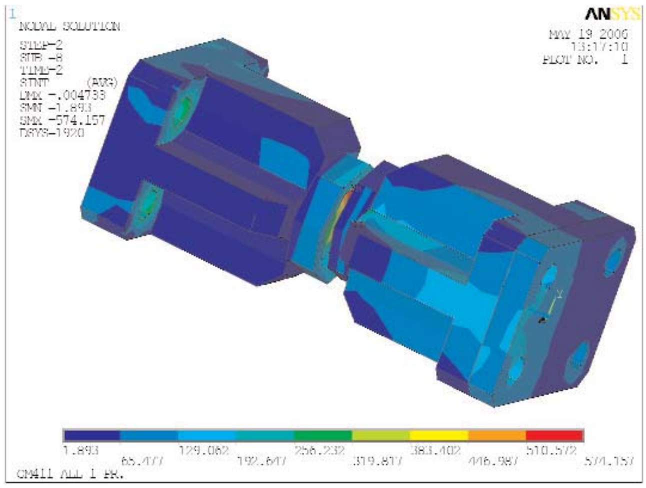


Figure 13: Contact Element analysis, Efremov Institute, Russia

In addition, the ANSYS FE cryostat global model is being refined (in cooperation with ENEA, Italy, and IGN, Germany) and updated with final geometry data of the complete plasma vessel, the ports, outer vessel, and machine base. The created FE model tree also provides the possibility to quickly analyze non-conformities reported by manufacturers, and to accept or reject inconsistencies with the reference design.

4.1.2 Magnet System

Global and local analyses were iteratively continued together with design changes which in turn led to changes of the models. An important issue still is the definition of the gap widths between the pads of one coil to its neighbouring coil when no current is flowing. By varying these gap widths it is possible to equally distribute the loads on the various components during operation. This optimization process is extremely tedious since each iteration requires checking the loads and deformations of all relevant support and structure elements. By now, this optimization process is converging so that the gap width between some of the coil pairings could be defined in agreement with the assembly schedule. The 72° global FE model including the crylegs was created during the year under report. The model allowed both accurate analysis of the magnet system behaviour under the combination of the cool down, dead weight and EM force applications as well as extraction of forces and moments for the cryolegs design and analysis. With this model, it became evident that two cryolegs per module are necessary in order to avoid significant toroidal rotation of the magnet system. Even though the original design of the CSS etc. allowed for this option, it took some analysis effort to define and confirm the final cryoleg design. Much global and local analysis work was done also for final definition of the lateral support elements on the outboard side of the coil system. All these LSEs are welded except the ones between coils of type 5, i.e. at the module interfaces.

Another task was to simplify the planar coil support elements (PSE) where the originally envisaged four sliding PSEs per coil could be reduced to two ones plus one fixed contact. Another issue was the investigation of buckling of the central support structure (CSS) which was performed in several steps. A worst case analysis (performed by IPP and CRIL, France) without considering the stiffening effect of the attached coils gave a safety factor of 2.4 which was considered as too marginal. Implementation of simplified coil beam models resulted in a safety factor of around 10, and final implementation of the coil system (conservatively without NSEs and CTEs) gave safety factors above 30 in the linear analysis which is considered by far sufficient, see figure 14. Another task which could be finished in 2006 was the investigation of the coil system deformation during assembly (by LTC, Italy (see figure 15). A new contract was awarded again to LTC for preliminary investigation of crack propagation within the coil casings. A program was launched which is intended to allow better understanding of stick slip phenomena and dynamic behaviour of the magnet system. Within the frame of this program a contract was concluded with LTC for a FE dynamic analysis of NPC 1 in order to study the dynamic response of the coils when a stick slip at a NSE occurs. Simultaneously the dynamic behaviour of the NSE test equipment at KRP is being analysed by SRS comp. (Italy) for better understanding the test results, and to evaluate the relevance of these results wrt. possible stick slip events in the real coil system. In addition, a dynamic FE analysis is also performed at IPP in preparation of a coil test in Saclay to investigate the superconductor stability vs. mechanical disturbances. The aim of the latter analysis is to find suitable mechanical excitation methods for the test coils in order to simulate possible stick slip events within the real W7-X coil system. All these dynamic calculations are expected to be completed in 2007.

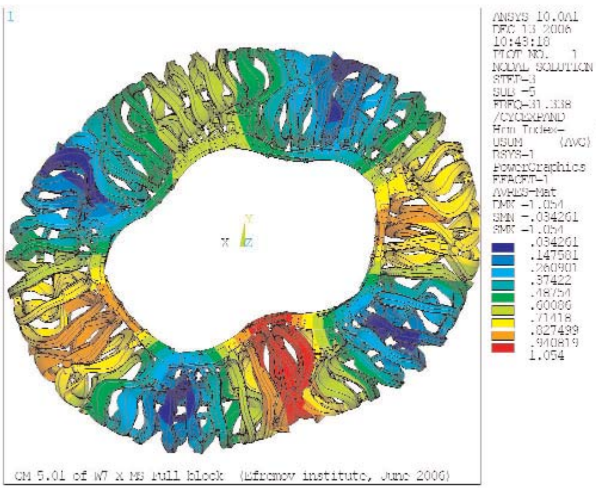


Figure 14: Linear buckling analysis of CSS and magnet system (Elfremov Evremov Inst. Russia; IPP)

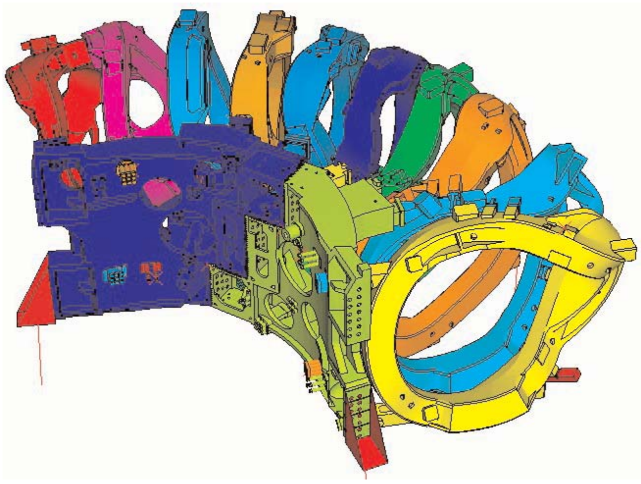


Figure 15: FE model of the complete module and the supporting structures for assembly studies (LTC, Italy)

4.1.3 Cryostat

4.1.3.1 Plasma Vessel

An update of the plasma vessel (PV) FE model was performed by IGN comp., Greifswald. The horizontal plasma vessel support system was improved by adding an adjustment screw to each joint adjustment tie rod as a dead stop for the radial U-port movement (figure 16).

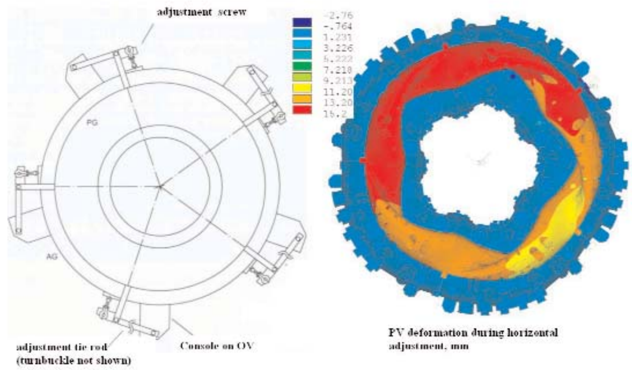


Figure 16: Improved PV horizontal support and adjustment system

This system allows simple adjustment of the PV position and also, to a certain degree, of its shape. Thus it is possible to compensate for manufacturing and/or assembly inaccuracies as well as for potential imbalances of thermal loads on the different divertor modules during plasma operation. An algorithm is being developed for controlled bolt and rod adjustments in order to achieve the intended PV position and shape by Rostock University. The required FE analysis concerning PV stresses and deformations is being performed by IPP. The work will be finished in spring 2007. Modelling of the PV distortions due to welding was developed. In a first test with yet an insufficient amount of input measurement data the translational displacements and rotation between both welded PV sectors could clearly be shown, and the remaining vessel deformations could be discerned. This method will be applied at further PV welding work in order to document and possibly anticipate weld distortions.

4.1.3.2 Outer Vessel

The outer vessel (OV) FE model update was completed by IGN company, Germany. An elasto-plastic buckling analysis was performed by ENEA (Italy) considering dead weight, outside pressure, and forces and moments on the ports. A load factor, applied to all of these forces gave a satisfy factor of 4.5 without collapse of the vessel (figure 17).

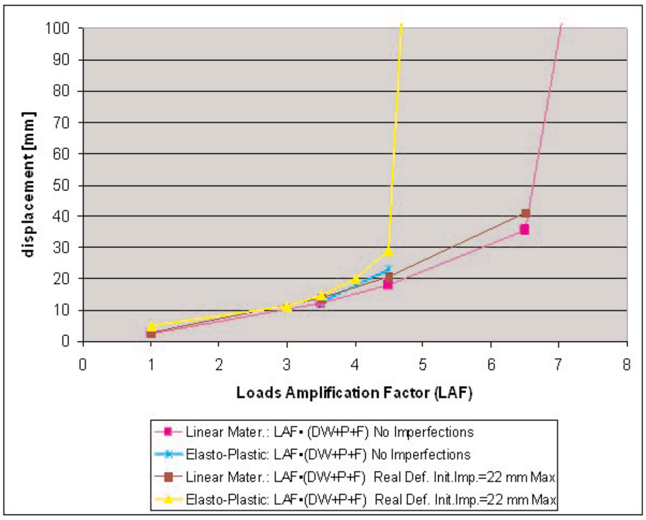


Figure 17: OV elasto-plastic buckling analysis: Collapse only after load amplification factor 4.5. LAF-load amplification factor, DW-dead weight, P-pressure, F-force (ENEA, Italy).

Practically the same load factor was reached for the structure with initial shape imperfections of 22 mm corresponding to the 1st eigenvalue form and expected maximum tolerances. This means that the OV is safe against buckling. FE analysis was also performed on the OV legs with optional openings. The latter are considered to simplify the cryoleg assembly. The OV FE model is also being used for the analysis of the OV upper and lower part deflections during assembly. The issue is deformation of the OV shell which has to be limited in order not to endanger the attached thermal insulation. Further FE analysis was required in order to specify new welds on some ports and domes which became necessary due to change of assembly sequence.

4.1.3.3. Cryostat Global Model

The cryostat global model (cooperation with ENEA, Italy) is close to completion. It contains the latest updates of the PV and OV models, and all the ports with accurate transversal and lateral stiffness of the bellows. The latter were also determined using FE analysis and agreed well with experiments whereas the stiffnesses given by the bellows producer deviated considerably from the test results. The cryostat GM includes also the machine base which is an elastic steel structure. All these components are connected in a realistic way in the model and form a complex mechanical system. This allows to finally substantiate the cryostat design with all loads fully considered. In addition, it is now possible, for example, to analyse and evaluate the influence of any component deviation from nominal position onto any other component. The cryostat GM will also be a valuable tool to evaluate the effects of PV adjustments or asymmetric heat loads during abnormal operation conditions. Figure 18 shows a first result with the cryostat global model including the machine base.

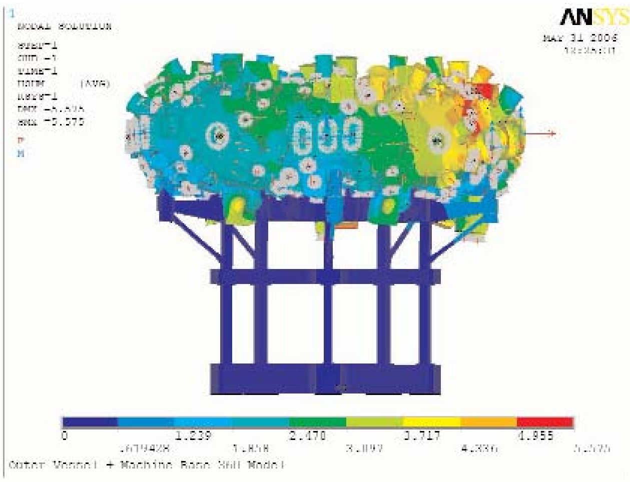


Figure 18: First deformations result from cryostat global model, including machine base (ENEA, Italy)

4.1.3.4. Weld Evaluation Criteria

In a workshop with participation of international experts the criteria for weld evaluation were defined for welds of the W7-X mechanical structure and cryostat components at room and cryogenic temperatures. Additionally, test requirements for different types of welds were agreed upon. These guidelines now give clear answers which standards shall be applied, and they proved to be very useful when evaluating the stresses in particular of the PV and OV port and dome welds as well as of the numerous welds of the cold structure.

4.2 Design and Test of the Coil Supports

The coil support elements that transmit the forces between the coils and the central support ring, and between adjacent coils, could be essentially defined. This was the result of the continued extensive development program which comprised FE calculations and tests under realistic conditions. Only questions of less relevance need to be clarified, and some detail design is still open.

4.2.1 Narrow Supports

The narrow support elements are sliding contacts (~30 per half module) located on the high field inboard coil side. When the coils are not energized there is a small initial gap (from 0 up to 4.5 mm) between the sliding surfaces. This gap closes during the coil current ramp-up. The initial gap distribution between NSEs is optimised in order to avoid overloading of the elements. The narrow support elements transmit forces up to 1.5 MN between adjacent coils while simultaneously allowing relative movement up to 5 mm when in contact, and tilting <1°. During sliding no stick-slip should occur since it might trigger a quench of the superconducting coil cables. The adopted solution consists of an Al-bronze pad that on one side is shrink-fitted into a stainless steel frame which itself is shrink-fitted into the coil casing. The sliding surface of the pad is covered with MoS_2 (coated by means of Physical Vapour Deposition, PVD) to reduce friction. The opposite sliding surface on the adjacent coil is spray-coated with an industrial MoS_2 compound. A movable dust cover protects the pad from debris (e.g. dust particles or thermal insulation flakes) that could fall onto the sliding surfaces during assembly and/or operation. The integrity of the MoS_2 layers is of vital importance to ensure that the expected number of load cycles of the experiment can be performed. Degradation might cause coil stick-slip effects during their load deformation which in turn might trigger quenching of the superconductors of the winding pack. A load cycle constitutes ramping up the coil current from zero to a value where most of the pad gaps have closed, and down again. In an extensive test program suitable preparation of the substrate surfaces and application procedures were developed. In addition, during assembly the relative humidity in the assembly and torus halls is kept below 50 % in order to prevent MoS_2 degradation. Figure 19 shows the improvement which could be achieved in the quality of the sprayed MoS_2-layer.

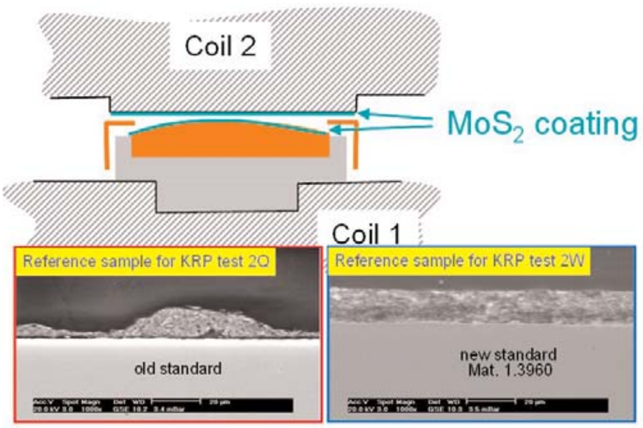


Figure 19: Top: Sketch of narrow support element Bottom: MoS2 layer micrographs showing the improvement of the spraying procedure

At KRP company full scale friction tests were performed in vacuum at 77 K for 4000 load cycles, maximum normal loads up to1.5 MN, and sliding distances of typically 2 mm. The test results showed typical friction factors between 0.03 and 0.04 which increase with deterioration of the lubrication layers (figure 20). Audible stick slip occurs only after the friction factor increase starts. The chosen design of the narrow support elements and the adopted coating procedure were thus qualified to meet these requirements. Additional tests are envisaged to also check the pad behaviour if the orientation of the load slightly deviates from the normal direction during sliding. Test will also to be performed to check the coating properties after exposure to air for a certain time, and whenever aluminium bronze with properties other than those tested has to be used for pad fabrication.

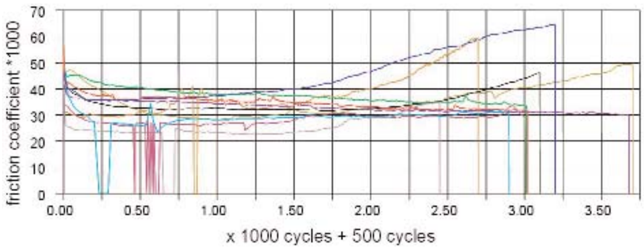


Figure 20: Friction factor development of different NSE samples during full load cycle tests (KRP comp., IPP)

As a back-up solution in case of degradation of the MoS_2 coating, the possibility to re-lubricate the sliding surfaces at a later stage of W7-X operation is kept open by installing permanent thin steel pipelines connecting each of the pad dust covers with access points near cryostat manholes: This would allow to inject fresh lubricant onto the sliding surfaces during shut down periods. In addition, these capillaries also allow access for possible fibre-optical inspection. The initial distribution of the gaps between the sliding pads and adjacent coil surfaces was optimized for evenly distributed loads that do not exceed the design values (1.5 MN). However, the NSE load distribution is quite sensitive to tolerances of the gap widths which means, that severe requirements are imposed on the assembly process. So far, the gap distances of the coil interspaces between NPC types 3 and 4, as well as between types 4 and 5 could be released.

4.2.2 Planar Supports

The planar supports fix the planar against of the non-planar coils. They have to transmit forces up to 500 kN and to reduce planar coil (PLC) deformation to reasonable values in order to avoid collisions with adjacent components. Originally four planar supports based on the sliding pad concept similar to the narrow supports were foreseen for each planar coil. They turned out to be quite complex on the one hand, and allowed too much deformation and deflection of the PLC on the other. Therefore, the option to use fixed supports instead was investigated, and a solution was found which allows to substitute one PSE per PLC by a fixed one (figure 21). The replaced PSEs would have been the most complex ones with three sliding pads each to limit radial and lateral coil movements. Besides simplicity, the advantage of the new solution is that the PLC deformation is reduced significantly, and another sliding element per coil can be saved. The remaining two sliding PSEs are rather simple and do not pose any problem concerning production, assembly or operation. The sliding distance of these elements is limited to <5 mm. The fixed PSE concept is now under detail design.

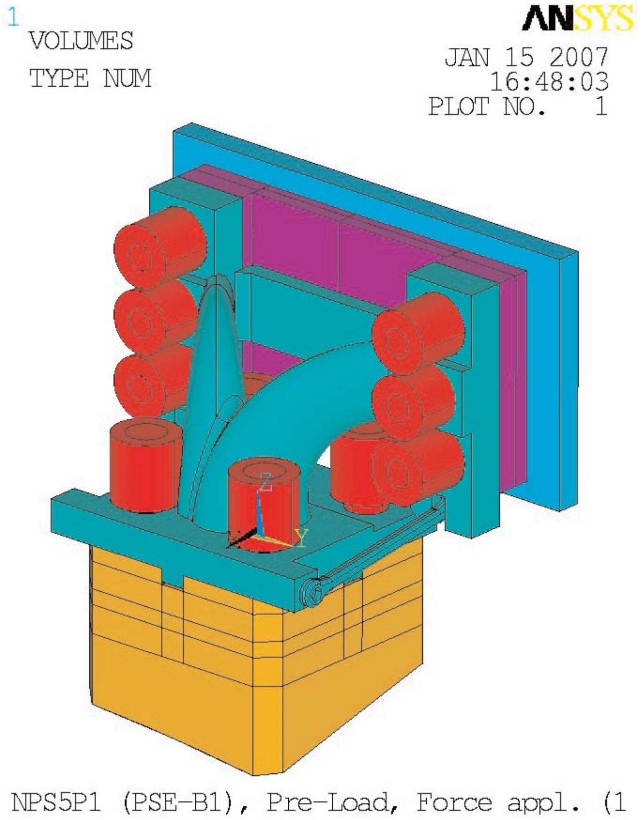


Figure 21: Design variant of new fixed planar support element PSE-B1

4.2.3 Lateral Supports

The lateral support elements (LSE) are located on the low field outboard side and transmit tensile, compressive and shear forces up to 1.7 MN, and bending moments up to 200 kNm. For the coil pairs 1-1, 1-2, 2-3, 3-4, 4-5 the limited space permits welded solutions only. At Forschungszentrum Jülich and IPP these welds have been thoroughly investigated in a test programme. All welds of the LSEs 1-2, 2-3, 3-4, and 4-5 can now be produced with shrinking tolerances according to the requirement not to alter the specified gap widths of the narrow supports. The highly loaded LSE 1-1 at the half-module interface requires massive welds; the corresponding welding test program is still going on. For the lateral support element between 5-5 at the boundary between modules, a bolted solution was adopted (figure 22) and the conceptual design is finished.

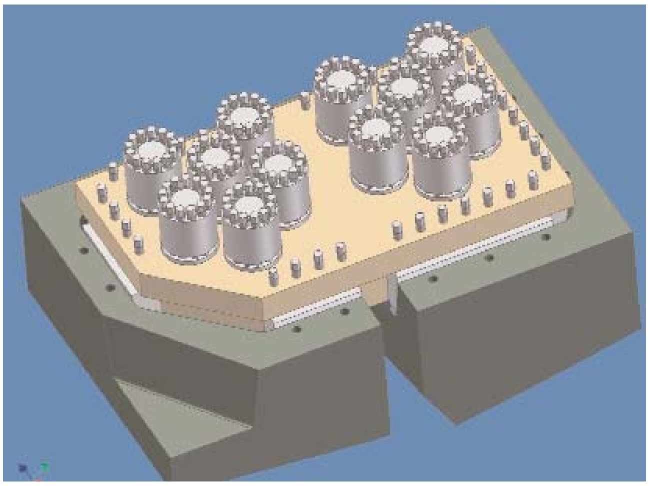


Figure 22: Bolted lateral support element for coil interspace 5-5 (IPP, ENEA)

4.2.4 Central Supports

For each coil, the central support consists of pairs of bolted connections between coil blocks and extensions of the central support ring. These connections are typically made of a matrix of up to nine Inconel 718 rods of sufficient length to obtain a preload of 650-900 MPa per bolt at 4 K. Since the frictional capabilities of the connection, given by the bolt preload, are not sufficient to generate all the reactive transversal and rotational forces between the coils and the central support ring, additional stainless steel wedges are inserted in between the coil blocks and the shoulders of the central support elements which are fixed by welding in position. The detail analysis, considering the loads from the updated global model, continued in close cooperation with Warsaw University of Technology (WUT). All CSEs were studied using simplified models. Six of the most critical CSEs are being investigated in more detail taking into account interference of the CSEs through the CSS structure; this program is close to completion. Intermediate results confirm the design which is, however, close to the limits. Another issue came up during the year under report when assembly full scale tests showed that the originally planned wedge weld to the coil block would cause too much weld shrinkage and distortion of the wedges. In cooperation with Assembly Division another welding concept was developed which employs two smaller welds per wedge which keeps the deformation within acceptable tolerances. Another advantage of the new welding concept is that it allows the gliding surfaces between wedges and shoulders to be lubricated with MoS_2 after welding, und thus to avoid overheating of the lubricant.

The corresponding FE analysis was also performed in close cooperation with WUT. Within the frame of this cooperation a parametric model was developed which allows to analyse the influence of weld and assembly tolerances of the CSEs, in particular of the wedges, on the mechanical integrity of these coil to support ring interfaces. With the help of this program it is possible to determine the final design and positioning of the wedges (figure 23) Another 3-bolt full scale mock-up test is being prepared which takes into account the new wedge design and the experimentally found weld shrink as well as tolerances. The first 3-bolt test performed in 2005 showed that such a connection is able to take the operational loads for more than 4000 cycles, and thus confirmed the required functionality. However, stick slip occurred between the wedges and shoulders which shall now be avoided by lubricating these interfaces with MoS_2 spray according to the procedure which was successfully qualified at the NSEs.

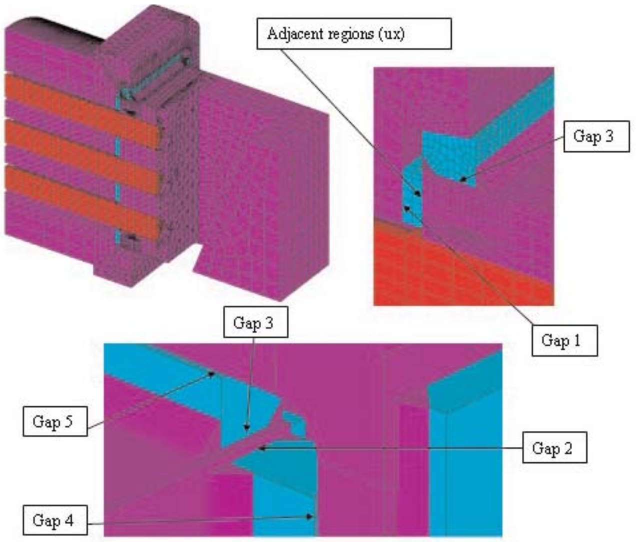


Figure 23: Parametric model for CSE wedge analysis. Wedge and shim plate gap variations due to manufacture, assembly and weld shrink tolerances (WUT, IPP)

4.3 Design Office

The Design Office is organized in five groups: Back Office, Configuration Control, Diagnostics, In-Vessel Components and Magnet & Cryostat System. Major tasks of the department are the design of components, the supervision of tolerances, adjustment and spatial compatibility control between adjacent components, as well as the geometrical evaluation of manufacture non-conformities (figure 24). The main focus was dedicated to the basic components of W7-X: coil system, central support ring, busbar system, plasma and outer vessel, ports, 1^{st} wall, divertor, various startup diagnostics as well as instrumentation and cabling. Predominant effort was put on the detailed configuration analysis of adjacent components of the basic machine with special attention given to NCRs (Non Conformity Reports) concerning manufactured components. For the collision analyses which are performed with regard to assembly and operation conditions, the as-built geometry and latest FEA calculation refinements are considered. For this purpose advanced technologies like laser scanning, reverse engineering (i.e. creation of as-built CAD geometry) and shape morphing (i.e. deformation of nominal CAD geometry according to FE analysis displacement results due to magnet forces, see figure 25) were developed and are being utilised. In addition, strategies for CAD data processing, tracking and archiving, as well as independent software tools have been developed. In correlation with manufacturing experiences the review of critical issues for all major components was continued. The magnet system, the central support structure (CSS), the cryolegs, and the busbar system, were verified as to geometrical non conformities – in 2006 more

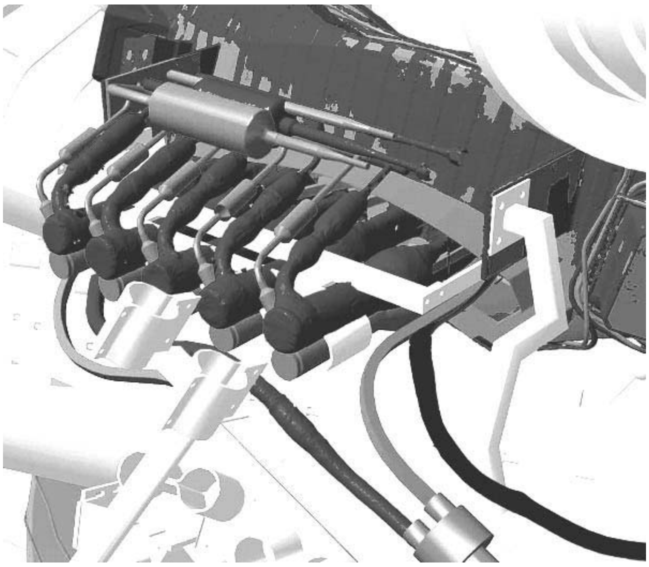


Figure 24: Reverse engineering revealing geometrical non-conformities: nominal (light grey) vs. as-built (dark grey)

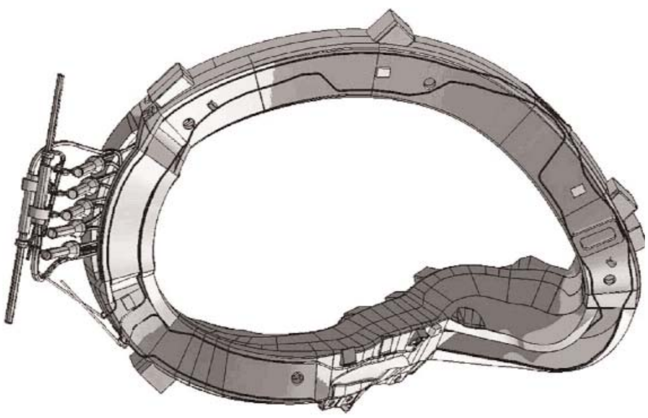


Figure 25: Shape morphing: nominal (light grey) vs. in-operation (dark grey)

than 50 NCRs were processed – and as to compatibility with adjacent components (e.g. thermal insulation shields of ports and outer vessel). Based on FEA calculations, the implementation of components and supports have been reviewed, in particular the coil fixation structure elements, and the coil headers. The interfaces between the central support ring and the coil system were investigated (bolts and nuts, conformity of thread dimensions, collisions with ports and busbar system). Special focus was devoted to the lateral connections between type 5 NPCs, and the PLC supports. As a result, the geometrical analysis of the magnet system resulted in 70 collision reports. In consequence, approx. 20 change notes for components of the magnet system had to be initiated. The detailed design of the in-vessel components (target, baffle, wall and port protection, cryo-pumps, piping) was continued. As for the diagnostics, the attention was concentrated on the design and/or prototype manufacturing of the Mirnov coils, the Langmuir probe array, the diamagnetic loop, the Soft-X multi camera tomography system, H_α infrared diagnostic, Thomson scattering bulk, bolometer, neutral gas manometers and the Rogowski coils. Furthermore, Design Office manages the engineering computer network which currently consists of 110 workstations, and provides support for the CAD and Reverse Engineering software for all designers at the Greifswald site of IPP. The Design Office staff comprises 33 members in Greifswald and 2 in Garching.

4.4 Electromagnetic Analysis

The evaluation of manufacturing errors of all 50 winding packs of the non-planar coils could be completed. The maximal absolute deviation from ideal geometry found was 3.0 mm, the maximal relative deviation was 2.0 mm. The latter value is the relevant one concerning distortion of the stellarator symmetry. The coils of type 1 and 5 showed the largest maximum but the smallest relative errors. Consequences of field errors are asymmetric loads on the divertor, reduction of plasma radius, additional islands of different periodicities, and creation as well as extension of stochastic regions. The trim coils which are planned for correcting field errors as well as for investigating the effect of small boundary field variations were conceptually designed (figure 26).

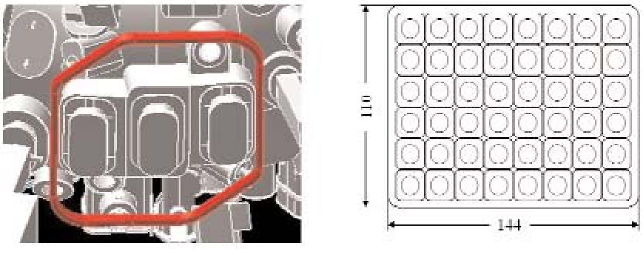


Figure 26: Trim coil type 1, layout on outer vessel and winding pack cross section

Another task was to analyse the transient currents, voltages, and forces due to an emergency magnet system switch-off using the as-built data of the power supply and discharge resistors and considering the currents induced in the coil casings. In addition, the effect of switch-off delays of one coil group was investigated. Due to the delay and additional induced current in the delayed coil group, the currents become significantly different and cause increased lateral forces on these coils. The maximally allowed delay of 50 ms as specified for the power supply system was confirmed. Longer delays would quickly increase the forces above allowable limits. Fault analyses were performed assuming such delays and short circuits across coil groups. Figure 27 shows the current distribution between the coil systems due to a short across the type 1 coil group during switch-off from the low shear (LS) field configuration. In LS the NPC 1 conducts the largest current.

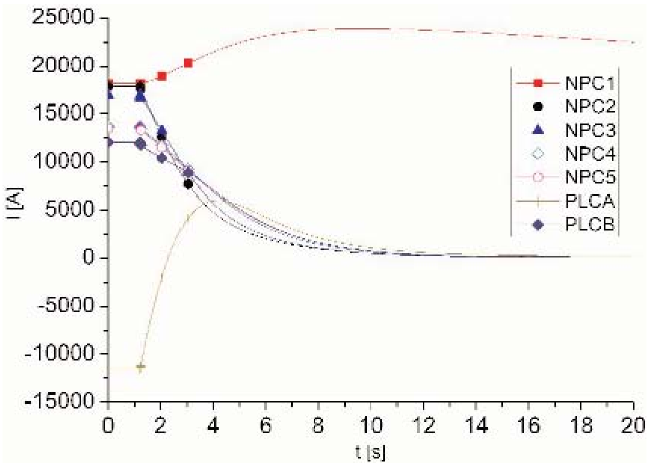


Figure 27: Magnet system failure analysis: Current distribution during shutdown from low shear configuration when coil group type 1 is shorted

4.5 System Integration

Tools were further refined to monitor, modify and update the space requested by the various W7-X components located in the torus hall, including diagnostics and auxiliary equipment. Detailed assessments were done for the cooling water lines in the second basement and the rack shelf in the torus hall, figure 28. Activities were continued to arrive at an integral solution in congested areas, such as the torus centre, in order to make optimal use of the available space and to avoid collisions. Common support structures and access routes are foreseen wherever possible, taking also into account the space required for assembly, repair, and maintenance. Furthermore, activities have started to determine the location of mechanical sensors at the central support ring and inter-coil structures to facilitate monitoring of critical areas during machine operation. Tools are being developed to derive allowable operation regimes from such measurements, taking also into account deviations of the as-built components from the specified requirements. Particular focus was put on qualifying the strain gauges on the non-planar coils to warrant reliable measurements of the stress distribution of the coils during machine operation.

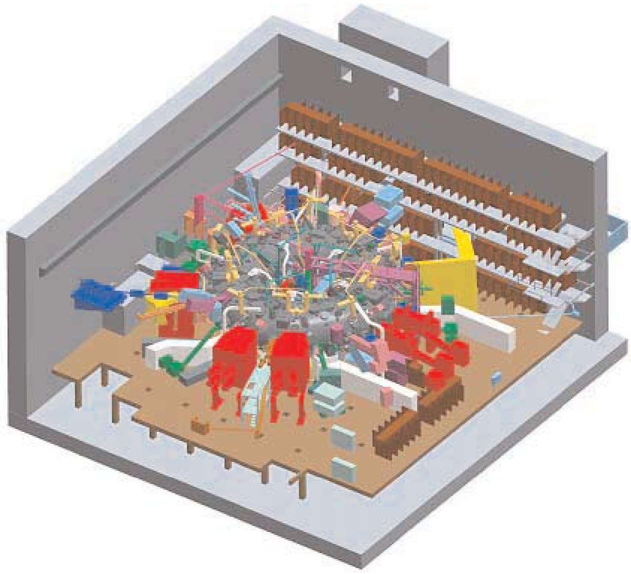


Figure 28: W7-X and periphery layout in the torus hall

5 Assembly

In 2006 the preparation of the assembly sites, the assembly equipment, and extensive assembly trials have been continued. An additional assembly area (preparation hall in Mesekenhagen) was put in operation. Contracts for the design and the procurement of further complex assembly devices (assembly ramps) have been launched. The machine base was delivered and installed as planned. The manufacturing of the bus-bars (cooperation with FZ Jülich) was started; the prototype of the optimised joint with the high pressure joint-housing was successfully tested in the Efremov Institute, the manufacturing pre-requisites for the mechanical supports of the bus-bars were further accomplished. The preparation of plasma-vessel sectors and coils was continued as planned. Two half-modules are presently assembled in both mounting stand MST I a/b. Expensive assembly trials have been performed to ensure the mountability of vessels, ports and support rings. Special welding procedures for aluminium welds and for the LSE welds with minimised shrinkage were qualified. Several new engineers and craftsmen started their work. The assembly process-planning, process documentation and work safety system run reliably.

5.1 Vacuum Technology

The work packages of the vacuum technology group in 2006 were leak detection on single components and monitoring of leak tests at suppliers (Tesla, ENSA, BNG) as well as leak and Paschen tests on coils and on cryo piping of thermal insulation during the coil preparation and assembly. Local leak tests with diverse test chambers for superconductor connections and cooling pipes at room temperature and at 77 K (if technically necessary) are routinely implemented during assembly. The design of these test chambers as well as the qualification of the process is extensive. Qualification tests of materials and devices concerning the suitability in vacuum (outgassing rates, Paschen stability) were realised in a laboratory. On the specification of the vacuum systems was worked at show speed because it depends on the progress of the layout in the torus hall.

5.2 W7-X Assembly

The work in the component preparation, especially on coils and plasma vessel sectors, has been continued as planned. The primarily preparation area in the future compressor hall were cleared to avoid obstructions when work on helium plant starts. At the moment three coils are prepared. Further twelve coils are being prepared.

Figure 29: Preparation of coils and plasma vessels

Due to quality deviations on coils and due to improving the design, it takes about eight weeks in two-shift-system to compare one coil for assembly. The design of the mechanical supports in the coil connection area was revised several times. Meanwhile, these supports are available for all coils. All coils will be coated completely with a reflective film in the component preparation. Because of the delay in delivery and of the changing delivery sequence, it requires additional space to store the coils. At the moment there are no technological problems in the component preparation.

The MoS_2-spray coating, developed at subdivision assembly; and the shrinking of the NSE-pads and the NSE-holder were completely qualified and have been used routinely. To protect the spray coating from air humidity during assembly phase, the assembly halls have been equipped with dehumidifying systems. Each coil is fitted with piping to allow additional MoS_2 respraying of the NSE later on. The preparation work on the ports has been started in an external hall. The hall in Mesekenhagen was refurbished and equipped with the necessary devices. The preparation work has become more extensive than original planned, but there is no effect on the assembly plan at present. In the pre-assembly, coils are threaded on MST Ia and Ib. The related weld and insulation work (MAN DWE) on the plasma vessel sectors function as planned. To quality the MAN DWE-assembly work two extensive test sequences on the half module separation plane were carried out at IPP. The test results of assembling the half module separation plane show that this separation plane has to be additionally prepared in future. The necessary equipment will be ordered in 2007. For this additional space and resources are needed. The currently reachable assembly times in the pre-assembly approximately meet the assumption of the updated assembly plans. The development works for welding of the LSE between the coils have become technically very extensive after the necessary welding seam thicknesses were significantly extended. The assembly technology for NSE and LSE had to be updated several times. Together with subdivision MC; assembly trials of the coil support structure were carried out with the manufacturer Rovera/Italy. The qualification of the assembly of the high-strength screw connection between coils and the coil support structure was successful. To avoid surprises during assembly of the coil support structure, further extensive assembly trials on MST I are planned for February 2007.

Figure 30: Two flip-symmetric half modules are being mounted in the pre-assembly hall

The machine base in the torus hall was mounted as planned. The installation of MST IV starts in January 2007. The installation of the second MST III starts in March 2007. The first MST III was delivered in summer as planned. To ensure the planned assembly concepts at MST IVa and IV special trials have been prepared. They will last the complete year 2007. The necessary trial equipment has been specified and tendered. The conceptual work and the procurement for the device of the final assembly were continued as planned. Very extensive assembly devices have to be designed and procured to ensure the mountability of the outer vessel shells under consideration of the requirement of the thermal insulation. Together with MAN DWE a team has been formed to carry out the conceptual preliminary work. Additional resources in 2007 will be required for the completion of this task in time. First assembly devices have been installed on the outer vessel shells at the manufacturer. The ramps and the bridge for the ports were specified in 2006. This required, extensive planning and detail investigations. Only a small number of tenderer responded to the call for the procurement of the very demanding devices.

Figure 31: Special assembly devices for the installation of the ports were tendered

The first delivery of these devices is expected at the beginning of 2008. To cover the mountability of the ports will be undertaken comprehensive assembly investigations and trials which will probably least for the complete year 2007 and need additional resources. The cooperation with the colleagues from Garching for the conceptual planning of the assembly of the in vessel components has been continued in 2006. Systematic investigations for interactions of the different tolerances and deviations on the components of the cryostat during manufacturing and assembly were carried out. A further optimisation of the assembly processes is necessary, especially for ports and their insulation. In 2007 the conceptual planning for the special ports which can probably will continued not be installed with the standard equipment.

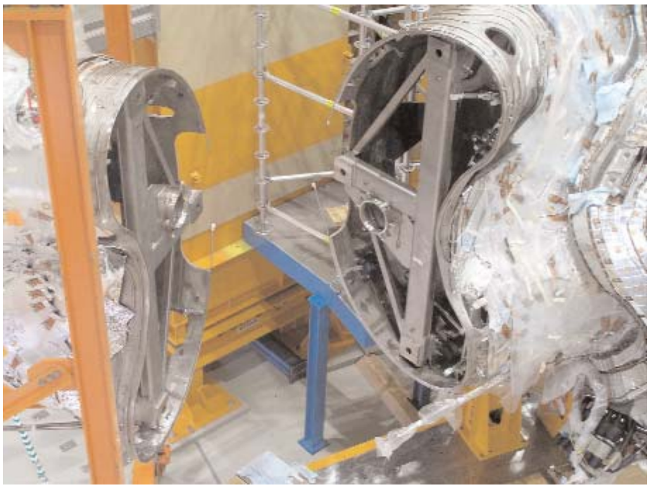


Figure 32: Assembly trials for optimisation of the mountability of the plasma vessel

The work on cryo instrumentation has been continued. The design for the first module is available. The extension of the low voltage power supply system is specified, tendered and ordered. The work runs as planned. The foundation has been completed. Detail planning for the concept of the grounding area in the torus hall and diagnostic hall has been started. The platforms for the control unit was specified and procured; the planned installation in the torus hall starts in January 2007. The first construction stage of the cooling system was specified, tendered and the order was placed with the company AKB. The work can start as planned. The effectiveness of the assembly control meets the expectations. The advanced weekly and 4-weekly plans are accepted within the project these identify missing items in time so that the other subdivisions and departments are able to provide the necessary information and decisions. The preparation of the assembly documentation (QAAP, work and test instructions) and the flow of materials operate reliably. The increase in the assembly work will lead to an increase in the required planning resourses. The detailed planning allows for the identification of required recourses in time in order to ensure that they are available when needed. Quality deviations are reliably recorded and monitored. The fast preparation of effective corrective actions due to quality deviation has to be improved. The complete assembly schedule and the plan of resources were extensive updated and optimised in detail. To partly compensate the effect of the delayed component delivery and the additional assembly work accelerated actions have been considered in the assembly plan, which have not yet been released. Additional personnel resources for assembly have been recruited (metrology, mechanics). Three additional responsible officers (welding supervision, ports and bus) took up their employment. More external staff will be included as from mid January to cover the two-shift system for the coil preparation. Additional engineering staff will start work shortly for the procurement of the extensive assembly devices for the outer vessel. A cooperation with engineers and technicians of the Polish Academy of Sciences is intended. A preliminary planning for an additional assembly line in Lubmin and the necessary structural and technical conditions have been defined. Building a complete new hall on IPP site is more expensive and will probably take more time. Additional hall space for the bus-bar preparation and for the storage of components has to be planned and prepared. The areas in Lubmin, already planned for accelerating actions, will be considered.

Figure 33: The machine base in the torus hall was delivered as planned

Assembly has achieved the planned steps the technological preparation of the different assembly stages in 2006. Revisions of already qualified assembly procedures due to the complex design of the components cause slight delays for several items. This will be compensated with assignment of additional external recourses in 2007. Device assembly could not be operated continued due to the delay the delivery of components. On the other hand, the delivery sequence, being not compatible with the assembly sequence, results in an accumulation of material and work which can be compensated in future only with additional storage and preparation space. The purchasing of the peripheral hall equipment (cooling circuit, electronics, vacuum…) generally occurred as planned. Due to the very close connection with the detail design work of other components there is a slight delay of design work. From the today’s point of view, this delay can be compensated with present resources in 2007. The assembly control, the planning and the documentation of assembly generally works reliably. In 2007, the weekly works coordination has to be complemented with daily coordinations. As get six companies provide skilled and well-trained technicians and engineers for the realisation of the assembly work on W7-X. In 2007 further companies will be qualified in order to meet the increase person required by subdivision assembly.

6 DIAGNOSTICS

6.1 Overview

The work concentrates on the "start-up diagnostics" set necessary for safe operation and control of the machine and those diagnostics adapted to and being indispensable during the initial operation phases of the experiment. Time, financial and manpower planning is adjusted to the agreed modified time schedules of the W7-X assembly. The diagnostics project/department is divided into nine expert groups and groups on technical coordination, documentation and control. A temporary working group within the project covers R&D on the development of heat-resistant plasma facing optical components.

6.2 Reports of Expert Groups

The following sections briefly summarise the main activities within the expert groups of the project. Due to assigned priorities there were no activities in 2006 in the subgroups on fluctuations, fusion products and heavy ion beam probe and fast particles.

6.2.1 Edge and Divertor Diagnostics

The feasibility study for a wide-angle IR/visible mirror based endoscope system which combines the IR divertor control thermography and the H_α imaging systems has been successfully completed. Such a system is particularly suitable for the required continuous divertor observation during long pulse discharges with high heat loads at the diagnostic front-end. Further activities regarding the divertor thermographic system focused on basic investigations of the temperature enhancement and its temporal evolution at surface heat loading of contaminated CFC-surfaces. The measured surface temperature excursions have been compared with values of analytic and numerical solutions of the heat diffusion equation taking into account a surface region with low thermal conductivity or poor thermal contact to the underlying substrate material. The conceptual design of the target-integrated pop-up Langmuir probe arrays has been improved accounting for relatively strong bending of the target elements under thermal load, as was predicted by new FEM calculations and verified by heat load tests in the GLADIS device. Instead of a common solid probe body, the probe tips will be supported by individual spring-loaded body elements mounted on a common movable frame, thus allowing for adaptation to changing shapes of the target surface. The fixation of the tips within the body elements was modified in order to allow for exchanging the tips from the plasma side. A prototype of the new probe elements has been designed in detail and shall be constructed and tested in 2007. In parallel, the present design of the array drives and support elements shall be adapted to the concrete design of the neighbouring target modules and sub-divertor structures which is now being worked out in detail. The number of ASDEX-type manometers, each inserted through a port via an immersion system, is initially limited to 25. Corresponding ports allowing for suitable manometer positions in the sub-divertor region as well as in the main chamber have been selected. Prototype manometers in combination with a modified power supply and digital data acquisition system have been successfully tested at WEGA and ASDEX-Upgrade. The full set of 25 manometers has been ordered at the end of 2006. The design of a prototype immersion system has been modified. The manufacturing of the improved system has been launched.

6.2.2 Microwave Diagnostics

The group prepares the multi-channel interferometry, an interfero-polarimeter, ECE and reflectometry. At the beginning of the W7-X operation the multi-channel ECE radiometer, a four-channel version of the multi-channel Interferometer and the Polarimeter will be available, insuring redundancy for the density feedback control system. The main design activities were related to the in-vessel components incorporated in the first wall elements. For the multichannel Interferometer a total of 11 wall integrated retroreflectors allow for some variation of the sightline geometry on demand. Their integration into the first-wall heat shield is supported by FE calculations to ensure their optical specifications despite possible inhomogenous heat load and cooling. The stepwise installation of the multichannel interferometer is being investigated in the framework of a PhD (to be finished early 2007) by means of forward calculations for selected plasma scenarii to study the information gain in the chosen sightline optimisation. In the laboratory the prototype two-frequency interferometer was upgraded to a CO_2-CO laser system, using the optimum wavelength combination of 10 µm and 5 µm for vibration compensation. Tests with different detector types showed that this system allows the use of a single common detector for both wavelengths which reduces sources for spurious vibration induced phase changes. In spring 2006 a cooperation with CIEMAT started which is dedicated to a comparison of the CO_2-HeNe Interferometer at TJ-II with the single channel prototype CO_2-CO system in Greifswald. It aims at the optimization of the diagnostic arrangement and components as well on the reduction of thermo-optic and vibration related effects. The Interfero-Polarimeter sightline is investigated in the frame of cooperations with the Akademia Morska, Szczechin, Poland and the Szczechin University of Technology, which both started in fall 2006. Different microwave based polarimeter or interferometer methods are being compared numerically in the complex magnetic geometry of the sightline available at W7-X, aiming at a robust density measurement for feedback control for the variety of possible magnetic configurations and long pulse operation. Preparation of ECE diagnostic and Reflectometry has not been continued in 2006.

6.2.3 Charge Exchange Diagnostics

The group develops the diagnostic beam needed for CXRS measurements. The injector is being developed in collaboration with FZ-Jülich and the Budker-Institute of Plasma Physics (BINP) in Novosibirsk, Russia. The latter will deliver the tested system, as agreed, in 2012. The project structure and schedule has been defined in a kick-off meeting at BINP. The dedicated high voltage power supply is presently being fabricated. RF or arc ion sources are considered for the Wendelstein 7-X diagnostic beam. Prototypes of both sources are being tested under real operating conditions making use of the diagnostic beam at TEXTOR. Depending on their performance, the selection of the injector plasma source will be made in 2007. Laboratory tests of various ion optics developed in beam modelling programs for the diagnostic neutral beam are being conducted. An ion beam divergence of $< \pm 0.5^{o}$ has been achieved for the Wendelstein 7-X diagnostic beam parameters. The planning of the required infrastructure has started.

6.2.4 Spectroscopy

The high-efficiency XUV overview spectrometer system (HEXOS) for fast monitoring of impurity line spectra of W7-X plasmas over an extremely broad energy range (2.5-160 nm) has been completed by Jobin-Yvon (France) and passed the acceptance procedure. After installation on TEXTOR (FZ-Jülich), the system already demonstrated its excellent performance in the presence of an extended fusion plasma during a first test period at the end of 2006. The achieved spectral resolution and overall efficiency seems to meet the expectations. The impact of discrepancies in the second-order reflectivity of two of the gratings (which might be related to the manufacturing process) on the resolvability of spectral lines in the presence of complex impurity mixtures is presently being tested making use of the TEXTOR plasmas. For further calibration and in order to gain experimental experience for the final deployment at W7-X, the HEXOS system will remain at TEXTOR until the installation of the diagnostic systems on W7-X can be started. The assembly of the remote control system is still ongoing but has been largely finished. A first design of the divertor bolometer which will be installed in the port AEJ40 has been completed. The designed bolometer-housing contains two cameras and via its shape minimises the neutral particle leakage from the sub-diverter region through the observation gap in the divertor baffle. To achieve the required sightline coverage of the plasma cross section for tomographic inversion, a slight enlargement of the standard cut-out in the baffle structure will be required and is presently being discussed with the KIP group. With respect to the bulk plasma bolometers required at start-up, the design concepts for the systems which will be installed in the ports AEU30 and AEV30 have been developed. A computer code has been developed for sightline optimisation via changing the camera geometry. The detailed diagnostic design has started. Some basic tests of the neutral pressure sensitivity of the metal foil detectors have been carried out in the laboratory, at VINETA and at WEGA. The design of the gas inlet system for the thermal He-beam diagnostic, which needs to be integrated into the sub-divertor structure has been completed. The feasibility optics design study for a wide-angle IR/visible mirror based endoscope system which is supposed to combine the IR divertor control thermography and the H_{α} imaging systems in a single long pulse high heat load compatible observation system has been successfully completed. The components for the upgrade of the high heat load plasma facing optical components test chamber for accommodating components up to 300 mm diameter have been delivered so that the refurbishing of the chamber can now be undertaken in 2007. The feasibility study regarding edge water cooled sapphire windows with 50 mm exposed diameter for heat loads of 50 kW/m^2 has been successfully completed. The video diagnostics – which is being developed by KFKI-RMKI (Budapest, Hungary) – is one of the start-up diagnostics needed for the safe operation and control of the stellarator. For observation the 10 equivalent tangential AEQ-ports of the W7-X vacuum vessel are selected, which give nearly full coverage of the entire plasma vessel. The conceptual design of the diagnostic was finished in 2006. Three different concepts were investigated, of which finally the one with the detector camera located at the plasma end of the ports has been selected. Monte Carlo calculations estimating the neutron fluence and the gamma radiation revealed, that the radiation level is probably acceptably low even at that location and therefore most likely will not affect the lifetime of the camera. This estimation, however, will be cross-checked under fairly realistic circumstances in the reactor of the Budapest University of Technology. The newly developed intelligent CMOS camera EDICAM (Event Detection Intelligent Camera) will integrate all the advantages of CMOS sensor chip technology and fast network connections with 10 Gigabit Ethernet interfaces. EDICAM consists of three different modules with two interfaces. A Sensor Module with reduced hardware and functional elements to reach a small and compact size and robust action in harmful environment as well. An Image Processing and Control Unit to handle the entire user predefined events and run image processing algorithms to generate trigger signals and reduce the redundancy at the image flow. Finally a 10 Gigabit Ethernet compatible Image Readout Card as a network interface for the PC is being developed. In 2006 the Sensor Module was built and the Image Processing and Control Unit's MatLab simulations were started to implement the required image processing algorithms.

6.2.5 Thomson Scattering

The design of a prototype polychromator for analysing the scattered light was continued. The concept considers the high variability of the electron temperatures expected for W7-X und high suppression of laser stray light. The concept for diagnostic control and data acquisition was developed. A water cooled shutter was designed, to protect the vacuum window at the observation port.

6.2.6 Soft X-Ray and Magnetic Diagnostics

The conceptual design of the in-vessel X-ray tomography camera system (XMCTS) is still in progress. Due to interferences with the thermal shield (which is almost completely designed) modifications of the camera design, in particular of the pneumatic shutter and the attached electronic box, had to be made. Also, the mounting and maintenance concept had to be reconsidered. The design of the preamplifiers has to be improved further because of too high crosstalk at high frequencies. Major activities in 2007 will be the completion of the conceptual design, the construction of a prototype camera and the design of the signal conditioning electronics. A new software package for calculation of the contribution matrix, prerequisite for tomographic inversion, was implemented. The intensity distribution on the detector arrays inside a set of pinhole cameras, given radiating volumes (voxels) inside the last closed magnetic surface, has been modelled. The results of the calculations are valuable for the design of the 400-Channel XMCTS (softX Multi Camera Tomography System). As an example the sight line density of the XMCTS is shown in figure 34. The new C++ code implementation is very modular (object-oriented design), experimental device independent, i.e. equally suitable for linear devices, stellarators, tokamaks, etc. and easily portable, since no external libraries are required. The old code was essentially limited to the W7-AS stellarator environment and rather slow (typical run: 1200 min, typical run of new code on same machine: 40 min; on modern PC: 2 min). However, the old code is still valuable and in use for benchmarking the new code. The development was done in close relation to the W7-X diagnostic software group and utilises the newly-established automated documentation standards.

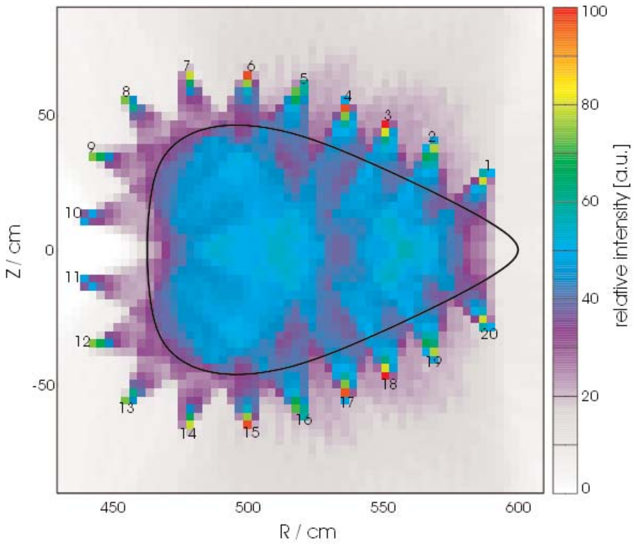


Figure 34: Sight line density of the 20 XMCTS pinhole cameras in the poloidal (R,Z)-plane. The solid contour represents the plasma boundary of the standard configuration (VMEC).

A collaboration contract with the IPPLM in Warsaw on X-ray pulse height analysis and on an electron temperature monitor system based on the filter foil method has been launched in 2006. The main R & D activities will take place in 2007-2008. The development and the assembly of the magnetic diagnostics have made significant progress. In particular the installation of the first Rogowski coil has been almost accomplished on the vessel sector HM11. The quality assurance for these coil types has been established with respect to the homogeneity of the winding density and the robustness of the insulation covering 12 manufacturing stages and the installation procedure. The diamagnetic loop design has been further developed towards the final the stage. The loop in the bean shaped plasma section is non-planar and requires an assembly stand supporting the long but flat housing of the loop wires during assembly. A template has been manufactured that keeps the loop in its shape during assembly, which is also being used for pre-assembly tests in order adjust the loop shape to the real geometric tolerances of the vessel. The prototype of the compensation loop in the triangular plasma section has been exposed to 10 kW/m^2 ECRH stray radiation in the MISTRAL test chamber. This test revealed significant microwave absorption by the Kapton insulation loop wires leading to overheating of the winding pack after 50 s exposure time. Minor design changes are now under development in order to screen the windings against the microwaves. The thermal analysis of the diamagnetic loop and the heat protection, based on finite element methods, has shown a maximum expected loop temperature of 140 °C at steady state heat loads of 500 kW/m^2, giving enough safety margin to the maximum allowed loop temperature of 270 °C.

The Mirnov coil system design has been continued with respect to the integration into the first wall and the cable routing inside the vacuum vessel. In particular the integration into the highly loaded wall elements and the clamped graphite tiles, made the modification of the heat sink shape mandatory. Those modifications have been accepted based on thermal FE analysis. Major progress has been made for the digital integrator in a second circuit refinement, in which the aspect of the common mode rejection ratio (CMRR) has been considered as given by the ITER requirements on magnetic diagnostics. The modification of the input stage led finally to a CMRR of 140 dB within the input voltage range of -1 to 1 Volt. A second prototype has been built for testing the compliance with the XDV DAQ system of W7-X. Four integrator channels circuits have been placed on one cPCI board, that installed in a cPCI crate of a prototype CoDa station presently being installed at the WEGA stellarator. The software for the digital signal processing is already successfully integrated into the XDV framework and 8 min. pulses were recorded without any significant signal drift. The conceptual design of the magnetic flux surface diagnostic has been started by defining the methods necessary for the determination of the flux surfaces. The concept proposes a system for the initial measurements prior to first plasma operation, based on an electron beam, following the magnetic field lines, impinging onto a fluorescent rod and with the such produced fluorescence signal at the interaction point being observed with a high resolution camera from a video diagnostic AEQ port. The fluorescent rods will need to be removed from the initially allocated ports after a start-up period. However, interim measurements also at later stages are expected to be highly valuable. Therefore, it is planed to keep at least the electron gun in a separate port. This electron source can then be used to make field lines in a highly diluted background gas visible.

6.2.7 Diagnostics Software

6.2.7.1 Physics Data Repositories

The development of data repositories for preparation of W7-X was continued. The Magnetic Configuration Database was amended after a pilot stage. A data base structure for the International Stellarator Profile Database was developed (in collaboration with ‘Wendelstein 7-X Applied Theory’). A systematic survey of predictive modelling entered the initial ‘Reference Database’ also compiling profiles of plasma quantities for diagnostics design.

6.2.7.2 Software Development Infrastructure

After agreement on physics software development guidelines, a documentation infrastructure was developed in cooperation with FH Stralsund. The DocSys system integrates freely available tools for automated documentation of application programming interfaces for different high-level computing languages (Fortran, C++, JAVA). The system also manages a web-based access to a central reference software repository (subversion SVN) which was set up in collaboration with XDV and W7-X Control. User defined documentation structures allow a freely configurable inclusion of documents and associated files. A coupling to the W7-X documentation system PLM was supplied by ZTE-Garching.

6.2.7.3 Integrated Data Analysis and Diagnostics Design

Efforts on Integrated Data Analysis were continued. Forward modelling of spectroscopic data allow quantitative analysis of emission spectra and the assessment of uncertainties in atomic data. The physics design of the W7-X interferometer was performed for different cost-functions and different realistic geometric constraints due to ports and mirrors. The characterization of the prototype polychromator for W7-X bluk Thomson scattering was started aiming at design studies for spectral filters (Cooperations with W7-X Diagnostics and ASDEX Upgrade).

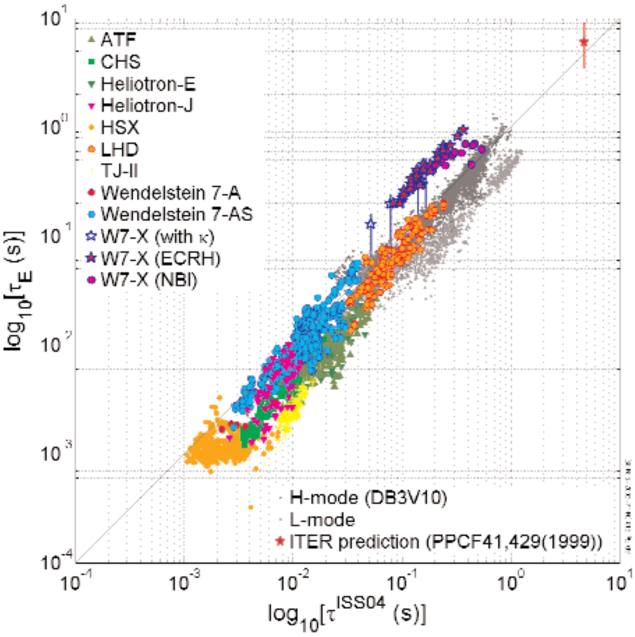


Figure 35: Global confinement times from different stellarators in the International Stellarator Confinement Database. Results from predictive neoclassical simulations are shown for ECR and NBI heating providing an upper limit of confinement time expectations for W7-X. Tokamak data are shown for comparison after being recast in figures of stellarator regression variables.

6.2.7.4 Energy Confinement Scaling

In the international collaboration (IEA implementing agreement) the International Stellarator Confinement Database was extended and scaling studies were continued (NIFS, CIEMAT, U-Kyoto, ANU, U-Wisconsin, U-Stuttgart, and IPP).

The confinement scaling ISS04 was assessed for different operational modes exhibiting good performance. Density and power scaling were confirmed in the respective data range. Bayesian probability theory was employed for the identification of scaling invariant first-principle models in high-beta data from W7-AS and LHD. The conditioning of the LHD data did not allow conclusive model identification. For W7-AS high-beta data, collisional high-beta models describe the confinement data best. Confinement times from predictive neoclassical transport simulations were compared to global energy confinement scaling indicating the beneficial impact of neoclassical optimization (see also W7-X Applied Theory).

6.2.8 Technical Coordination

To locate as much as possible of the diagnostic electronics outside the torus hall, a number of useful locations in the adjacent rooms and hallways were identified. Respective additional wall break-throughs for cables and pipes, combined with additional neutron shielding, were investigated. For the configuration management inside the torus hall, the components of the diagnostic injector and the electronics of the C-O-monitor, the soft-X pulse height analysis and the microwave reflectometer were updated. Regular meetings on assembly technology and assembly scheduling were initiated to incorporate the assembly of the individual diagnostics into the assembly of W7-X. The tender document for a prototype rack for diagnostic electronics has been completed. A temporary working group on cable labelling, cable routing and standardisation of connectors inside the torus hall and the diagnostic hall was formed. The amount of emergency electrical power needed by the diagnostics in case of an outage of the general power supply systems was established and submitted to the system coordination department. The demands on the cooling water for all diagnostics were re-determined. Together with the periphery department, possibilities were sought how to meet these demands. The demands on the gas supply for all diagnostics were specified. The test of the W7-X control system at the WEGA stellarator was supported. Candidate diagnostics for participation were investigated.

6.3. Collaborations

The diagnostics are being developed in close collaboration with FZ-Jülich. In particular in case of the HEXOS VUV spectrometer and the development of the diagnostic neutral beam FZ-J is heading the projects. Contracts could be placed with the Budker Institute in Novosibirsk, Russia, to develop and to construct the diagnostic neutral beam injection system, with KFKI/RMKI in Budapest, Hungary, to develop and to construct the video diagnostic systems for W7-X, with IPPLM, Warshaw to develop a neutron activation system and perform MCP calculations for W7-X, furthermore with the university of Opole, Poland in the fields of X-ray and VUV spectroscopy and with the Akademia Morska, Szczechin, Poland and the Szczechin University of Technology to investigate the sightline of the Interfero-Polarimeter and different microwave based polarimeter or interferometer methods.

7 Heating

7.1 Project Microwave Heating for W7-X (PMW)

The Electron Cyclotron Resonance Heating (ECRH) system for W7-X is being developed and built by FZ Karlsruhe (FZK) as a joint project with IPP and IPF Stuttgart. The 'Project Microwave Heating for W7-X' (PMW) coordinates all engineering and scientific activities in the collaborating laboratories and in industry and is responsible for the entire ECRH system for W7-X. ECRH is designed for a microwave power of 10 MW in continuous wave (CW) operation (30 min) at 140 GHz, which is resonant with the W7-X magnetic field of 2.5 T. It will consist of ten Gyrotrons with 1 MW power each, a low loss quasi-optical transmission line and a versatile in-vessel launching system. PMW is strongly envolved in advanced and ITER related R&D activities.

7.1.1 The W7-X Gyrotrons (FZK)

Both R&D Gyrotrons from TED are operated at IPP and serve as a test bed for high-power tests of ECRH-components for W7-X and ITER (see section 6.1.5). The CPI Gyrotron passed the acceptance test at IPP (0.9 MW for 30 min), but opened a vacuum leak later on and had to be returned to the manufacturer for warranty repair. The TED Gyrotron SNo.1 was mothballed after having passed the acceptance test at IPP (0.92 MW for 30 min). The delivery of all superconducting magnets and the related power supplies for the Gyrotrons was completed. The site acceptance test of all magnets was performed successfully. The tests of the TED Gyrotron SNo.2 were continued at FZK and 1.2 MW was achieved in short pulses (1 ms, 50 A beam current). A small extension of the pulse length (3 ms), however, lead already to a significant decrease of the output power due to mode hopping. At 50 ms the accelerating voltage hat to be reduced to 74 kV corresponding to 500 kW output power to suppress mode hopping. As no further progress was achieved with this Gyrotron, the tests were terminated in April 06 and the tube was returned to TED for inspection. The test program was continued in May 06 with TED Gyrotron SNo.3. An output power of 1 MW was obtained in short pulse operation at a beam current of 42 A. An extension of the pulse length, however, was only obtained with reduced acceleration voltage and consequently reduced power output (e.g. 750 kW for 1 s and 650 kW for 180 s). As no further progress was obtained, the tests were terminated in July 06 and the Gyrotron was shipped to IPP, were the tests were continued.

Again the maximum power at this pulse length was limited to 650 kW and any influence of the test-stand environment could thus be excluded. The observed power limitation showed some similarities with the behavior of SNo.2 and it was agreed with TED to stop the tests and postpone the completion (and delivery) of the Gyrotron SNo.4. The inspection at TED showed strong defects in the electron beam tunnel between gun and cavity. TED presented a failure analysis indicating a fabrication problem during brazing of these parts. An improved procedure for the manufacture was qualified and the damaged parts are presently being replaced in all three Gyrotrons.

7.1.2 High-voltage System for Gyrotron Power Control and Protection (IPF)

The HV-control system for the W7-X Gyrotrons consists of a high-voltage modulator unit, which provides the Gyrotron body voltage, and a crowbar unit with thyratron-switch and integrated heater supply for the Gyrotron cathode. The modulator is capable of delivering modulated body voltages up to 30 kV at a rise time of up to 600 V/µs. Power modulation with a frequency up to 10 kHz was demonstrated during the tests of the TED Gyrotrons. It also monitors currents and voltages of the Gyrotron via optical fibre links.

Figure 36: High Voltage Installation in the ECRH-hall at IPP Greifswald

The crowbar works as a protection unit in case of internal or external break downs (overcurrent, overvoltage, arcing) at the Gyrotron with a switch-off time of <500 ns. The HV system is remote controlled via optical fibre links by a special control unit in the control centre. Seven complete sets of the HV-modulator/crowbar system were successfully installed and tested at IPP Greifswald, the installation is seen from figure 36 The remaining three systems are in different states of installation and test. The integration of the many subsystems into the central control system is being performed by experts from IPF and IPP, the technical documentation is in progress.

7.1.3 Transmission System (IPF)

To prepare the matching optics (M1, M2) for the TED Gyrotrons S.No.2 and S.No.3, the output beams of these tubes were recorded thermographically at FZK; the power distributions were used for phase retrieval and subsequent calculation of the surfaces of the corresponding matching mirrors. A high content of the fundamental TEM_{00} mode in the beams (above 95 % for both tubes) was derived from the Gauß-Hermite mode analysis. The surfaces of the matching optics including the integrated directional couplers were fabricated. The design, manufacture and installation of the optical transmission line components were continued. All mirrors for the transmission of the 10 millimetre-wave beams from the Gyrotrons to the torus hall are now installed, including the short and long-pulse calorimeters, stray radiation absorbers and two retro-reflectors. These retro-reflectors will allow high-power tests of the multi-beam waveguide (MBWG). They can be moved on a linear stage into the beam path to redirect either one of the ten 140 GHz forward beams back into the absorber loads via the central MBWG channel. The retro-reflectors as seen from figure 37 are presently being integrated in the main remote-control system, high power tests are scheduled for early 2007.

Figure 37: The retro-reflectors in the beam duct at IPP, a set of MBWG-mirrors and microwave absorber panels are seen in the background

The design of the transmission section in the torus hall between the beam distribution optics and the launcher was optimized with respect to high operation reliability and efficiency in the frequency range from 103 to 140 GHz. The maximum power density for transmission in normal atmosphere was experimentally determined yielding a safety factor of at least two for the existing design. The design of the surfaces for the corresponding mirrors (Type M13 and M14) with the overlaid phase gratings for beam diagnostics was frozen and the tender action for series-fabrication was launched. The design of the ECRH-towers, which house all optical elements near the W7-X ports, including the mounting frames for the M13 mirrors was completed and manufacturing contracts were placed with industries.

7.1.4 In-Vessel-Components (IPP)

The in-vessel front steering launchers are designed to meet the coupling conditions for different heating and current drive scenarios, such as 2^{nd} harmonic X and O-mode, 3^{rd} harmonic X-mode, and mode conversion heating (O-X-B). A motor driven prototype launcher was built and tested with respect to cyclic fatigue under vacuum conditions and with microwave stray radiation loading in the MISTRAL (Microwave Stray Radiation Loading) test chamber. No arcing or damage was found up to a microwave peak loading of 450 kW/m^2, which is significantly above the expected stray radiation level in W7-X. During cycling tests of the full range front mirror motion in vacuum two ball joints of the same type broke after approximately 1000 cycles. The joints were redesigned replacing the stainless-steel ball by a ceramic ball. With the new joints the prototype antenna passed the specified 10000 cycles in vacuum successfully and the design was released for the serial ECRH antennas. The design of the four equatorial plane Plug-in Launchers was completed and the tender action for the manufacture was launched. The manufacturing of the in-vessel launcher mirrors has already started. The gate valves, which separate the microwave barrier window from the vacuum vessel in the case of emergency were tested by transmitting a full power microwave beam through the open valve. The standard Viton O-rings, which are used in commercial gate valves, do strongly absorb microwave stray radiation and were completely destroyed in the tests. The O-rings were thus replaced by special ones made from material with low microwave absorption properties. A temperature increase of 62° was found in the test under steady state conditions, which qualifies the selected O-ring material for the application at W7-X. The expected single pass absorption for the heating scenarios with the second harmonic ordinary mode (O2) and the third harmonic extraordinary mode (X3) ranges from 40 % to 80 %. This would lead to a thermal overloading of the inner wall armour graphite tiles by the non-absorbed part of the microwave beams. The graphite tiles will thus be replaced in selected positions by highly reflecting TZM-tiles (titanium-zirconium-molybdenum-alloy). The tile positions were optimised by ray-tracing calculations for each individual microwave beam and provide a controlled reflection back through the plasma center with a high second pass absorption. A water-cooled prototype TZM-tile was build and tested with an equivalent high power microwave beam, the test arrangement is seen from figure 38. Even though the maximum temperature increase was about 70 % higher than expected from ANSYS calculations, the use of the TZM-tiles seems to be feasible. In a next step the heat contact of the tile with the actively cooled base plate will be improved and the surface of the tile will be polished in order to minimise the microwave absorption by surface roughness.

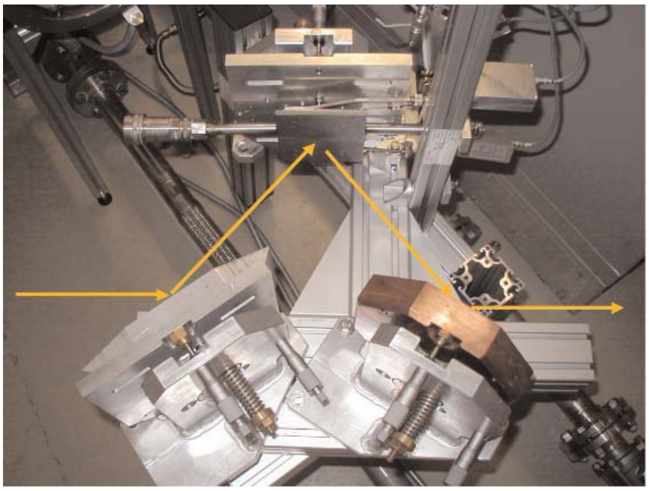


Figure 38: The TZM-tile under test. The microwave beam path is sketched. The tile was exposed to a 350 kW microwave beam under atmospheric pressure in steady state operation.

7.1.5 Advanced Components and ITER-related R&D

7.1.5.1 Improved e-Beam Power Dissipation at the Gyrotron Collector

The existing experimental set-up with the TED Gyrotron SNo.3 at IPP-Greifswald was used to investigate and optimize the power distribution of the electron beam on the collector surface. So far all TED Gyrotrons are equipped with a conventional vertical sweep system. By this method a broad power deposition profile with strong peaking at the upper and lower turning points of the beam is achieved. As the Gyrotron operation is limited by the peak-loading of the collector, the experiments aimed at a reduction of the power peaking. In a first step, experiments with a rotating transverse field sweeping system (TFSS, 6 coils, 3 phase power supply, 50 Hz, constant amplitude) showed, that an improved power distribution profile with reduced peak loading at the upper turning point is achieved. The TFSS is shown in figure 39. A further improvement of the deposition profile is expected, once the amplitude of the rotating transverse magnetic field is modulated. As a first approach to this concept, we have combined both, the TFSS and the vertical sweeping system. By proper tuning of both systems an almost perfectly flat power deposition profile along the collector area was obtained. In particular the peak loading at the lower turning point is reduced by about a factor of 2, which increases the safety margin of the present collector design significantly and/or allows to operate the TED series tubes at higher electron beam currents (and higher output power). The results are of importance for a safe cw Gyrotron operation and may also be important for the next generation Gyrotrons with up to 2 MW output power as being developed at FZK for ITER.

Figure 39: The TED Gyrotron with the transverse field sweeping coils

7.1.5.2 Fast Directional Switch of High Power Beams

The IPP Greifswald, IAP Nizhny Novgorod, IPF Stuttgart, FZ-Karlsruhe, and IFP Milano have established a strong collaboration with the aim to develop a fast directional switch (FADIS) for high-power microwave beams, which is of importance for future large scale ECRH installations like W7-X and ITER. The collaborating research laboratories have formed a 'Virtual Institute' of the 'Helmholtz Gemeinschaft deutscher Forschungszentren'. FADIS is a novel concept and will allow switching and/or combining high power microwave beams on a fast timescale without losses and without mechanically moving parts. The FADIS device is based on a small frequency-shift keying of a Gyrotron (some tens of MHz), and a narrow-band diplexer, which switches the Gyrotron input beam to one of the two output channels. Now, various concepts are under discussion and in development. At IPF Stuttgart and IFP Milano, waveguide diplexers based on interferometers using the Talbot-effect in square waveguides for beam splitting are designed and tested (see IPF Stuttgart part of this report). A quasi-optical prototype based on a ring-resonator (see figure 40) was designed by IAP Nizhny Novgorod and IPF Stuttgart matching the W7-X frequency of 140 GHz.

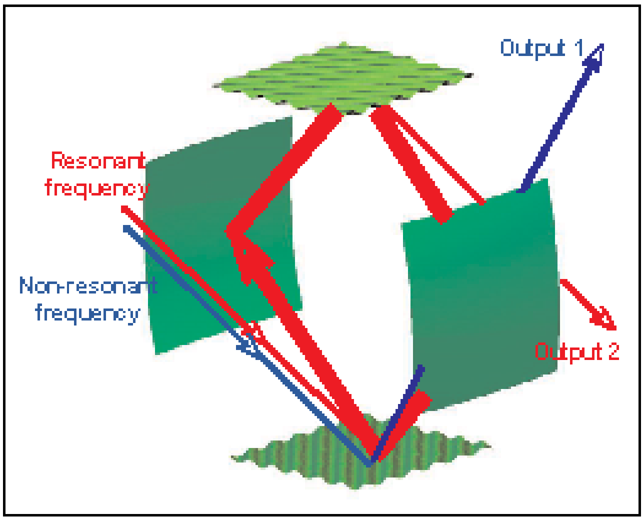


Figure 40: Principal sketch of a quasi-optical diplexer

Figure 41: Complete mirror arrangement of the FADIS device

The FADIS-device as seen from figure 41 was manufactured at IPF and consists of a four mirror ring resonator, which is coupled via phase gratings on two of the mirrrors to the input and output beams. Note that the device is designed as a four-port system to allow switching and combination of two beams simultaneously. The performance was investigated in low-power experiments. The results show a transmission function in good agreement with theory, with transmission efficiency of 98 % in the non-resonant and 93 % in the resonant channel. The switching contrast is typically 1: 50, and the TEM_{00} mode purity is better than 99 %. The device is now prepared for shipment to IPP Greifswald, where it will be integrated into the beam duct of W7-X. High-power tests are scheduled for 2007.

7.1.5.3 High Power Tests of a 2 MW Load for ITER

The ECRH installation at IPP-Greifswald served as a high-power test bed for a 2 MW prototype absorber-load, which was developed by IFP Milano under EFDA contract for ITER. As there are no 2 MW microwave sources available at present, a method for emulating 2 MW conditions while using a 1 MW Gyrotron was applied. A spherical hybrid load consisting of two half shells was fabricated, one of them is coated with absorbing dielectric and the second half shell has a highly reflecting pure copper surface. The microwave power is then absorbed only by the coated hemisphere and the resulting loading for 1 MW input power is the same as for 2 MW when shared by both absorbing hemispheres. In the configuration used for the 2 MW emulation tests at 140 GHz the peak heat load is higher than for a nominal 2 MW configuration at 170 GHz. It follows that the high-power tests were performed in more severe conditions, thereby providing an extra safety margin. The tests have been performed both in air and with vacuum inside the system. Since the ECH transmission line for W-7 X is quasi-optical and operates at normal atmospheric pressure, a boron nitride window was mounted at the entrance port to close the load and allow for vacuum pumping. The heating of the load during high-power tests is seen from figure 42. The load was tested successfully at 800 kW (equivalent power on the coating 1.6 MW) for 100 ms with and without vacuum inside the system and at 140 GHz, 500 kW (equivalent power on the coating 1.0 MW) for 200 ms without vacuum. No particular problems were identified and the tests were completed successfully on schedule.

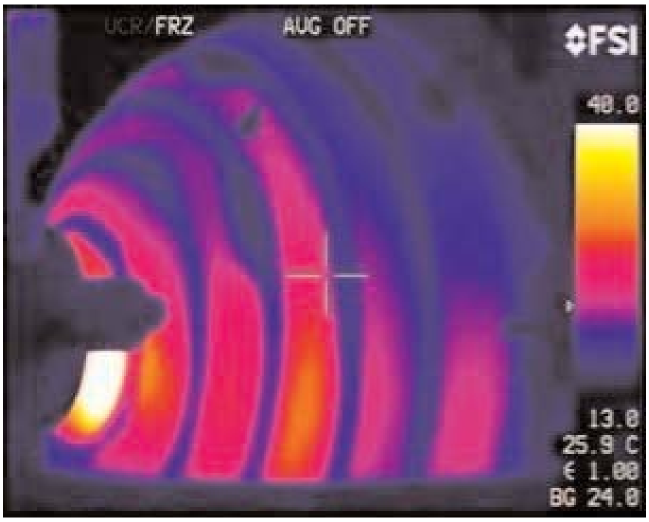


Figure 42: Thermographic image of the 2 MW prototype load developed by IFP Milano during the high power test at IPP-Greifswald (800 kW, 100 ms)

PMW Staff

Staff at IPP (W7-X-P and ZTE): V. Erckmann, B. Berndt, H. Braune, F. Hollmann, L. Jonitz, H. P. Laqua, G. Michel, F. Noke, F. Purps, T. Schulz, P. Uhren, M. Weissgerber.
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7.2 Neutral Beam Injection

Neutral beam heating is foreseen in W7-X for bulk heating of the plasma, necessary in particular for the high-beta regime at elevated densities. A total power of up to 14/20 MW with beams of 55 keV H^0 / 100 keV D^0 has been approved and will be built up in two stages: 5 MW first in stage I, additional 15 MW later in stage II (EURATOM phase II approval pending). In 2006 some progress of NBI for W7-X has been achieved despite the unchanged staffing situation. In June a proposal by the NBI group was submitted to the W7-X board to start work gradually at least in the mechanical engineering and fabrication of smaller components. This approach (dubbed "softstart") foresees re-allocating some of the NBI staff gradually and starting the manufacturing of smaller mechanical components in house rather than buying those from industry. Therefore it does not require significant financial commitments in the years 2006 till 2009. Work has started by organising regular meetings and placing a few minor orders. The first step is the partial pre-assembly of the injector boxes in the NBI assembly hall. In this context the installation of the conventional vacuum systems on the injector boxes is under way. Further activities concentrated on interface definitions in the torus hall and the outer vessel/duct and the cryo supplies for the NBI cryo pumps.

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Wendelstein 7-X Applied Theory

Head: Dr. Henning Maaßberg

The group concentrated on the physics modeling and data evaluation for W7-X. This includes work on neoclassical transport, development of a predictive stellarator transport code, equilibrium reconstruction by function parametrization, edge physics simulations, and modeling of NBI and ECRH heating. Additionally W7-AS data in connection with island-divertor modeling have been analyzed and benchmarking of equilibrium codes has been carried out.

Predictive Transport Simulations for W7-X

Predictive transport modeling for pure ECRH and pure NBI scenarios for the W7-X standard configuration has been performed to study the energy confinement properties of W7-X assuming neoclassical diffusion in the bulk plasma and anomalous transport at the edge. The anomalous diffusivity scales inversely with plasma density with exponential decay towards the center of the plasma. Power and density scans have been carried out for heating powers from 2MW to 10MW and various densities. The shape of the density profile has been fixed with a rather large gradient region of about 10 cm. The ECRH scans have been simulated for densities 0.2-1×10^{20} m^{-3} and X2-mode heating (140 GHz at B=2.5 T) with a central power deposition approximated by a Gaussian profile with 10 cm half-width. For the NBI-heated plasma with densities 0.5-3×10^{20} m^{-3}, the power deposition to ions and electrons is self-consistently calculated with the temperature profiles up to steady-state. In most cases considered the energy confinement times τ_E are higher than predicted by ISS04 scaling (see Wendelstein 7-X section). The neoclassical predictions give an upper limit of plasma performance in W7-X.

The same set of calculation has been done for a classical stellarator with the same dimensions, rotational transform, and value of magnetic field as W7-X but without elongation. The results for the classical stellarator are in good agreement with the ISS04 scaling. The energy confinement time for W7-X is about two times higher then that for the classical stellarator. This improvement is attributed to the neoclassical transport optimization in W7-X.

The simulations of the plasma heated by 'positive' NBI (p-NBI, 60 keV H^+) have shown that the performance of dense plasmas (higher than 2×10^{20} m^{-3}) deteriorates with increasing density; the energy confinement time saturates and even decreases. In order to clarify behavior of the energy confinement time at high densities, the simulation of dense plasma heated by a 150 keV hydrogen beam has been performed. The simulation results of the plasma heated by 10MW positive NBI or negative NBI (n-NBI, 150 keV H^-) are presented in figure 1. In the p-NBI case, the main power is absorbed at outer radii, in particular the 1/2 and 1/3 energy components of the beam. This leads to τ_E degradation with density, whereas for the n-NBI case the much higher central deposition allows for higher temperatures and improved global confinement. For example, τ_E=0.45 s at $<\beta>$=4.2 % and τ_E=0.6 s at $<\beta>$=5.4 % are obtained for p-NBI and n-NBI, respectively. These results demonstrate that it is not the confinement that is degraded due to high densities but the NBI power deposition that is affected. The high-energy n-NBI is needed to avoid edge deposition at plasma densities higher than 2×10^{20} m^{-3}. Another noteworthy result of the above simulations is that high-β plasmas up to 5 % are achieved at a magnetic field of 2.5 T, and thus W7-X discharges at full magnetic field near beta and density limits may be considered plausible.

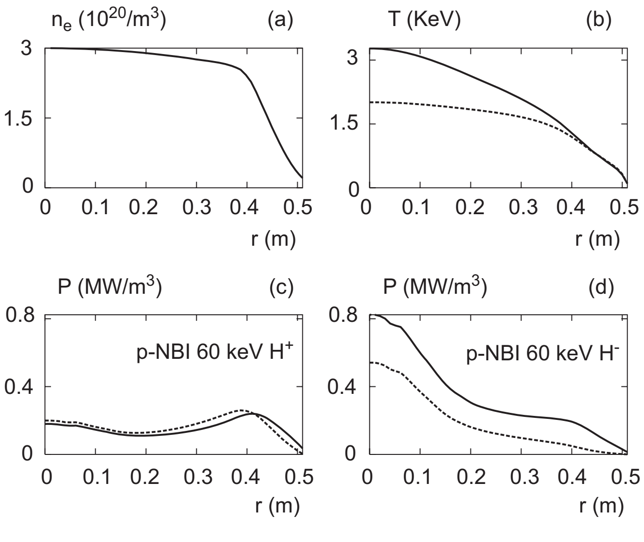

Figure 1: (a) and (b): Plasma profiles for a 10 MW NBI predictive 1-D simulation of W7-X. The dotted line in the temperature figure (b) refers to p-NBI power depositions shown in plot (c) and the solid line refers to n-NBI power depositions in plot (d). The dotted line in (c) and (d) correspond to the power deposited to ions.

The outcome of transport simulations show rather high value of the energy confinement time and naturally the question arises as to how strong the dependence of the results is on anomalous transport. The sensitivity analysis of W7-X performance has been done for several models of anomalous diffusivity at the plasma edge: 0.014/n, 0.07/n, and 0.35/n. The examination has shown weak dependence of plasma parameters on the level of anomalous transport. For example, at 0.5×10^{20} m^{-3} plasma heated by 4 MW ECRH the plasma energy decreases by a factor of 1.8 whereas the anomalous heat diffusivity increases by 25 times.

It is planned to continue self-consistent 1D transport simulations for different magnetic configurations and heating scenarios of W7-X to create a reference profile database which is needed for various purposes, e.g. calculations of neutron production and for the development and testing of diagnostic software.

Ray Tracing Calculations for W7-X

Development of the new ray tracing code TRAVIS (the former BRT) has been completed. A successful benchmark with the reference Scenario-2 for ITER against the codes TORAY, GENRAY, TORBEAM and GRAY was performed. The TRAVIS code is now routinely exploited for modeling of heating at various harmonics of the ordinary and extraordinary mode (O1, O2, X2, X3) in different configurations, supporting also the design of the ECRH launcher for W7-X. Coupling of TRAVIS with the predictive transport code is in preparation.

As an example of the code's application and for demonstrating the flexibility of W7-X, where the fraction of trapped particles can be varied in configuration scans, the scenario of O2-heating from the high-field-side (launch close to the triangular plane of the W7-X standard configuration) is analyzed. The simulation is performed for central n_e=1.5×10^{20} m^{-3} and T_e=3 keV with almost flat core profiles, and B_0=2.7 T.

Since the plasma is optically gray for O2-mode, the deposition profile is quite broad, and the power shine-through is about 13 %. As seen in figure 2, the shapes of the deposition profiles for trapped and passing electrons are quite different.

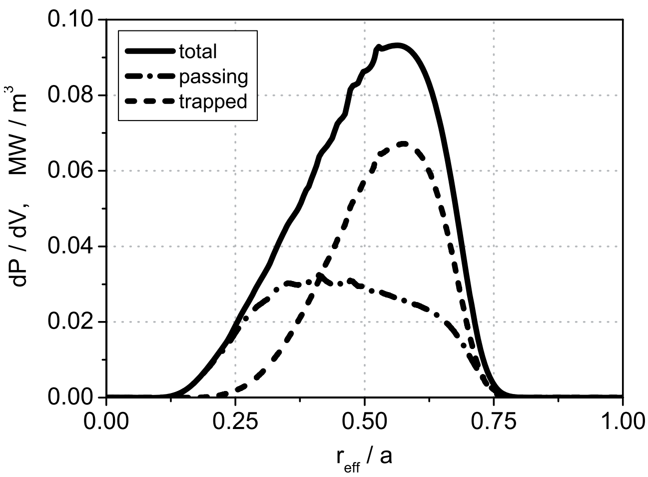

Figure 2: O2 HFS launch, total deposition profile and contributions from both passing (dashed) and trapped (dot-dashed) electrons

ECCD, which will be used counteract the residual bootstrap-current, is an important topic for W7-X. In order to estimate the range of possible current drive efficiencies, a density scan has been performed (figure 3). While the X2 launch was tested for highest CD efficiency angles, the launch of O2-mode was tested only for two angles defined by the position of the reflecting mirrors at the inner wall. The results obtained confirm the expectations of high CD efficiency for the low density scenarios.

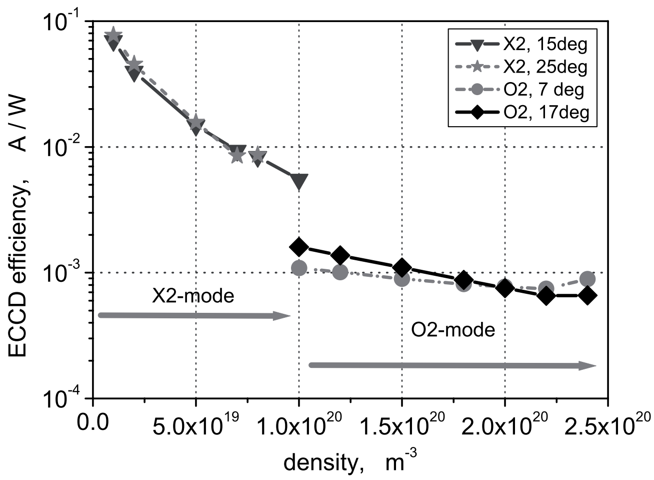

Figure 3: ECCD density scan for both X2 and O2 mode ranges

Neoclassical Transport in Stellarators

Within international collaboration on neoclassical transport the benchmarking of DKES and VENUS δf-Monte Carlo calculations of the mono-energetic bootstrap current coefficient were continued. For the standard configuration of W7-X, the dependence of this coefficient on the magnitude of the radial electric field was verified over the full range of experimentally relevant values. Additional benchmarking for the LHD and NCSX configurations was also initiated in support of the international collaboration on neoclassical theory – IEA Implementing Agreement (collaboration with M. Isaev, KIAE).

At the workshop on neoclassical transport in stellarators (Kyoto, 2006) it was decided to document the results of this international collaboration with an extended review paper. The (fairly old) review papers on this topic present only the analytical theory for classical stellarators whereas present-day optimized configurations are characterized by a rather complex |**B**| structure which makes a numerical solution of the drift-kinetic equation mandatory. The planned review paper shall document both the benchmarking of the codes used for the estimation of the mono-energetic transport coefficients as well as the quite different concepts of stellarator optimization (IEA Implementing Agreement).

Quasi-Neutrality and Impurity Transport

Variations of the density and electrostatic potential on flux surfaces must be allowed for in neoclassical theory to obtain solutions of the kinetic equation which satisfy local quasi-neutrality. The resulting radial component of the E×B drift has been shown to strongly modify the transport coefficients of impurities in stellarators and to call into question the usual ordering assumptions made to obtain a mono-energetic kinetic equation.

DKES Database for W7-X

An extended database of the 3 mono-energetic transport coefficients calculated with the DKES code for the main W7-X configurations has been initiated. These coefficients depend on radius, collisionality, and radial electric field.

Function Parametrization for W7-X

Function parametrization (FP) is foreseen to supply fast 3-D equilibrium information for online evaluation needs. The work on the finite-beta FP based on 8000 VMEC-equilibria was continued. Special focus was given to sensitivity studies and noise treatment which was reconsidered so as to improve the stability and accuracy of the regressions.

HINT2 Calculations for W7-AS

The further development HINT2 of the 3-D MHD equilibrium code HINT has been installed at IPP. Initial calculations for both W7-X and W7-AS have been done. For W7-X, benchmarking with the PIES code was of special interest (see Stellarator Theory section). For W7-AS, the results for the high-iota configuration obtained from with the older HINT version were reproduced. Calculations for high-beta cases in high-iota configurations with control coils in effect showed similar magnetic field structures as those obtained with the PIES code, namely an ergodization of the outer confinement volume which is weak enough so that gradients can still be sustained.

Island Divertor Transport Modelling

The transport of the wall-sputtering CX-neutrals induced by the divertor recycling neutrals in W7-AS was investigated using the EMC3/EIRENE code. A parameter sensitivity study was made in the parameter space of cross-field transport coefficients, core density profile and island density. The island density was scanned to cover different plasma confinement regimes. It was found that the island density is the most effective parameter for reducing the sputtering CX-neutral flux on the wall and thereby the iron production rate, (a) by moving the CX-neutrals to a low energy spectrum band, (b) by reducing the divertor-region leakage and (c) by moderating the interaction between the core plasma and the wall recycling neutrals. The core density and density profile show a strong effect on the neutrals from the core center region, however a weak impact on the edge-concentrated CX-neutrals resulting from divertor recycling. The total iron production rate decreases roughly exponentially with increasing n_{es} and a flat n_e-profile further reduces the overall sputtering yield. These results are not strongly affected by uncertainties in the cross-field transport coefficients in the SOL, since the resulting effects in ion temperature and total recycling flux tend to compensate each other.

Preparation for W7-X

A systematic numerical pre-study for the W7-X island divertor has been planned. This long-term project has been started by preparing 3D computational meshes for relevant magnetic field configurations. In view of the large SOL size of W7-X (in volume by more than one order of magnitude larger than W7-AS), mesh optimization is necessary for improving the computational efficiency. A key element in the mesh optimization procedure is to estimate the form and location of the outermost boundary of the computational domain for plasma transport. For this, different concepts are currently being tested for W7-X configurations.

International Collaboration on 3D SOL Transport Studies

The international collaboration on 3D SOL and divertor transport modeling, which was started with TEXTOR-DED and continued with LHD, has been extended to ITER for assessing the power load deposition and Be-impurity production, transport and radiation behavior in the 3D SOL induced by two discrete limiters during the plasma start-up phase. In addition, interest in a collaboration has been expressed by PPPL, which has proposed to implement the EMC3/EIRENE code for NCSX starting in 2007. The rapidly increasing international collaboration activities open a large application spectrum in device type and in edge magnetic field topology, allowing a comparison of the edge transport physics both between tokamaks and stellarators as well as among different devices within the stellarator community.

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Stellarator System Studies

The tokamak impurity transport code STRAHL has been extended to describe the impurity behavior in nonaxisymmetric configurations. It was shown, that repetitive injection of small pellets under reactor conditions leads to an effective screening of the bulk plasma from heavy impurities without a threatening increase of the power loading of the divertor. For HSR4/18, the calculation gives the required pellet frequency and size to be about 10Hz, and 10^{21}, respectively.

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Laboratory Plasma Devices WEGA and VINETA

The experiments on WEGA were focused on measurements of the wave field of the plasma heating microwave, on biasing of the plasma edge and on fluctuation experiments. Furthermore, a new ECR heating system, new diagnostics have been installed. The research focus of VINETA was the development of spatiotemporal control schemes for drift wave turbulence, investigations of the radial propagation of turbulent structures, and the dispersion characteristics of large-amplitude Alfvénic waves.

WEGA

Head: Dr. Matthias Otte

Electron Cyclotron Wave Physics

Mode conversion heating with 2.45 GHz was investigated. The heating power was modulated with a frequency of 12.5 kHz, which is much faster than the characteristic confinement time of about 1 ms. The plasma was scanned utilising Langmuir probes and the respond of the plasma parameters on power modulation was analysed. Local power absorption of the fast electrons inside the overdense plasma was found as shown in figure 1. Phase measurements show clearly a propagation of the perturbation. This enables transport investigations of fast electrons, which are already in the long mean free path regime, at different magnetic configurations. The power deposition location strongly depends on the ambient magnetic field strength, which points on a resonant absorption in the overdense plasma. A new 20 kW ECRH system operating at a frequency of 28 GHz was installed. It enables ECRH plasma operation at a magnetic field strength of 0.5 T. Initial plasmas were produced with second harmonic extraordinary X2 mode heating with an expanding Gaussian beam launched from a HE_{11} antenna. First Argon discharges at $|\boldsymbol{B}_0|$=0.5 T produced densities up to the R-cutoff of $n_e=4.9\times10^{18}$ m^{-3}.

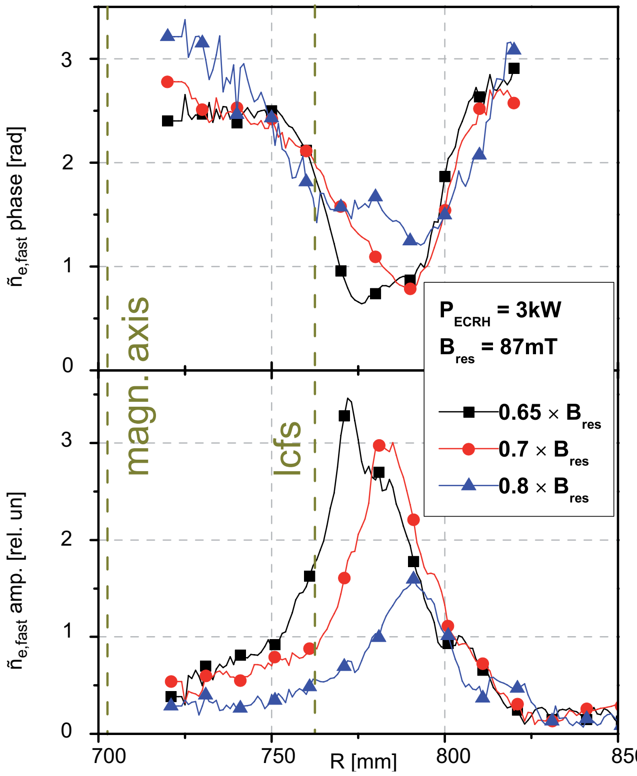

Figure 1: Spatial behaviour of phase and amplitude of the fast electron component during modulated ECR heating experiments for different magnetic configurations

Results from Plasma Operation

For electrostatic fluctuations Langmuir probe measurements have been carried out. The spatiotemporal structure of density fluctuations has been studied using a poloidal probe array and a single probe separated by a toroidal angle of φ=135°. The direct connection length parallel $\boldsymbol{B}$ between the two probe systems anticipated by field line calculations was verified using an electron beam technique. The results show a turbulent behaviour of the plasma. In the frequency domain broadband spectra with most power below some 10 kHz are observed. In some magnetic configurations the turbulence is less strongly developed and shows additional coherent modes. The fluctuation amplitude is generally strongest at the position of the steepest density gradient which is in the region of the last closed flux surface. A reconstruction of the correlation function in the radial-poloidal plane shows localised structures propagating both in electron diamagnetic drift direction and radially outwards.

Setup and Test of the HIBP Diagnostic

In collaboration with the Institute for Plasma Physics in Kharkov/Ukraine a Heavy Ion Beam Probe (HIBP) diagnostic was setup and tested in helium plasmas. The diagnostic is optimised for operation at a magnetic field strength of $|\boldsymbol{B}_0|$=0.5 T (28 GHz operation regime). Na^+ ions with an energy of 40 keV are used as primary beam particles; the secondary Na^{++} beam is detected. Energy analysis of the secondary beam yields the electrostatic plasma potential inside the secondary ionisation volume with an estimated spatial resolution of around 1.5 cm. Radial profile scans can be obtained using a deflection system to vary the injection angle of the primary beam. Due to the strong dependency of the secondary ionisation cross section on the electron energy, the secondary signal intensity will be very sensitive on the existence of supra-thermal electrons. The intrinsic temporal resolution is high enough to measure plasma parameters in experiments with modulated heating power.

Hard- and Software for W7-X Diagnostic

Within the framework of Wendelstein 7-X diagnostic development tests of a bolometer, a neutral particle manometer and the data acquisition hardware for the magnetic diagnostics have been started or continued. Furthermore, the setup of a prototype installation of the W7-X control system has been started.

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VINETA

Head: Prof. Dr. Olaf Grulke

Device and Operational Parameters

VINETA is a long, cylindrical helicon plasma device, specifically tailored to study plasma waves and instabilities. The non-resonant rf helicon wave heating provides high plasma densities at relatively low electron temperatures ($n \leq 10^{19} m^{-3}$, $T_e \approx 3$ eV for a rf frequency f_{rf}=13.56 MHz, rf power of $P_{rf} \leq 5$ kW, and magnetic field B=0.1 T). The main diagnostic tools are electrostatic and magnetic probes. Langmuir probes are used to obtain time-averaged plasma profiles and to measure density fluctuations. The time-averaged plasma profiles are benchmarked with a 160 GHz heterodyne microwave interferometer. In addition to single probes, electrostatic probes are arranged as arrays covering the azimuthal plane to investigate the spatiotemporal evolution of plasma density fluctuations. Additionally, advanced active induction probes have been developed to achieve reasonable signal to noise ratios at the low frequencies of drift wave and Alfvén wave existence ($f \leq 50$ kHz).

Drift Wave Control and Radial Turbulent Structure Propagation

The major goal is to develop spatiotemporal control schemes to influence the drift wave instability and its associated turbulence. An azimuthal array of 8 saddle coils is used to generate travelling magnetic fluctuation patterns. The amplitude and phase of each coil can be varied independently over a frequency range of 1-10 kHz to produce azimuthal mode numbers of $m \leq 4$ with amplitudes of 10 % of the maximum ambient magnetic field. In figure 2 the power spectra of plasma density fluctuations for different frequencies of the magnetic coil array, applied to an m=2 drift mode is shown. An azimuthal magnetic perturbation with mode number m=2 is produced and consecutively changed in frequency to scan the frequency range around the m=2 drift mode at 3.5 kHz. For small frequency mismatch the drift mode locks to the control signal and its frequency is dragged along until it unlocks at a frequency mismatch of 20 %. Frequency pulling is only observed if the azimuthal velocity of the magnetic propagation is in parallel to the drift mode phase velocity, which indicates the spatiotemporal character of the control.

The studies of the propagation characteristics of structures in drift wave turbulence were continued. Probe arrays were used to investigate the spatiotemporal evolution of turbulent fluctuations in the entire azimuthal cross section. Due to radial transport plasma density peels-off the gradient region and propagates radially outwards. By structure tracking the radial and azimuthal propagation speeds are quantified. The radial structure velocity is found to be half its azimuthal velocity and corresponds to 10 % of the local ion sound speed.

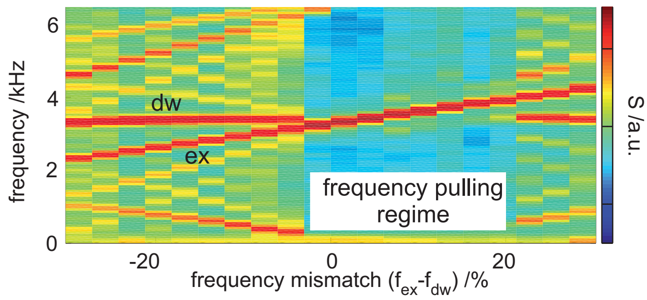

Figure 2: Power spectral density of plasma density fluctuations vs. the frequency of the magnetic m=2 perturbation. The frequencies of the drift mode (dw) and the perturbation (ex) are indicated.

Alfvénic Waves

The investigation of Alfvén wave dispersion has been studied intensely. For small-amplitude Alfvén wave excitation good agreement of the dispersion behaviour with the linear Alfvén wave dispersion relation, including effects arising from neutrals, has been found. The studies have been extended to large-amplitude excitation by low-frequency amplitude modulation of the helicon plasma source. As the plasma response the propagation of an electromagnetic wave is observed at the modulation frequency, which phase velocity at low frequencies is given by the Alfvén velocity. The dispersion behaviour, however, differs considerable from the linear Alfvén wave dispersion (figure 3) and is probably the result of nonlinear wave coupling with the helicon wave. The details of the Alfvénic wave excitation is subject of further investigations.

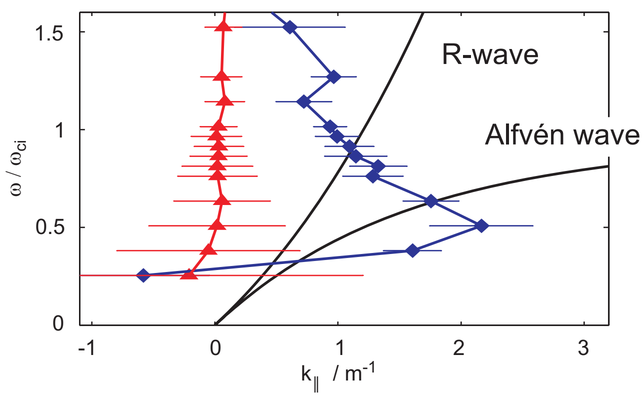

Figure 3: Dispersion behaviour of the magnetic (blue) and electric (red) wave field. The linear Alfvén and R-wave dispersion are shown as black solid lines.

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Part of the VINETA program is carried out under the auspices of the Transregional Special Collaborative Research Center SFB-TR24 "Fundamentals of Complex Plasmas".

ITER

ITER Cooperation Project

Head: Dr. Lorne Horton

The IPP contributes to the ITER Project in a wide range of activities. Tasks range from R&D for heating systems and diagnostics to development of integrated plasma scenarios. In addition, the IPP is playing a leading role in contributing to the ITER physics definition and objectives as part of the ongoing ITER design review.

Introduction

With the signing of the ITER Implementing Agreement and the assembly of an ITER Team at Cadarache, the contribution of IPP to ITER increased significantly in 2006 and this is expected to continue in the future. During 2006, IPP was chosen to lead a consortium of European Fusion Associations that will develop a Project Plan for the ITER bolometry diagnostic procurement package. IPP is also expected to lead the group that develops and procures the ion sources for the ITER neutral beam heating system.
The IPP contributes actively to the physics definition of ITER via the International Tokamak Physics Activity. In this forum, the results of the ASDEX Upgrade tokamak are compared to those of the world's other tokamaks. With the launch of the ITER design review, IPP has played a leading role in identifying the remaining physics issues in the ITER design and is now contributing actively to defining solutions to these issues. IPP expertise is in demand for a wide range of activities in support of ITER, based not only on ASDEX Upgrade experience but also on know-how in the Theory, Materials and Stellarator Divisions. This work varies from studies of plasma scenarios to work on specific technical systems and is carried out largely under contracts within the European Fusion Development Agreement (EFDA).

Heating Systems

Development of RF Negative Ion Sources

In 2006 the development of a large area RF source for negative hydrogen ions has made further substantial progress. The IPP RF source is now a serious candidate for the ITER neutral beam system; the decision on source technology is expected in summer 2007. IPP has now three test facilities in operation for negative ion source development: (1) the small, flexible and well diagnosed test bed BATMAN (Bavarian Test Machine for Negative Ions), (2) the long pulse test facility MANITU (Multi Ampere Negative Ion Test Unit) and (3) the large source test facility RADI (re-use of the former radial injector of W7 AS), which went into operation recently.
In BATMAN routine operation within the ITER parameter range has been demonstrated for hundreds of beam pulses, as shown in figure 1. Diagnostic techniques for optimization and better understanding of physical processes in negative ion sources have been further developed at BATMAN, in close collaboration with Augsburg University (see University contributions) and with strong exchange with modelling of the source and the extraction area. Optical emission spectroscopy is now established as a standard diagnostic tool for negative ion densities and for normalised caesium signals. Laser Detachment and Cavity Ringdown Spectroscopy systems for the measurement of the negative ion density in front of the plasma grid are also now operational at BATMAN in a noisy RF environment. All these diagnostics are being calibrated presently at BATMAN for their application at RADI.

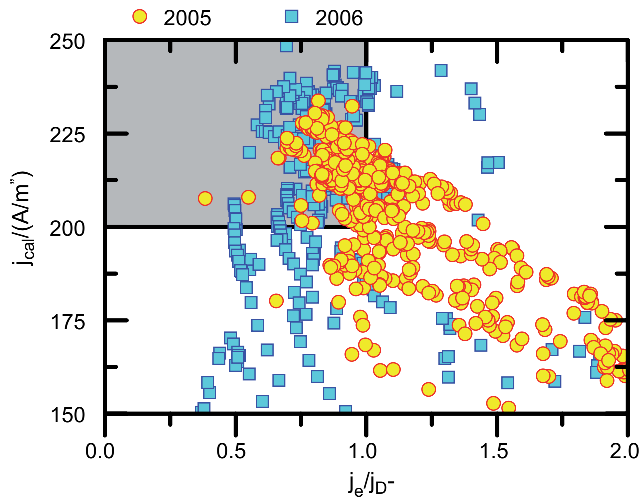

Figure 1: Performance of the IPP RF source for deuterium pulses in the required pressure range in 2005 and 2006. The ITER requirements of the calorimetric current density (j_{cal}) and the electron to ion ratio (j_e/j_{D^-}) are indicated by the grey box.

The long pulse test facility MANITU was further upgraded to cw operation in the last year by installing an actively cooled Faraday screen, an air-cooled plasma grid, and an actively cooled calorimeter. In addition cooling of the back plate of the source was improved. The air-cooled plasma grid is derived from a plasma grid of the AUG positive ion system, which has cooling channels between each row of extraction holes, but with a 3 mm deep chamfer on the plasma side. The extraction area is reduced by a molybdenum mask; at present 0.0188 m^2. This mask is attached to the plasma grid without a cooling loop of its own. Using the mask has the advantage that the largest possible extraction area can easily be identified by varying the opening in the mask; however, the mask heats up during long pulses and thus limits the pulse length to about 10 minutes. Best results obtained so far in hydrogen have been ion currents approaching 4 A (210 A/m^2) and pulses of up to 800 s (figure 2). Common to all pulses in excess of about 200 s is a rising electron current with time. This is most probably a consequence of a change in the Cs distribution due to a temperature increase of the un-cooled grid cover. The first deuterium experiments at MANITU showed that the source efficiency in deuterium is the same as for hydrogen, as was previously seen in BATMAN.

The deuterium discharges suffered even more from the increasing electron current during the pulse, due to the much higher electron to ion ratio in deuterium. Nevertheless, 200 s pulses have been achieved with reasonable ion current densities (120 A/m^2), but with an electron to ion ratio in the range of 2. For these first deuterium experiments, the source was not fully optimized due to the restrictions of the neutron budget and hence to the limited experimental time.

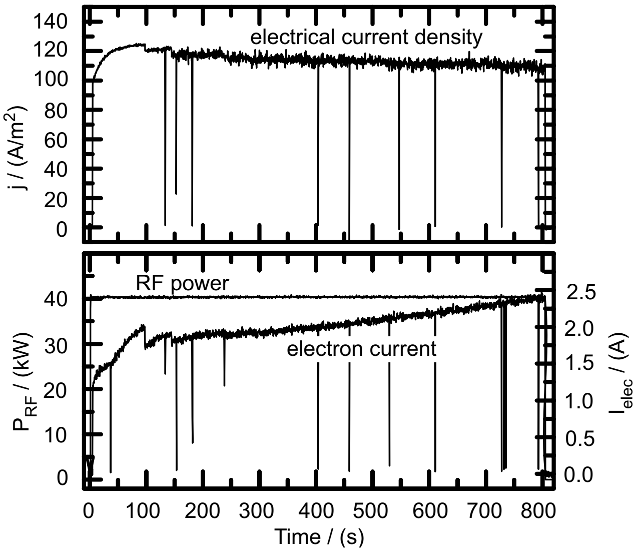

Figure 2: Electrically measured H- ion current density, RF power, and electron current as a function of time for a 800 s pulse at MANITU at a source pressure of 0.37 Pa

The third test facility RADI was recently commissioned with first plasma pulses. RADI is equipped with the so-called half-size source with the width and half the height of the ITER source. Its aim is to demonstrate the required plasma homogeneity of a large RF source; its modular driver concept will allow an extrapolation to the full size ITER source. The source is equipped with four standard IPP drivers powered by 2 RF generators. Full size extraction is presently not possible due to the lack of an insulator, a large size extraction system and a beam dump, but is foreseen in a later phase (see below). Measurements of the plasma homogeneity have now started. First experiments at low power with pure plasma, i.e. no magnetic fields, no bias and no Cs, have already shown that there is sufficient plasma overlap between the drivers and that the plasma is sufficiently homogeneous across the dummy plasma grid. Although RADI will demonstrate the operation of a large RF source and the homogeneity of large RF plasmas, the results will have limited significance. Beam extraction changes the plasma parameters in front of the plasma grid and hence plays an important role not only for the negative ion and electron transport, but also for the Cs dynamics. Furthermore, there is evidence that the magnetic filter field which is required for the suppression of the co-extracted electrons causes a spatial non-uniformity of the plasma and consequently of the beam. It is therefore essential to optimise the magnetic filter field with respect to the plasma uniformity together with a sufficiently suppressed co-extracted electron current. Hence, IPP is preparing a new test facility for long pulse and large-scale extraction from the half-size source. The new planned project will replace the RADI test facility and (to a large extent) makes use of existing hardware at IPP.

IPP continued its contribution to the design of the planned 1 MV neutral beam test facility, mainly by supporting RFX Padua in the design of a full size RF source, the RF circuit and the transmission line. The source consists of an arrangement of four pairs of drivers where each pair is supplied by a common generator. An alternative scheme of RF matching by adjusting the frequency, instead of tuning a capacitor nearby the drivers, was successfully tested on MANITU. Smaller contributions are the development of a Cs monitor for the source diagnostics and further support of the design of the alternative magnetic ion removal system.

Ion Cyclotron Resonance Frequency Heating

In the framework of an EFDA task, the influence has been calculated of different types of Faraday screens on the coupling and the losses in the ITER antenna. This will be accompanied by actual experiments on ASDEX Upgrade where an optically closed Faraday screen is being installed on one antenna, for testing in the next campaign. As part of the same EFDA task, an approximate but fast method to model the edge plasma was devised by using an anisotropic material with negative epsilon in the electromagnetic codes. This approximation will be tested by comparison with a code (TOPICA), which includes the real edge plasma. TOPICA (containing in parts the TORIC code developed at IPP) was developed by the Torino Politechnico, and has been installed at IPP.

The ICRF group is coordinator of a Euratom Fusion Training Scheme (EnTicE: European network for Training ion cyclotron Engineers). The programme is a cooperation of 8 partners to train 6 young engineers. Two of the trainees will be hired by IPP, each for 3 years.

The IPP is further involved in the ITER ICRH system via participation in the ITPA, in the European CYCLE consortium, which plans to take the responsibility for building the ITER antenna, and in the working group on heating and current drive, which has been established as part of the ITER design review.

Optimisation of the Upper ECRH Launcher

For the period 2006-2007, IPF Stuttgart has taken up three subtasks.

For the optimization of the free-space beam in the “front-steering” launcher, the analysis of the optics in the launcher has been started. Development of appropriate software for mode converter optimization is ongoing.

The characterization of plasma-exposed mirror samples is needed to enlarge the database on ohmic losses of launcher mirrors. Several launcher mirrors from ECRH systems of ASDEX-Upgrade and W7-AS were collected and are being prepared for tests. The resonator measurement equipment was optimized and is now ready for detailed investigations.
For the present version of the "remote-steering" launcher, the design of phase correcting input mirrors for optimum beam performance continued. Calculations have been performed to generate amplitude distributions at the entrance of the square waveguide, which simultaneously yield high aperture efficiency and low mode conversion at the waveguide exit. In the context of this work, optimization of groove profiles in corrugated square waveguides to reduce the ohmic loss was performed.

Physics Integration

3D SOL Transport and Limiter Load at Start-up

The edge transport properties of the limiter configuration in the ITER start-up phase have been analyzed with the 3D edge transport code, EMC3-EIRENE, for three equilibrium configurations, 2.5, 4.5 and 6.5 MA. The small size of the two limiters in the presence of a significant magnetic shear introduces a complex pattern of open field lines having connection lengths, L_c, ranging from 250 m to infinity. The radial power transport from the high-temperature long flux tubes to the low-temperature short flux tubes is very effective due to the small radial scale lengths, so that the power-load of the limiters is typically found to be smooth despite the strongly inhomogeneous L_c distribution on the limiters (figure 3).

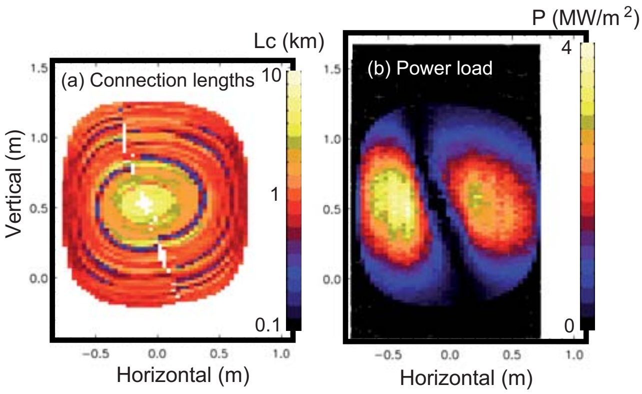

Figure 3: (a) Lc distribution on the limiter. (b) Power deposition on the limiter. The two wetted areas reflect the power efflux in positive and negative field directions.

For all three configurations, the SOL input powers, separatrix densities and diffusion coefficients were scanned to check their effect on the power deposition. For high plasma current (e.g. 6.5 MA), the peak power load is predicted to be close to the engineering limit of 8 MW/m^2, especially for the lowest chosen perpendicular transport coefficients and the highest input power.

Design of the Upper ECRH Launcher

In 2006, the work on the analysis of the physics capabilities of the ITER Upper ECRH Launcher focused on the analysis of the new default design, the front steering (FS) option. In collaboration with CRPP, the goals of ECRH/ECCD in ITER were examined for the whole system, i.e. the combination of upper and equatorial systems. The new proposal of an "extended Physics Launcher" put forward by CRPP is based on this assessment.
Concerning the requirements for NTM stabilisation in ITER, more work was done on evaluating the criterion for the driven current based on present day experimental data. It was shown that both misalignment of the driven current and corrections of the (circular cross-section) theory will have to be incorporated into the ITER fit; neglecting the latter, as had been done before, will underestimate the power requirements.

Studies of Tritium Retention

CFC targets were exposed to plasma in the PISCES-B divertor plasma simulator. Samples were exposed to both pure deuterium plasma and beryllium-seeded plasma at high fluences (up to 10^{27} ion m^{-2}) and high surface temperature (1070 K). The deuterium content of the exposed samples has been measured using thermal desorption spectrometry during baking at 1400 K. Although the full deuterium inventory could not be desorbed, a relative comparison can be done between different fluences by assuming that the thermal desorption process and the activation energies do not depend on the fluence to the target. This is consistent with the observation that the temporal evolution of the desorbed deuterium flux for the different samples is very similar. In the analysed fluence range at a target temperature of 1070 K, no fluence dependence was observed. The measured released deuterium is $1.5 \cdot 10^{22}$ at m^{-2}. This is a lower limit for the actual deuterium retention. In the case of target exposure with beryllium-seeded plasma no change in the released amount of deuterium was found.

Confinement Scaling

In order to improve upon simple power-law scalings such as ITERH-98P(y,2) near the density limit, a new scaling has been derived including dependencies on a general shaping factor (q_{95}/q_{cyl}) and a non-linear dependence on n/n_{GR} where n_{GR} is the Greenwald density. The saturation of confinement with density near the Greenwald limit was confirmed by pellet-fuelled discharges.
For L-mode discharges, the confinement ratio with respect to the standard ITERH-89P(y,2) scaling was shown to depend on Larmor radius as well as on aspect ratio. A new L-mode scaling has been derived, including an interaction term between Larmor radius and effective isotope mass and a roll-over term near the Greenwald limit.

Diagnostics

Divertor Thermography

A main result of the concept development for ITER divertor thermography was that the mirror-based concept is most flexible in selecting the detection wavelength and bandwidth. However, it remained to be shown that a mirror-based optical system could be kept aligned under ITER relevant conditions. For this reason a passive two-mirror system was designed which tolerates a change of the optical axis in 3 directions of about 5 degrees. A prototype was manufactured and the concept proven in a proof-of-principle experiment.
Measurements in existing machines have shown that the surface temperature measurement is influenced by the intrinsically inhomogeneous structure of the CFC material. The surface behaviour can be parameterized by at least three different thermal resistances. Using these resistances, a correction curve can be calculated which allows the deduction of the true bulk temperature from the surface temperature measured on a millimetre spatial scale.

In-Vessel Neutral Pressure Measurement

The proposal to use ASDEX-type pressure gauges in the ITER divertor has been updated with respect to changes in the ITER geometry, the distribution of the gauges and the expected upper limit of the pressure range. It was originally foreseen to install most of the gauges in such a way that they measure the particle flux in shaded regions on the plasma-facing surface of the divertor structure. More important are neutral flux measurements in the volumes behind the plasma facing structures and in the pump ducts and the gauge layout has been modified to reflect this.
Since the time of the original design of the ITER pressure gauge system, model calculations have shown that neutral pressures up to 20 Pa may be expected in ITER. This is more than a factor of two above the maximum pressure accessible until now using ASDEX pressure gauges. Tests were performed in order to determine the real upper limit of these gauges and it has been found that, after some minor changes to the gauge geometry, it is possible to use them in one operational mode surely up to 15 Pa and in another mode probably up to more than 26 Pa.

Test of a Compact Soft X-Ray Spectrometer

ASDEX Upgrade is testing an ITER relevant X-ray spectrometer in the framework of an EFDA task. A first prototype of such a spectrometer has been designed at the Kurchatov Institute in Moscow. It consists of a spherically bent crystal (d=35 mm, R=500 mm) in a Johann type configuration and an asymmetric Rowland geometry with two diffraction channels. The crystal is made of high purity quartz, making it resistant to high neutron fluxes, and is placed on a substrate of fused quartz, by means of an “optical contact” technique. There are two crystals available, one each for the measurement of He-like lines of Ar and Fe. Due to the large diffraction angles used (≈70°), a theoretical resolving power of $\lambda/\Delta\lambda \approx 5000$ can be reached (4000 measured in the laboratory). At present, one spectrometer channel is equipped with a deeply depleted back illuminated CCD camera chip for radiation hardness. The spectrometer was tested offline with an X-ray tube and is now installed at ASDEX Upgrade with a line of sight from the top, looking almost through the plasma centre. First results concerning its performance are expected during the next campaign.

CODAC

In 2006, a review of the ITER Control and Data Acquisition (CODAC) system was launched. The work was organised by an ITER visiting researcher who was assisted by experts from 6 participating associations (IPP, CEA, UKAEA, ENEA, CIEMAT, IST). Initial efforts were aimed at understanding the ITER CODAC organisation, concept view, task separation and inter-dependencies, and to develop a common linguistic understanding sufficient to start cooperation. Work was then started on specific research tasks. IPP activities focussed on the institute’s known fields of expertise, i.e. plasma control, time system, pulse schedule, continuous data logging, data archiving and data access. The preliminary results of these tasks were reviewed by an IPP expert group in order to identify inter-dependencies and conflicts and to balance the overall design. By the end of the year, final working documents were being compiled for each of the topics (except for data access where a broader forum should try to balance the different views among ITER partners).

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Plasma-wall-interactions and Materials

Plasma-facing Materials and Components

Head: Prof. Dr. Dr. Harald Bolt, Dr. Joachim Roth

Within the project "Plasma-facing Materials and Components" the areas of plasma-wall interaction studies, material modification under plasma exposure, development of new plasma-facing materials and their characterisation have been merged to form a field of competence at IPP. The work supports exploration and further development of the fusion devices of IPP and also generates basic expertise with regard to PFC-related questions in ITER and fusion reactors.

Surface Processes on Plasma-Exposed Materials

Structural investigation of the Be-W intermetallic system

The Be-W intermetallic system shows three different alloys: Be_2W, $Be_{12}W$ and $Be_{22}W$. Having different physical properties, it is important to know under which conditions the different alloys are formed. Since W will be used in the divertor region of ITER due to its high melting point (T_m=3695 K), the lower melting point of all known alloys is detrimental to the stability of the W components. Especially $Be_{22}W$ (T_m<1800 K) and $Be_{12}W$ (T_m<2000 K) have significantly lower melting points. Little is known on the reactivity of Be and W in the literature. Most data reported by now are measured as bulk data. The focus of our investigations is on surface and near-surface processes, since two cases can be distinguished concerning processes in a fusion device. Namely, tungsten can be deposited onto a beryllium surface or vice versa. Thus, two approaches were chosen in the investigations. A tungsten film was prepared on a beryllium substrate as well as an inverse system. By this means, we can investigate diffusion or desorption processes, and alloy formation. After preparation, the samples were heated up by progressive steps and investigated with Rutherford backscattering spectroscopy (RBS), X-ray photoelectron spectroscopy (XPS) and X-ray diffraction (XRD). Whereas RBS and XPS measurements provide information on elemental composition and chemical states, the XRD powder patterns allow the identification of crystallographic phases. The films were annealed up to 1070 K and the alloy formation was investigated by a combination of RBS and XPS. For the structural analysis and identification of the formed alloys, XRD was used. In addition to the stoichiometric information from RBS and the chemical shifts from XPS, XRD confirms the structural identity of the formed layer as $Be_{12}W$. The reverse system, Be deposited on a W substrate, only shows alloy formation restricted to the film-substrate interface. Both, XPS and XRD measurements, indicate the formation of Be_2W.

Round-robin characterization of ultra-thin AlNO films by ion beam analysis techniques

IPP and twelve other institutions used various IBA techniques to determine quantitatively the thickness, areal density, and concentration of aluminium, nitrogen, and oxygen in AlNO films having nominal thicknesses in the range 1-100 nm. Most of the results reported are not statistically different from the reference values taken as the median of all observations, and only very seldom large deviations were observed. This observation demonstrates the capability of IBA techniques to analyse quantitatively this very demanding system.

Only about half of the participants (including IPP) could measure the ultra-thin films, which pose a severe challenge to any analytical technique. However, it was not possible to identify a given technique or a group of techniques as being more reliable for analysing the ultra-thin samples.

Unexpected deviations in some results reflect a need for further measurements of fundamental quantities, namely cross-sections and stopping powers in energy ranges useful for IBA. Tentative recommendations have been made regarding how to obtain optimised results using IBA techniques. Quality assurance and quality control procedures should be established and implemented. Finally, traceable data analysis, including a detailed analysis of errors and their sources, is essential and should become standard in IBA practice.

The implications of high-Z first-wall materials on noble-gas wall recycling

Recent experiments in ASDEX Upgrade have experienced surprisingly high He plasma impurity concentrations. Such high He concentrations have not been observed with C walls, and have only been observed since the increase of the W first-wall coverage of ASDEX Upgrade to 85 %. The high He plasma concentration appeared to be linked to the fraction of W surfaces open to plasma contact that are not covered by boronization layers and to the number of He glow discharges performed for wall conditioning prior to normal plasma operation. This pointed to the different retention and release properties of W and C for He. To elucidate these differences, dedicated laboratory experiments have been performed. To study the retention, different types of W and C targets, including those used in ASDEX Upgrade, were implanted with ^{3}He at 200 eV and 600 eV and the amount of retained He was determined through thermal effusion spectroscopy (TES) and ion beam analysis (IBA) methods. These experiments showed that W can retain up to 10 times more He than C depending on the energy of the implanted ^{3}He (see figure 1). The differences in the release of He from W and C surfaces due to particle bombardment was investigated by exposing the ^{3}He implanted W and C surfaces to a ^{4}He or H^2 plasmas and measuring the loss of ^{3}He. It was found that for 100 eV bias three times more He is released from W than from C exposed to H_2 plasma. For 100 eV ^{4}He between 2 and 10 times more ^{3}He was released from W than from C depending on the type W and C compared. The stronger release of He from W due to particle bombardment can be explained by the higher retention in combination with the comparable release rates of He from W and C.

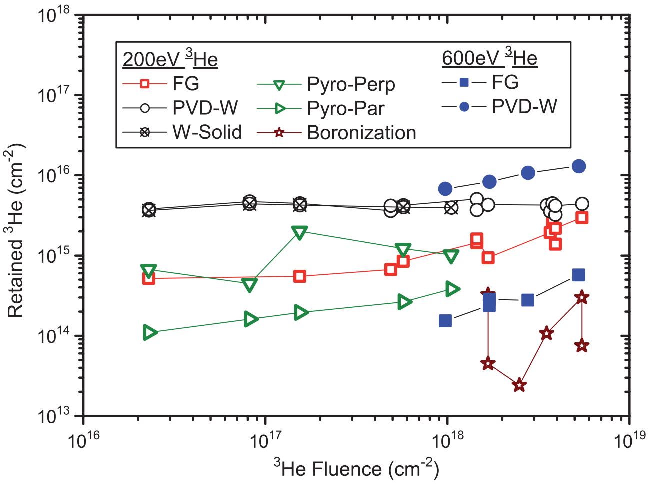

Figure 1: He retention in different types of graphite and tungsten targets at 200 eV and 600 eV. (FG:Fine grain graphite, Pyro-Perp/Par: Pyrolythic graphite perpendicular or parallel to graphene planes, PVD-W: AUG-type W layers on Graphite, Boronization: B layers on PVD-W from the 2005 AUG campaign, W-Solid: Solid polycrystalline W).

Sputtering of tungsten by simultaneous bombardment with deuterium and carbon

Because carbon and tungsten are planned as plasma-facing materials for adjacent divertor components in ITER, tungsten surfaces will be subject to simultaneous bombardment by fuel ions and redepositing carbon impurities. Simultaneous impact of fuel ions and carbon leads to both tungsten erosion and implantation of carbon and deuterium/tritium ions in the W surface. These processes have been studied experimentally in the IPP dual beam experiment (DBE) by simultaneous bombardment of magnetron deposited W layers with D and C ions at energies in the keV range. At the onset of bombardment, the system is characterized by a dynamic change of the surface composition which approaches steady state with increasing bombardment fluence. Two principal steady state regimes of continuous W erosion and continuous growth of a C layer on the surface are possible. At given impact energies, the key parameter separating the two regimes is the C fraction in the incident flux. A new and unique feature of the DBE setup is the capability to measure in-situ the dynamical change of the surface composition with increasing fluence by ion beam analysis. This allows, in contrast to previous experiments, to independently determine the implantation of C and the erosion of W and to determine the dynamical change of the depth distribution of both elements. The experimental results can be well reproduced by the TRIDYN code, which models the implantation and erosion processes, including the evolution of target composition using a kinematic model in binary-collision approximation (figure 2). Chemical erosion of carbon was neglected in the simulations because the concentration of retained D, measured by nuclear reaction analysis, is so low that significant contributions of hydrocarbon formation are unlikely.

To benchmark the TRIDYN model in a system where chemical effects can be excluded by principle, W layers were deposited by magnetron sputter deposition on polished single crystalline silicon substrates to eliminate the influence of surface roughness on the experimental results. This projectile-target system is subject only to kinematic processes and therefore ideal for benchmarking the TRIDYN code. The TRIDYN calculations match the experimental results very well, which demonstrates both the validity of the kinematic model and validity of the model used for the description of surface composition dynamics.

The surface roughness of the specimens was found to be mainly responsible for the observed shift of the transition point from continuous C layer growth to steady state tungsten erosion with increasing D fraction in the incident ions.

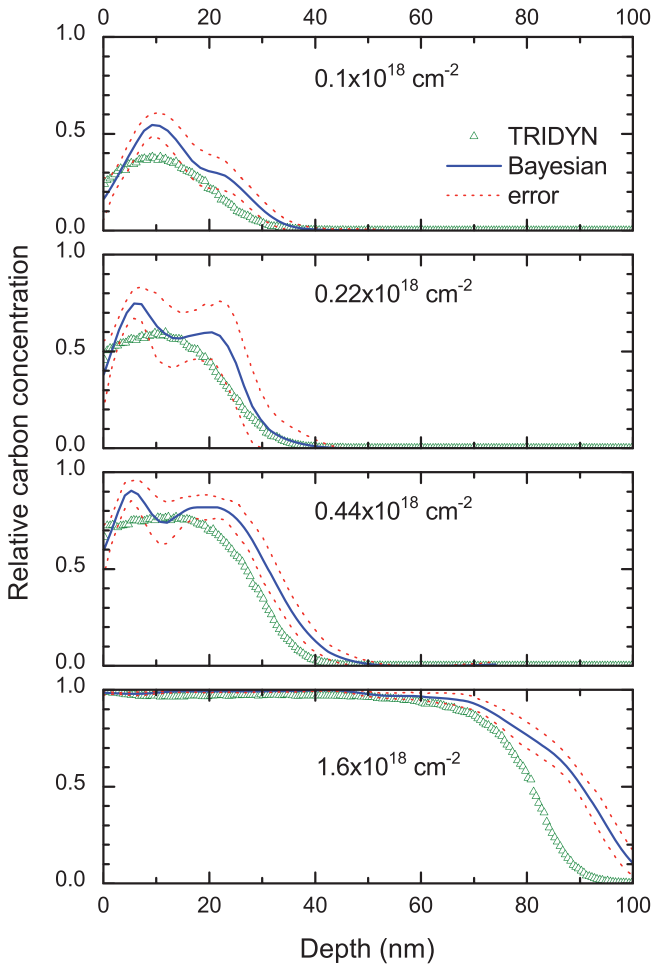

Figure 2: Dynamical change of the carbon concentration depth profile in a tungsten target bombarded with 6 keV C^+ ions. From the top to the bottom graph the bombardment fluence increases by a factor of 16. The solid curves represent experimental depth profiles obtained by Bayesian analysis of Rutherford backscattering spectra. The triangles represent the corresponding depth profiles from TRIDYN simulations.

Bombardment of W samples with a surface roughness significantly exceeding the incident ion range shows that surface morphology can strongly affect the erosion/implantation dynamics. This was studied in detail by bombardment of samples with different roughness scales and by comparing the experiments with a newly developed version of TRIDYN, SDTrimSP-2D, which includes a model of surface roughness. First simulations show already good agreement between experiment and model. Additional experiments are planned with conditions specifically matched to the model approximations used in SDTrimSP-2D for more detailed benchmarking.

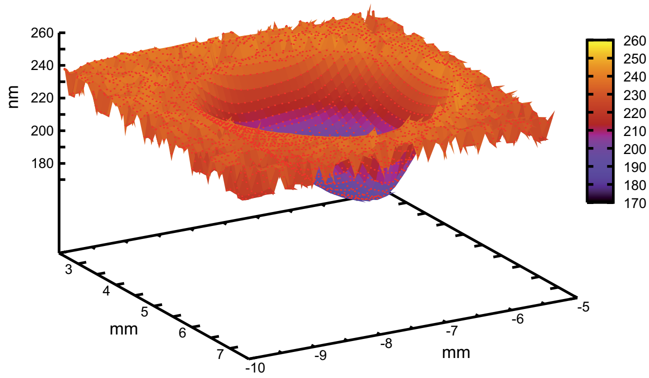

Figure 3: Depth profile obtained by Bayesian evaluation of the ellipsometry data. The erosion dominated area in the center of the beam spot is nicely reconstructed, also the thickness of the deposited a-C:H-layer outside of the beam spot is in excellent agreement with the expected thickness of d = 230 nm.

Surface Analysis: Ellipsometry

Ellipsometry is an experimental technique for determination of the optical properties of thin films. It measures the change in the state of polarization upon reflection of a light beam at a surface and carries information of the complex refractive indices of both the substrate and the thin film, and the film thickness.

In ellipsometry, sub-monolayer sensitivity to changes of film thickness can be achieved. This extraordinary sensitivity suggests to probe reactive particle beams by eroding marker samples (e.g., plasma deposited a-C:H films) and subsequent analysis by ellipsometry. However, in the case of energetic particle bombardment, not only the thickness but also the optical properties of the marker samples are modified, complicating the analysis of ellipsometry data. This situation represents the generic case with limited knowledge about the optical properties and the (multi-)layer thicknesses of the samples. The complex dependence of the measured optical response on the model parameters in combination with lacking phase information due to phase wrapping poses an under-determined parameter estimation problem. To tackle this difficulty the different length scales of thickness changes and changes of the optical properties were exploited by a multi-scale approach based on Bayesian probability theory.

This new algorithm has been applied to an a-C:H coated silicon sample where the central area of the film was exposed to a 3 keV D_3^+ ion beam. The outer area was shielded by an aperture. The initial optical properties of the sample corresponded to a so called dense a-C:H-layer with a hydrogen content of about 0.33 and a refractive index of 2.1-i·0.1. The average thickness of the film before exposure was d=230 nm. For the quantitative analysis of the erosion crater it has to be taken into account that the optical constants are modified due to the ion impact. The depth profile of the multi-layer-system was determined and the result is shown in figure 3. From these measured thickness variations the particle beam flux and the beam profile can be quantified.

This new approach extends the applicability of ellipsometry to the most common case where layer thickness and the optical constants are unknown.

Beam-sweep facility at the tandem accelerator

In fusion applications, plasma-facing materials are subject to energetic ion and neutron irradiation leading to radiation damage and structural changes in the crystalline lattice. Implantation of impurity ions will additionally change the surface and sub-surface composition of the material. Plasma-wall interaction processes such as hydrogen retention and permeation depend critically on lattice disorder and composition and need to be studied for irradiated samples. Most of the experiments following irradiation require samples with typical areas of 1 cm^2. In general, the irradiation has to be homogeneous over such an area and extend to a depth interval of several hundred nm.

To allow deep implantation, the tandem accelerator with terminal voltage of 3MV is used. The sputter ion source for negative ions allows the use of nearly all kinds of ions with energies from below 100 keV up to more than 20 MeV (depending on their charge state). Lateral homogeneity requires sweeping of the irradiation beam over the sample and perpendicular homogeneity varying the beam energy. Therefore, a beam sweep system has been installed in the beamline of the TOF-IBA chamber which covers a scan area up to about 20×20 mm^2. The samples mounted in the implantation chamber can be water cooled. Beam position, ion flux, and fluence are controlled by an arrangement of four small-diameter Faraday cups located at the four corners of the sample mask. Standard ion beam analysis techniques (RBS, NRA, Foil- and TOF-ERDA) can be applied in the same chamber to control the resulting implantation.

The system is used for irradiation experiments to produce lattice damage and to implant impurities. It is planned to investigate the influence of these two processes on the hydrogen content in and the permeation behaviour through fusion-relevant materials. First implantations have been performed using 350-500 keV O^+ ions to produce radiation damage in

Al_2O_3 permeation barriers and 500 keV C^+ ions to produce buried carbide layers in W. The system can also be used for preparation of marker layers for erosion studies in fusion experiments.

Migration of Materials in Fusion Devices

Erosion of tungsten and carbon markers in the outer divertor of ASDEX-Upgrade

The erosion of tungsten and carbon in the outer divertor of ASDEX Upgrade during the 2004/05 discharge campaign was studied by measuring the change in thickness of µm-thick marker layers by ion beam analysis techniques. The outer strike point area and a large fraction of the outer baffle are net erosion areas for both materials. The highest erosion is observed at the strike points and exceeds 0.3 µm tungsten for this discharge campaign. The net erosion rate of carbon is about 10-20 times larger than the net erosion rate of tungsten. The erosion is strongly inhomogeneous due to surface roughness, with large erosion on plasma exposed areas of the rough surfaces, and deposition in recessions and pores. These results are in good agreement with results obtained at JET.

Deuterium inventory in ASDEX Upgrade

The long term deuterium retention in ASDEX Upgrade was studied for the 2002/03 discharge campaign by ion beam analysis and SIMS. During the 2002/03 discharge campaign, ASDEX-Upgrade was a carbon dominated machine. An almost complete survey of the D inventory in all relevant machine areas was performed, including inner and outer divertor tiles, roof baffle tiles, remote areas below the roof baffle, pump ducts, inner heat shield, main chamber limiters, upper divertor, and passive stabilizer loop protection tiles. D is mainly trapped in co-deposited deuterium-rich hydrocarbon layers in the inner divertor and at or below the divertor roof baffle just opposite to the inner strike point. About 70 % of the retained D is observed on divertor tiles in the inner divertor, about 20 % below the roof baffle, and about 10 % in other areas. The D detected by ion beam analyses amounts to about 3 % of the total deuterium input. However, as can be seen from SIMS depth profiles and a low D/C ratio, this number is too low due to outgassing of D from some tiles by a singular event after about 2/3 of the discharge campaign. The outgassing can be taken into account from the amounts of deposited B and C and assuming a D/(B+C) ratio of 0.4, which increases the retention to about 4 %.

Tritium Inventory – Understanding and Control

Erosion of carbon layers due to combined bombardment with argon ions and molecular oxygen

Recently, significant efforts have been undertaken to develop and study techniques which might be applicable in ITER for removing tritium from co-deposited films. One discussed method is the erosion of such layers in low-pressure glow discharges using O_2/He gas mixtures. An important microscopic plasma-surface-interaction process during erosion is the interaction of energetic ions and molecular oxygen with carbon surfaces.

Therefore, the combined interaction of molecular, thermal oxygen and argon ions with a-C:H films was recently studied in the low energy regime (20-800 eV) using the MAJESTIX setup. While at 300 K the physical sputtering yield for argon ions at 400 eV is about 0.3 (removed carbon atoms per argon ion), the chemical sputtering yield in the presence of molecular oxygen is about 3 (figure 4).

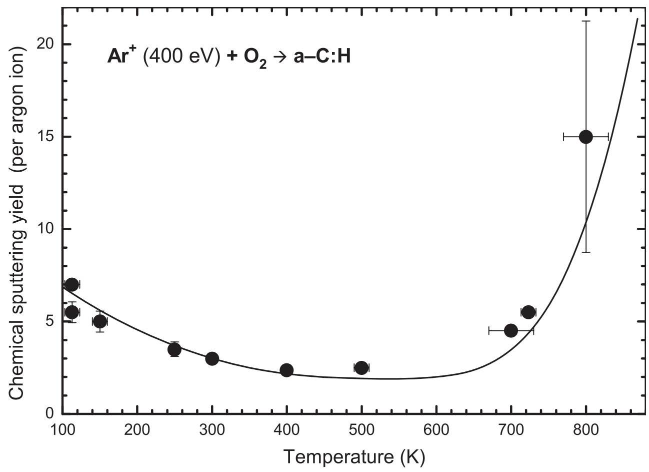

Figure 4: Chemical sputtering of a-C:H films due to combined irradiation with Ar+ ions and molecular oxygen as a function of temperature at a fixed ion energy of 400 eV. The flux densities toward the sample surface were approximately 4×10^{12} Ar^+ cm^{-2} s^{-1} and 1×10^{16} O_2 cm^{-2} s^{-1}. The line is only a guide to the eye.

Obviously, the energy deposited by the incident ions causes reactions between oxygen and carbon. With increasing target temperature, the yield increases to about 15 at 800 K due to an increasing contribution of thermally activated oxidation. Surprisingly, it also increases if the target temperature is decreased from room temperature to 110 K. The latter observation can tentatively be explained as follows: Oxygen adsorbs at the surface into a weakly bound state. Incident ions cause chemical reactions of the adsorbed oxygen due to local heating and damage production, which lead to the formation of carbon oxides. With increasing temperature the desorption rate of the adsorbed oxygen increases, whereby the steady-state oxygen coverage decreases and, hence, the average number of oxides formed per incident ion decreases. The chemical sputtering yield rises also with increasing ion energy. This can be explained by enhanced energy deposition and damage production at the surface with increasing ion energy.

It is assumed that this process, i.e. damage creation by energetic particles and consecutive reaction of molecular oxygen with damage sites, contributes significantly to the erosion of redeposited layers in oxygen containing plasmas. Reactions of other active species produced in the plasma, such as oxygen atoms and ozone, will lead to additional erosion. However, the very efficient ion assisted erosion is only possible on plasma-wetted surfaces, while neutral species such as oxygen atoms and ozone may also lead to erosion in shadowed or remote area, e.g., tile gaps. Their contribution and their relative efficiency have to be investigated in further experiments.

Tritium Permeation Barriers

To provide a means for the active control of hydrogen isotope permeation into and through metallic components of fusion reactor systems, the materials research division has been investigating thin ceramic coatings for several years. One of the important aspects of this barrier application in fusion is the stability of its permeation properties under neutron irradiation. So far, there is no literature on how these barriers perform after neutron irradiation, and this was under investigation in the framework of the Underlying Technology Work Program by EFDA.

The barrier selected was a thin aluminium oxide film (0.4 µm), which had earlier been proved to suppress deuterium permeability from the gas phase by a factor of 10^3. It was deposited on a EUROFER sample by the filtered vacuum arc deposition technique. To simulate the damage in the aluminium oxide layer caused by neutron irradiation, the new beam-sweep system of the tandem accelerator facility was employed (see Par.: “Beam-sweep facility at the tandem accelerator”). Irradiation was carried out using O^+ ions to minimize chemical conversions. Defect production and the estimation of the achieved displacements per atom (dpa) were modelled using the SRIM2006 computer code (J. Ziegler). The beam energy was varied from 100 to 350 keV in order to improve the uniformity of the damage profile within the aluminium oxide film. An average defect production of 6 dpa was obtained.

Permeation tests of the virgin, or non-irradiated, and irradiated samples were conducted. The former shows a permeation reduction factor (PRF) similar to that reported earlier – in the range of 1000. The latter reveals similar values of PRF with a small decrease in performance upon irradiation. It was observed that the lag time for occurrence of permeation for irradiated samples is much higher than for the virgin sample. An explanation could be that irradiation produces many defects both in the film and the substrate which have to be filled by permeating deuterium atoms before any permeation signal can be detected.

These results have to be reproduced and validated by investigating the influence of other ions as well as that of different irradiation damage levels.

Permeation of deuterium through tungsten

The ion-driven permeation of deuterium through 50 µm thick polycrystalline tungsten foils was investigated in the temperature range from 823 to 1023 K at implantation energy of 200 eV. The stationary value of the permeating flux is about 5×10^{-4} of the incident flux. The coverage of the foil backside by oxygen and carbon has a strong influence on the permeation rate. This was investigated by cleaning the backside with a 1.5 keV Ar^+ beam, resulting in an increase of the permeating flux by a factor of five.

Materials – Processing and Characterisation

Total erosion by deuterium of carbon films doped with nanometre-sized carbide

The total and chemical erosion of different metal-doped carbon films was investigated for 30 and 200 eV deuterium impact and temperatures between room temperature and 1100 K. The metal-doped carbon films were produced by magnetron sputtering. The dopants, W, Ti, V, and Zr, are present as nanometre-sized carbide crystallites following annealing at 1300 K. The total erosion yield was determined from changes of film thickness measured by ion beam analysis (Y_{IBA}) and weight-loss measurements. The CD_4 production yield was measured by mass spectrometry (Y_{QMS}).

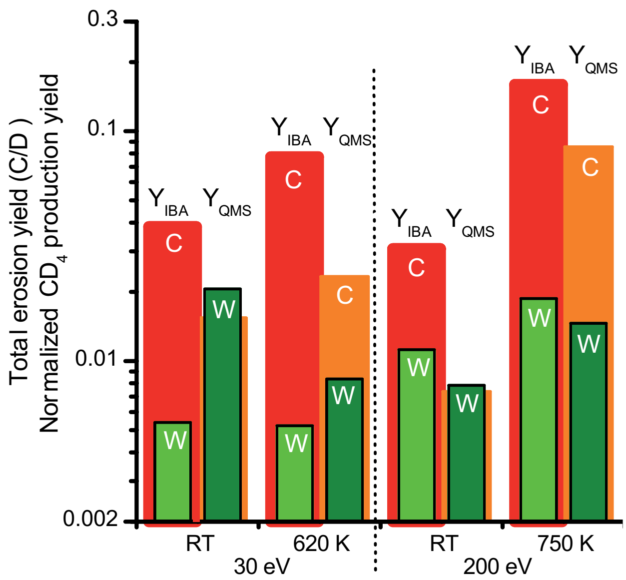

*Figure 5: Total and methane yield for pure and 3-4 at% W-doped carbon films**

* *Part of the work has been performed within the framework of the Integrated European Project “ExtreMat” (contract NMP-CT-2004-500253) with financial support by the European Community. It only reflects the view of the authors, and the European Community is not liable for any use of the information contained therein.*

All doped films have a reduced total erosion yield compared with that of pure carbon. The reductions are higher for 30 eV than for 200 eV and also higher at elevated temperature than at RT. The ratio of the total erosion yield of the films doped with 1-9 at% metal to the total yield of pure carbon films is in all cases below 0.7; in some cases below 0.1; the lowest ratio is ~0.05.

From the comparison of Y_{QMS} based on the CD_4 signal to Y_{IBA}, it was inferred that by doping the distribution of the erosion species is strongly shifted to an increased production of methane. From chemical erosion yields in the literature, including the contributions of heavier hydrocarbons or even radicals, it was inferred that for 30 eV/D at RT, most of the eroded carbon atoms are released in form of methane molecules. Furthermore, the large change of the ratio of Y_{QMS} to Y_{IBA}, by doping, supports the conclusion that a significant fraction of the chemically eroded carbon by low energy D impact at RT is released as hydrocarbon species with high sticking probability. Therefore, it can be speculated that doping reduces the formation of re-deposited layers.

Metal Matrix Composites

To increase the operational temperature range of divertor components from 350 °C to 550 °C, which is a requirement for future fusion reactors such as DEMO, it was suggested to strengthen the interface between the CuCrZr heat sink and the plasma-facing material by application of metal matrix composite (MMC). A possible MMC for this application is SiC fibre-reinforced copper. The fibres will contribute the strength and the copper has the requested thermal conductivity of at least 200 W/mK.

SiC fibres (SCS 0, Specialty Materials) were galvanically coated with copper and packed into a copper capsule. The capsules were hot isostatic pressed (HIP) at 650 °C and 100 MPa to form the composite. Push-out tests of individual fibres in the composite specimen were used to determine the interfacial properties between fibre and matrix. In other experiments, single fibres were coated and subsequently heat treated at 650 °C to simulate the temperature of the HIP process. Next, the tensile strength of these fibres was measured at room temperature.

The bonding between SiC and Cu in the composite was found to be very poor. With a load of 15 N, the SiC fibres could easily be pushed out. The tensile strength of the Cu coated and annealed single fibres was 2200 MPa.

The bonding between SiC fibre and copper matrix plays a decisive role in the improvement of the macroscopic mechanical properties of MMC. Therefore, several different interlayers between SiC and Cu were investigated. Among them were W, Cr, Ti, Ta, TaWN and TiCTaC. The interlayers were deposited by magnetron sputter-deposition.

A Cr interlayer leads to a significant increase in bonding between the fibres and the copper matrix. At loads around 60 N, the push-out tests were stopped to avoid damage to the indenter tip. The single fibre tensile tests, however, showed a dramatic decrease of the tensile strength to 1200 MPa. This is most likely caused by chemical reactions between Cr and SiC during heat treatment at 650 °C leading to fibre degradation.

The most promising option to improving the bonding and in maintaining the fibre strengths in the SiC/Cu system is a TiCTaC interlayer. During push-out tests, a maximum load of 50 N was observed, indicating a very good bonding between the fibres and matrix. The tensile strength of coated single fibres increased to 2400 MPa without degradation of fibre properties even after long-term heating at 550 °C for 500 h.

Component Behaviour

Cyclic plasticity constitutive modelling of heat treated copper alloy and pure copper

CuCrZr alloy and pure copper have been applied to plasma-facing components as a water-cooled heat sink and stress-relieving bond interlayer, respectively. Considerable plastic strains can be accumulated in the highly stressed copper part during manufacturing or high-heat-flux plasma operation. The latter is a cyclic loading mode, causing plastic fatigue cracking or progressive plastic collapse, which finally leads to overall component failure. In this context, computational estimation of the cyclic evolution of plastic strains is an important design concern, since it is a direct measure of material damage and structural lifetime.

To this end, an appropriate constitutive model should be chosen which is capable of describing the essential features of cyclic plastic behaviour. In addition, reliable data of material parameters are needed for the temperature range of interest.

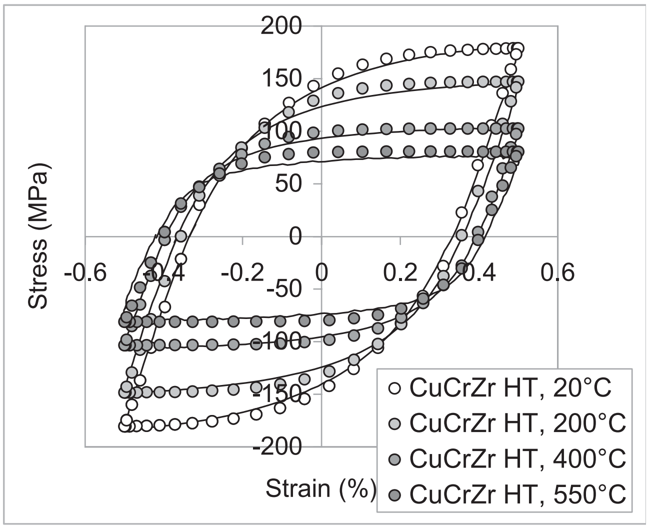

Figure 6: Simulated and measured saturation curves of heat-treated CuCrZr alloy (annealed at 700 °C) under uni-axial cyclic test

However, currently available cyclic testing data for copper and copper alloys for fusion applications are still limited. In this work, the plastic material parameters of soft copper and two sorts of precipitation-hardened CuCrZr alloys (as-received and heat-treated at 700 °C, respectively) were experimentally determined, based on the constitutive model of Frederick-Armstrong. The parameter sets were obtained for five temperature levels ranging from 20 up to 550 °C by means of numerical regression in which the predicted cyclic deformation curves, determined by finite element analysis, were fitted to the experimental curves. The simulated saturation curves were in excellent agreement with those of cyclic testing at all temperature levels. This result demonstrates the suitability of the considered constitutive model and the identified plastic parameters.

High Heat Flux Test Facility GLADIS

The powerful ion beam facility GLADIS (Garching Large DIvertor Sample Test Facility) is used for the high heat flux (HHF) testing of plasma-facing components with heat loads similar to the expected operation conditions in current and future fusion experiments. The main activities in 2006 were focused on qualification tests of W7-X pre-series divertor target elements and on continuation of the thermal cycling tests of W-coated CFC tiles in the frame of the JET ITER-Like-Wall Project (see topic JET cooperation). Technical improvements of the GLADIS facility itself led to an extension of the pulse length up to 30 s and a repetition rate of 60 pulses per hour for a power density of 10 MW/m²

A set of 20 full scale pre-series elements was manufactured by PLANSEE SE to validate the materials and manufacturing technologies prior to the start of the series production (see topic W7-X, in-vessel components). To evaluate the fatigue behaviour, all elements were tested for about 100 cycles at 10 MW/m². The applied pulse length of 10 s is sufficient because the actively water-cooled target reaches its equilibrium temperature after 6-7 s loading and the thermo-mechanical stresses are fully developed. Some elements were tested more extensively with cycle numbers up to 1000. After the loading of 20 elements (corresponding to a total of 200 bonded individual CFC tiles) with 100 cycles, 70 % of the tiles did not show any defects.

No tile detachment occurred, but several hot spots at the outer edges of tiles indicated local bonding problems between CFC and AMC interlayers (15 % of the tiles). Six of these elements were further tested with an increased heat flux of 13.5 MW/m² for 50 cycles. Only one new defect on the tile edge was observed. The defects which were already present on the four tiles before the additional cycling tests grew slowly. All other tiles survived without any visible defects.

The power load limits of the target element design were experimentally investigated with heat loads considerably exceeding the expected operating conditions in W7-X. For 15 s pulses of up to 18 MW/m² heat load, no bonding defects were detected. These experimental results confirm the corresponding FEM analysis. Compared with the nominal 10 MW/m² loading, the higher component temperature resulted in reduced stress during loading, but also in increased plastic deformation of the Cu interlayer close to the CFC interface. Three target elements were loaded up to 24 MW/m² for 15 s in a stable heat transfer regime. Figure 7 shows the power load distribution for these loading conditions. The applied heat load of 24 MW/m² resulted in a CFC surface temperature above 2200 °C and a corresponding temperature at the CFC/Cu interface close to the melting point of Cu. Partial detachment of the tile above the outlet of the cooling channel (tile no. 8 in figure X) was observed, but no tile loss occurred.

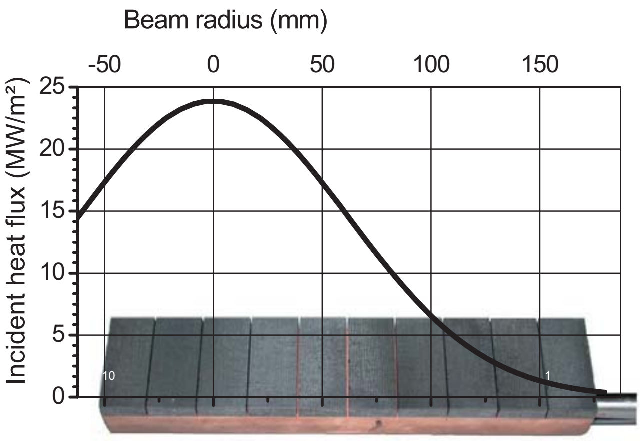

Figure 7: Schematic view of the power load distribution of the 24 MW/m² tests. For this example, the beam centre is located on tile 8. The end tile (no.10) received 17.5 MW/m² without any damage. The length of the element is 250 mm, the width is 58 mm. Tile numbers 1 (right-hand side) and 10 (left-hand side) are marked.

A further increase of the heat load could result in a breakdown of the heat transfer to the cooling water and subsequent melting of the cooling structure. The heat flux threshold for this breakdown is called critical heat flux (CHF). The target design and cooling conditions have to avoid such an event during operation in W7-X. A CHF test was performed with a stepwise increase of the power load up to 31 MW/m² on a target with removed CFC (15 °C cooling water inlet, 10.4 m/s axial velocity, 10 bar static). The breakdown of the heat transfer occurred after 2.6 s heating. This result exactly meets the local and temporal predictions.

In summary, the results of the 10 and 13.5 MW/m² cycling tests and the loading up to 24 MW/m² demonstrate the reliability and the sufficient "heat load safety margin" of the W7-X target concept.

The good agreement of measured temperatures and strains compared with the predictions of 3D nonlinear FEM calculations confirms the chosen FEM approach. This allows an effective component optimization focused on the stress reduction in the CFC/AMC bonding. The reduction of CFC tile size, change of the orientation of the CFC tiles, or reduction of the AMC thickness combined with an additional Cu interlayer are favoured to reduce the stress situation in the bonding. These improvements resulted in an additional manufacturing and testing of 17 elements to prepare a successful series production of the W7-X divertor target elements.

Integration of and Collaboration in EU Programs

EU Task Force on Plasma-Wall Interaction

The EU PWI Task Force was established in 2003 in order to provide ITER with a sound data basis for evaluation of PFC lifetime and build-up rates of the in-vessel tritium inventory and to suggest concept improvements for the first wall, including alternative materials, which could be implemented at a later stage. In 2006, the task force leadership passed on to the MF division at IPP Garching.

Most results originate from the work of Special Expert Working Groups (SEWG). Seven SEWGs are presently operating: Chemical Erosion and Transport, Gas Balance and Retention, Transient Heat Loads, High-Z Materials, Removal Methods. In 2006, two new SEWGs were initiated: In the SEWG on Dust in Fusion Devices, the experience on dust formation from many tokamaks will be combined with dust generation and mobilisation studies in low-temperature plasmas in order to assess this safety-related issue for ITER. The new SEWG on ITER-like Material Mixtures will address plasma-wall interaction processes on mixed materials from the combination of the ITER material choice Be, CFC and W and support the JET ITER-like Wall experiment.

At the 5th General TF Meeting in Ljubljana in Nov. 2006, reports from the SEWGs and from 24 participating Associations demonstrated greatly enhanced European collaborations resulting in numerous publications from joint experiments. Highlights in 2006 were the clarifications of chemical erosion in detachment conditions, of the gas balance in different devices, the development of the “good housekeeping scenario” for minimising the tritium inventory, and the evaluation of heat load during ELMs and disruptions. Details can be obtained from the TF web page http://www.efda-taskforce-pwi.org.

ExtreMat – New Materials for Extreme Environments (an EU Integrated Project in FP 6)

The European research project, ExtreMat, is coordinated by IPP and brings together 37 European partners from industry, research centres and universities with the aim of developing new materials for very demanding applications. Application fields besides fusion are advanced fission, electronics and space applications, as well as gas turbine compounds, brake systems, X-ray generators etc. as spin-off applications. Common requirements are the basis for the development of self-passivating protection materials, new heat sinks, radiation-resistant materials and of compounds integrating these materials with their favourable properties. The second project year was devoted to the first part of the *Research & Development* phase of the project. During this phase, materials and compound development was carried out based on the 15 *Materials Requirement Specifications* elaborated at the end of the first project year. The selected concepts for the R&D phase are based on the industrial needs and are selected on feasibility studies and risk minimization. Processing of materials was initiated at lab-scale levels. After determination of the material properties, for the most promising materials the processes were optimized and up-scaling efforts were started. The irradiation conditions and the test matrix of the neutron irradiation campaign were developed. With selected materials from all subprojects the development of processes for compound formation was started and joining techniques are under investigation. Procedures and techniques for environmental testing of materials and compounds have been improved in interactions between material producers and partners responsible for testing.

Scientific Staff

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Plasma Theory

Theoretical Plasma Physics

Head: Prof. Dr. Jürgen Nührenberg

The project "Theoretical Plasma Physics" is devoted to first-principle based model developments and combines the corresponding efforts of the divisions Tokamak Physics and Stellarator Theory, of the Junior Research Groups "Computational Studies of Turbulence in Magnetised Plasmas", "Theory and Ab Initio Simulation of Plasma Turbulence", and "Computational Material Science", and the EURYI Research Group "Zonal Flows". It is headed by one theorist on the board of scientific directors at a time.

Tokamak Physics Division

Heads: Prof. Dr. Sibylle Günter
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Tokamak Edge Physics Group

Earlier simulations of AUG experimental discharges with the SOLPS code showed a systematic tendency for the code to overestimate the density in the divertor and to underestimate the temperature. As possible explanations, two hypotheses were raised: effects arising from neutrals or from kinetic electrons. Runs with an artificially enhanced parallel heat transport provided a hotter divertor, closer to experimental observations. In the observed experimental conditions, electrons responsible for the bulk of the parallel heat transport (with energies 3-5 times T_e) are expected to be only weakly collisional, and poorly modelled by a fluid ansatz. Modelling of an Ohmic discharge supported these conclusions. Kinetic effects in the parallel electron transport are expected, in addition to raising the divertor T_e, to also increase E_r in the main SOL, upstream of the divertor. Comparison between E_r values predicted by SOLPS and EDGE2D and experimental data from AUG and JET reveal a large discrepancy between simulated and experimental E_r values. The ratio $-eE_r/\nabla T_e$, when calculated from reciprocating Langmuir probe measurements, was found to be much higher in experiments on a number of divertor tokamaks than in code simulations. This may have large implications for parallel ion flows in the SOL. Such flows, measured by double-sided Langmuir probes (Mach probes), were earlier found to be considerably larger than simulated in 2D fluid codes. They are believed to be strongly affected by the radial electric field and thus the underestimation in the present-day 2D edge fluid codes can therefore be related to the E_r underestimation. Three types of discrepancies between experiment and modelling have thus been identified: in the divertor T_e, radial electric field in the SOL, and parallel ion flows in the SOL. The present hypothesis is that all three are likely caused by non-local kinetic parallel electron transport from the SOL to the divertor.

The B2 part of the edge simulation package, SOLPS, has been extended to include mixed materials. The changes include: (1) the tracking of eroded material from the "base" material of the targets and walls of the tokamak; (2) the subsequent deposition and possible re-erosion of this material; (3) the change of surface material composition as a result of the build-up of mixed layers ("base" material plus a possible mix of deposited species); (4) a simple model for sputtering from these mixed material layers which makes a smooth transition from "base" material sputtering in the absence of any deposited layers to sputtering from the deposited material(s) only when the deposited layer becomes thick; and (5) different time-steps for the surface physics effects and the plasma. Simulations have been performed for $^{12}C/^{13}C$ and C/Be scenarios for AUG, JET and ITER. Amongst the more interesting results for ITER are: (1) substantial C deposition onto the outer wall Be surfaces; (2) a drastic drop in the net C erosion rate from an initial rate of 1.8×10^{23} s^{-1} (corresponding to approximately 4 ITER 1000 s discharges in the presence of T co-deposition) to later values of 3.7×10^{21} s^{-1} (about 200 ITER 1000 s discharges); and (3) Be fluxes to the inner target sufficient that Be suppression of C chemical erosion might become important.

Other work included, continuing activities associated with the EFDA Task Force on Integrated Tokamak Modelling as well as activities associated with JET.

MHD Theory Group

Kinetic MHD and Fast Particle Physics

Recently, the model and the implementation of LIGKA were extended to rigorously capture the coupling of the shear Alfvén wave to the drift and sound waves, which important for modes like the Cascade modes that chirp from the geodesic-acoustic frequency up to the TAE frequency. Furthermore, energetic particles modes in experimental discharges are also often observed in this intermediate frequency regime. Concerning the theoretical model for LIGKA, these low frequencies require a more careful treatment of the drift operator: it was shown – similar to the kinetic ballooning theory – how the fast compressional wave can be filtered out consistently and how the geodesic-acoustic correction of the continuum can be obtained. First benchmarks with analytical formulae were successful. With these improvements the damping rates of Cascade modes were investigated: the basic properties of these modes, as predicted by analytical theory, such as their dependence on the background temperature or q''_{min} were reproduced. Especially interesting in this context is the transformation of the Cascade mode into a TAE mode: non-local continuum damping and radiative damping which depend strongly on the details of the q-profile increase the mode damping considerably at the transition point. This may explain why the experimental mode signal, as measured by magnetic pick-up coils or reflectometry, often vanishes at a critical value for q_{min}.

Linear MHD stability analysis

Within the Integrated Tokamak Modelling effort (IMP#1), the Castor_Flow, Mishka1, and Mishka_D codes have been integrated into one single, comprehensive linear MHD code, called ILSA (for Integrated Linear Stability Analysis).

By use of this new tool, a linear stability analysis has been carried out for several ASDEX Upgrade H-mode discharges. By variation of the pressure and current profiles within the

experimental error bars, the stability thresholds for the generated equilibria have been studied. Within ideal MHD full stabilization of the peeling/peeling-ballooning modes by the influence of the q-shear and the plasma shape was found when the simulation domain extended close to the separatrix. To study the effect of finite resistivity in the region close to the separatrix, a model for neoclassical resistivities has been implemented into ILSA.
Within the EFDA project "DEMO Physics Studies" the beta-limits in tokamak reactor scenarios were investigated. The studies showed that within linear MHD theory high-beta tokamak equilibria with appropriate profile and magnitude of the bootstrap current, and desirable stability properties are possible. Optimized equilibria with a bootstrap current fraction exceeding 50 %, and a stability limit of β_N>5 % seem possible. Nevertheless, none of the investigated equilibria is stable without an external wall. This result underlines the need of stabilizing structures, i.e., a resistive wall plus feedback system, to reach stable high-beta equilibria.

Feedback stabilization of resistive wall modes

The STARWALL code, a 3D finite element code to compute the ideal MHD stability of resistive wall modes (RWMs) in the presence of an active feedback coil system, now takes into account the full 3D geometry, including holes, of the conducting wall structures and of the active coils, as well as the positions and orientations of sensors measuring magnetic field anomalies. The feedback logics are described by a gain matrix. The STARWALL code computes the stability of the RWMs for a given gain matrix. As a complement to STARWALL, the eigenvalue optimization code OPTIM has been developed, which automatically computes a gain matrix so that the system is optimally stable.

Heat transport in magnetized plasmas with magnetic islands and local stochastic fields

Heat diffusion was studied in an equilibrium with circular cross section and large aspect ratio using a recently developed numerical scheme. This scheme allows studying cases with realistic values of parallel and perpendicular heat diffusion coefficients albeit no coordinate line must be aligned exactly with the magnetic field lines. The heat flux around magnetic islands was examined and the consequences for the stability of neoclassical tearing modes were considered, revealing a significant correction to the widely used analytical approximation. The heat diffusion across highly stochastic layers was in good qualitative agreement with analytical predictions.

Non-linear MHD studies

The effect of plasma rotation and ECCD have been included in the code TM1 and tested. In agreement with AUG experimental results, one finds that modulated rf current drive has a stronger stabilizing effect than a non-modulated one when the wave deposition width is larger than the island width.
The non-linear diamagnetic drifting effect was included in the code TM1. The effect of an externally applied rotating resonant helical field on tearing modes and the condition for error field penetration were studied for comparison with observations on TEXTOR. It was found that a perturbation frequency coinciding with the mode frequency minimizes the penetration threshold. For a higher electron diamagnetic drift frequency or a higher plasma β value, the penetration threshold increases, indicating the role of the ion polarization current.
The non-linear growth of drifting magnetic islands was studied. If the bootstrap current perturbation is neglected, the island driven by the electron temperature gradient in a certain range of the electron diamagnetic drift frequency is f^*_e found to saturate close to the critical island width W_c.

Fast particle losses caused by toroidal field ripple and NTMs

We have investigated the loss of fast NBI injected ions due to magnetic field ripple and magnetic islands. The fast particles were traced from the interior of the plasma up to their intersection with plasma facing components outside the plasma. These computations were performed for axisymmetric as well as fully three-dimensional magnetic fields including the field ripple and magnetic perturbations caused by Neoclassical Tearing Modes (NTMs), as measured in ASDEX Upgrade. The computed energy and pitch angle distributions of the lost particles agree very well with experimental data obtained with the fast ion loss detector (FILD). The computations showed that the toroidal field ripple leads to a loss of trapped particles only, while the NTMs cause an additional loss of trapped particles, but also a small amount of passing particle losses. Most of these particles are lost because of the stochastization of their guiding centre orbits due to the magnetic field perturbations.

Transport Analysis Group

Group activities have focused on core particle impurity and momentum transport.
Particle transport was studied by means of an empirical statistical approach. A combined database of AUG and JET observations of H-mode plasmas has been built to study parametric dependencies of density peaking and obtain related scalings. The statistical analysis identified collisionality as the most relevant parameter. The neutral beam particle source accounts for less than 30 % of the observed peaking. The obtained scaling which includes collisionality and other significant parameters predicts a peaking $n_e(\rho_{pol}=0.2)/\langle n_e\rangle vol=1.45$ for the ITER standard scenario. This value is very close to the peaking found by ASTRA transport simulations of the ITER standard scenario with the GLF23 transport model, or by gyrokinetic calculations in the collisionless limit.
Impurity transport produced by ion temperature gradient and trapped electron modes was computed with the gyrokinetic code GS2. It was shown that, differently from neoclassical transport, these microinstabilities do not produce mechanisms of impurity pinch which increase strongly with increasing charge and therefore do not predict strong accumulation.

This agrees with the fact that no strong impurity accumulation is observed in AUG and Jet for anomalous impurity diffusivities. This is also promising for ITER, provided the α-heating is sufficiently strong and central to drive the transport anomalous up to the centre of the plasma column.

A theoretical study on the toroidal momentum transport has demonstrated the existence of a radial pinch for the first time. The pinch arises in the presence of an equilibrium toroidal velocity due to the particle drift generated by the Coriolis force. It leads to a peaked toroidal velocity profile even in the absence of a torque in the plasma. Gyrokinetic calculations found that the normalized logarithmic gradient R/L_v produced by this pinch is in the range 2-4, representing a moderate peaking, similar to that of the density. This pinch mechanism could explain the observations in many devices of toroidal velocities in the plasma core in the absence of external torque. Moreover, it is predicted to be sizeable in ITER with positive consequences on the stabilisation of both core microinstabilities and resistive wall modes.

An analysis of a database of AUG H-mode observations revealed a strong correlation between the toroidal momentum gradient and the ion temperature gradient which can be explained by a constant ratio of the effective momentum to the ion heat conductivities. In AUG H-mode plasmas such a ratio is close to 1 in the confinement region. The experimental values are in the same range as the predictions obtained using gyrokinetic theory for ion temperature gradient instabilities.

Electron temperature gradient (ETG) driven turbulence may be responsible for the high level of residual electron transport observed in many tokamaks. Recent global particle-in-cell (PIC) simulations yielded a lower level of anomalous ETG transport than local flux tube Eulerian codes. Radially elongated streamers with widths of several ion Larmor radii have been identified,

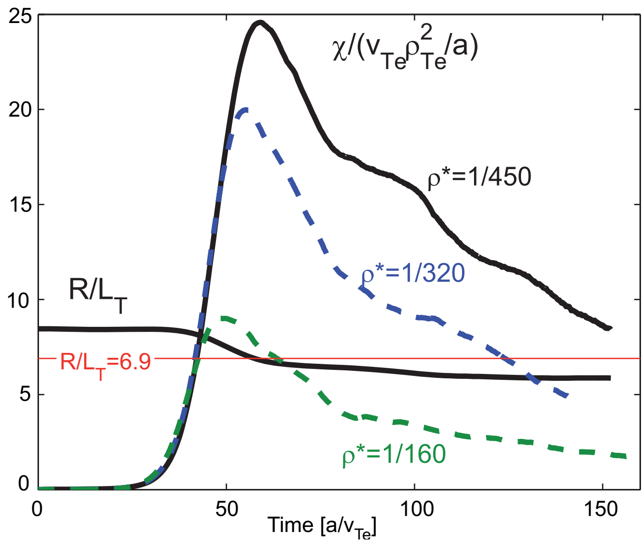

Figure 1: Time evolution of radialyl averaged R/LT for ρ^*_e=1/450 and χ/χ_{gB} for ρ^*_e=1/450, 1/320, 1/160. Parameters are taken from the CYCLONE base case. The radial average is over 0.52<s<0.62.

but the transport scaling was found to be Gyro-Bohm. We have used the electrostatic global PIC code ORB5 to clarify the discrepancy between flux-tube and global PIC results by developing a new measure of the statistical noise based on a signal-to-noise ratio which provides a good indicator of the quality of PIC simulations. Results show that low noise PIC simulations produce levels of transport comparable to flux-tube simulations even for relatively large values of $\rho^*_e \equiv \rho_{vth,e}/a$ and show no evidence of a Gyro-Bohm scaling of the heat transport, as it is illustrated in the figure. Moreover, the statistical noise clearly has a strong influence on the non-linear behaviour of ETG turbulence.

The behaviour of the turbulence in the presence of a magnetic island can be investigated using ORB5 by modifying the equations of motion to include the radial component of the perturbed magnetic field. The island modifies the turbulence by reducing the temperature gradient which drives the turbulence, thereby also reducing the heat flux. The amplitude of the turbulent modes decreases with respect to the case without island, in particular close to and immediately after the overshoot.

The study of the parallel current in rotating islands was continued with particle simulations of ions and electrons including electron-ion collisions but without anomalous transport. For small islands (small compared to the thermal ion banana orbit width), quasineutral solutions can only be obtained for island rotation in the ion diamagnetic drift direction.

Power Plant Conceptual Study

Transport modelling of a fusion power plant scenario has been performed with the first-principle GLF transport model with the objective of improving the reliability of existing scaling based predictions by using theory based transport models. Rather moderate performance is predicted by the GLF model for the inductive (pulsed) scenario resulting in a rather large size of the device. As an alternative to this conservative approach, an advanced scenario with an internal transport barrier (ITB) has been proposed. The barrier can be maintained by an appropriately tailored external current drive (LH or EC) at the plasma periphery. A regime with 60 % of the bootstrap current and 40 % of the driven current was found. A feedback control algorithm was proposed to stabilize the bootstrap current at a prescribed level. The regime allows for high-performance steady state scenarios for a fusion power plant.

Density profile investigation

Electron density profile simulations with the BALDUR 1.5D transport code permitted to derive scalings for the ratio v_{in}/D. The partial correlation coefficient between C_v (the normalised ratio of inward velocity v_{in} and particle diffusion coefficient D) and the normalised electron temperature gradient length is considerably higher than for previous candidates in log-linear multiple regression analysis. Both a trivariate log-linear model and a two-term scaling were derived. In a simulation for ITER FEAT, the scaling predicts a rather peaked density profile with $C_v \approx 0.7$.

Wave Physics Group

We have done several optimizations and added diagnostics to the TORIC code. In particular, we made a detailed analysis of the different ICRF scenarios at ASDEX-Upgrade and started to implement a realistic NBI source in the Fokker-Planck solver of the TORIC package, motivated by ASDEX-Upgrade experiments which suggest a synergy of NBI and 2nd-harmonic heating.
We further analyzed with TORIC the mode conversion to ion cyclotron waves. The asymmetry suggested by the numerical results might alter the efficiency of rf current drive.
We re-derived the quasilinear operator describing the evolution of the ion distribution function under the effects of cyclotron heating in a toroidal plasma, using the standard bounce averaging technique. We showed that it predicts the same radio frequency induced radial diffusion as the operator obtained using the more complicated orbit-averaging procedure which requires the introduction of action angle variables. By assuming the rf field to be known as a superposition of toroidal and poloidal Fourier modes, the quasilinear operator is obtained in a form which can be naturally evaluated using the output of a spectral solver of Maxwell equations in the plasma, such as the TORIC code.

Development of mathematical tools

Existence and dynamical properties of solutions of parameter dependent quasilinear evolution problems were investigated for various sets of equations. A simple standard model for the evolution of the electrons and electromagnetic fields in a gyrotron was studied. A Poynting theorem was obtained directly from the model and the Hamiltonian character of the electron motion was demonstrated. The start-up and final state in the gyrotron were also examined. The efficiency of energy flux transfer from the electron beam to the wave was estimated. Problems with only piecewise differentiable coefficients were considered. Time-like iteration schemes for computation of steady state solutions were revisited, in search for more efficient schemes in certain equilibrium codes.

Turbulence Theory Group

We continue to study low frequency fluid like drift turbulence employing gyrofluid models extended to capture important kinetic effects such as Landau damping and finite gyroradius (FLR), as well as gyrokinetic models treating all phenomena at the scales of interest (1 mm to 10 cm, 10 kHz to 1 MHz). Both types of model have been recast for greater accuracy within a wider set of parameter regimes. The gyrofluid model GEM and the gyrokinetic model dFEFI are intended to treat equilibrium and turbulence phenomena together at all collisional regimes, as especially needed for the tokamak edge.

Gyrofluid/Gyrokinetic Studies of Edge Turbulence

The GEM model with extensions to account for closed and open flux surface regions, separatrix topology, and self consistent equilibrium was used to study turbulence across the last closed flux surface. To model the scrape-off layer (SOL), a Debye sheath is prescribed where a material surface cuts the field lines. The SOL effects were compared for single and double null configurations, each null modelled by a limiter surface. As expected, the turbulence extends along the field lines to cover the region in parallel connection to the outboard midplane, so that in the double null setup nearly no activity was found on the inboard midplane of the SOL. By contrast, the out/in asymmetry of the turbulence in the edge region was much less pronounced. The results agree qualitatively with SOL density fluctuation observations going back to ASDEX data from the 1980s.
Shaping effects on the turbulence and zonal flows were studied by using a metric computes within an MHD equilibrium model. A strong stabilising effect of increasing ellipticity was found. Study of the zonal flow energetics found that enhanced zonal flow consistent with the weaker geodesic curvature was part of the overall effect.
Electromagnetic effects on the system of ion temperature gradient driven (ITG) turbulence and zonal flows were studied. Previous results from gyrokinetic models concerning the nonlinear upshift of the ITG threshold (in gradient strength) caused by turbulence-driven zonal flows were recovered. The zonal flows represent a perturbed equilibrium. The capture of this by the GEM model is the first such result from a gyrofluid model which does not neglect geodesic curvature. The electromagnetic effects were both linear stabilisation and enhanced zonal flow generation. The actual plasma beta value of the Cyclone base case was sufficient to bring the calculated transport value in line with the level observed in the experiment.
Ongoing efforts include global treatments of all these phenomena. Detailed comparison of the self consistent edge between the GEM model and gas puff imaging observations on Alcator C-Mod was started. In addition, we began a study of the ELM crash process. Findings so far indicate that the dynamics must be resolved down to the ion gyroradius to obtain converged statistical results. After the crash begins, the energy in the initial MHD instability is largely converted to electromagnetic ITG turbulence which then controls the further evolution.
Gyrokinetic edge turbulence was studied using the dFEFI code. Populations of electrons with mostly parallel or perpendicular kinetic energy are found to become dynamically separate. This smoothes the shutoff of electron drift wave effects as one approaches the core even in the absence of magnetic trapping.

Fundamental Theory

Our efforts to establish the theory of gyrofluid equations within a globally nonlinear setting were advanced sufficiently to enable construction of the GEMX code. Initially the isothermal model is used, with a finite background temperature for an arbitrary number of species. Energy and entropy theorems are constructed and used to guide the derivation. The theory itself was extended to anisotropic temperatures. Variation of a gyrofluid Lagrangian density within an action minimisation principle yields the equations. The role of dynamical heat fluxes outside diffusive

approach to thermodynamic equilibrium was studied. Relations between different formulations of thermodynamic energy are involved, with one giving the usual thermodynamic equations and the other recovered by variation of the Lagrangian which includes contributions proportional to the square of each heat flux. An important consideration is the relationship between gyrofluid equations and the collisional fluid Braginskii model. Our most recent work has shown that the polarisation nonlinearities in the fluid model are recovered by the gyrofluid FLR nonlinearities in the long wavelength limit. Together with the correspondence in the dissipative viscosity and heat flux effects in the strongly collisional limit, the gyrofluid equations are thereby established as a complete superset of the collisional fluid equations.
In parallel to this effort a different derivation path was found for the gyrofluid equations, starting with the complete gyrokinetic theory, restricting to the local limit, expressing the distribution function as a set of orthogonal Hermite polynomials whose coefficients are the gyrofluid moment variables. The energy theorem, which is the same for both the gyrokinetic and gyrofluid models, is used to drive the derivation, an approach which guarantees consistency among all the models and within each. Using the above correspondence results, the derivation path from complete gyrokinetics to low frequency collisional fluid equations is closed.

GEMX code development

The isothermal GEMX code was built together with the self consistent equilibrium including MHD, flows, and heat fluxes.

EU-Task Force on Integrated Modelling

We are participating intensively in the turbulence benchmarking projects under the auspices of the EU Task Force on Integrated Tokamak Modelling.

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Stellarator Theory Division

Heads: Prof. Dr. Per Helander, Prof. Dr. Jürgen Nührenberg

Introduction

In 2006, the work of the Stellarator Theory Division was concentrated on widening the scope of theoretical work of the Greifswald branch and on further development of the stellarator concept[1, 2].

MHD Theory of Stellarators

Benchmark PIES vs. HINT

The PIES code was benchmarked vs. the HINT code on the “Large-Volume” case described in Ref[3]. For a plasma pressure of $<\beta>=4$ %, good agreement was found between PIES and HINT[4], see figure 2 after modifying the HINT code to reduce the plasma pressure beyond the last closed flux surface. Analogous work performed on LHD showed similar agreement for plasma pressures of $<\beta>=1$ % and 2 %.

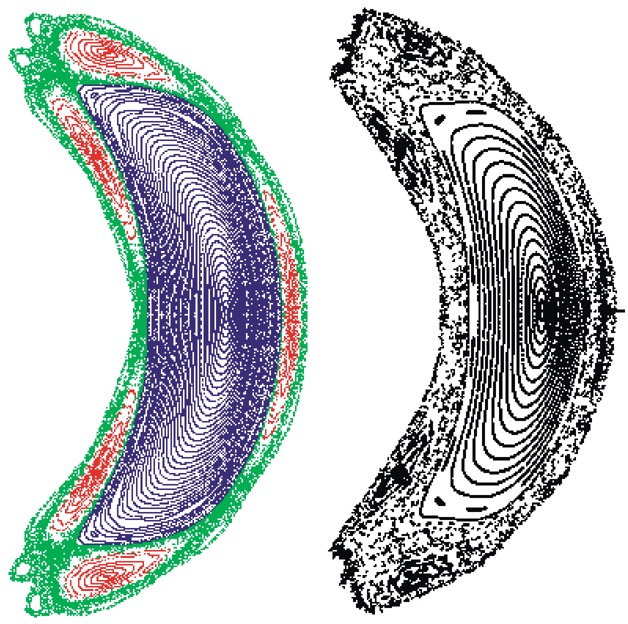

Figure 2: Poincaré Data HINT vs. PIES

Coils for High β Stellarators

Coil optimisation studies were done for a 6 period configuration[2] at $\beta \sim 9$ %. Preliminary coil systems obtained[5], see figure 3, had a slightly stronger shaping than the coils used in W7-X. Parameterisation of the coils by periodic splines was observed to be more efficient than the use of Fourier series.

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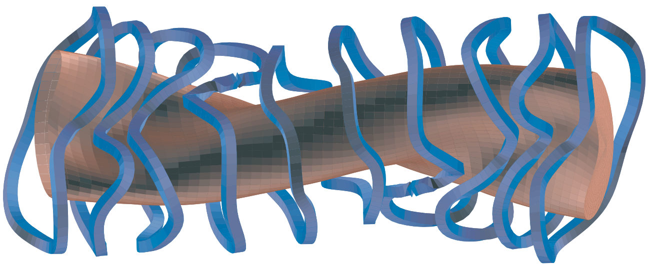

Figure 3: Coils and Plasma boundary of the 6-period configuration of ref.2

Geodesic acoustic modes in general geometry

Acoustic plasma oscillations and zonal flows were investigated in general geometry in the framework of linear MHD. The stationary flows are divergence-free (as the current density) so that – analogous to the reduction of the parallel current density – they are primarily oriented perpendicular to the magnetic field in W7-X. For comparable mode numbers, the frequencies of acoustic modes are significantly smaller in W7-X than in a tokamak geometry and the mode structure is sound-wave like, i.e. the plasma displacement parallel to the magnetic field is dominant, in contrast to the structure of geodesic-acoustic modes with mainly perpendicular displacement in tokamak geometry.[6]

MHD-stability with kinetic effects

Higher gaps in the Alfvén continuum (HAE, MAE, NAE) are often closed even in weakly sheared systems like the Wendelstein stellarators. In highly sheared systems as LHD already the TAE gap is closed. To access the experimentally explored fast particle driven modes in LHD and overcome the limitations of ideal MHD with respect to continuum and radial damping, a new three-dimensional finite element code has been written. This Code for Kinetic Alfvén waves (CKA) employs a reduced MHD model with additional finite gyro radius effects.

Gyrokinetic Simulations

Global linear gyrokinetic particle-in-cell simulations of fine-scale modes in a tokamak

The Ion Temperature Gradient driven (ITG) instability and the Trapped Electron Mode (TEM) are considered as important candidates to explain the anomalous transport in tokamak plasmas. These microinstabilities have been extensively studied in the regime $k_\perp\rho_i \leq 1$. At the same time, their properties at $k_\perp\rho_i > 1$ remain unexplored in many aspects[7].

Such fine-scale instabilities in a tokamak have been studied with the PIC code GYGLES applying the so-called generalized gyrokinetic solver[8].

The Short-Wavelength-Ion-Temperature-Gradient driven (SWITG) mode has been identified[9]. The effect of the kinetic electrons turned out to be important.

Gyrokinetic treatment of GAE modes

Global Alfvén eigenmodes (GAEs) are investigated in screw pinch geometry both analytically and numerically. These modes are of particular importance in stellarators with low-shear magnetic configurations. After linearising the equations of gyrokinetics with neglect of magnetic drift effects, a generalized dispersion relation for GAEs with FLR and kinetic effects is obtained. It reduces to the well-known MHD counterpart in the appropriate MHD limit. An eigenvalue code is developed to solve the dispersion relation, which is used to investigate the kinetic analogues of GAE modes in various regimes with different β. Also, GAE modes are simulated with a global linear particle-in-cell (PIC) electromagnetic gyrokinetic code following the self-consistent time evolution of electromagnetic fields and plasma dynamics. The damping rates of the observed GAE modes agree with predictions made by the eigenvalue code[10]. In low-β plasmas, energetic species do not significantly affect time evolution of the modes in screw pinch geometry.

Many-particle approach to gyrokinetic theory

Gyrokinetic theory is a basic framework to describe micro-instabilities, turbulence, and the resulting anomalous transport. The basic equations of gyrokinetic theory are the gyrokinetic Vlasov equation and the equations for the electromagnetic self-consistent fields. Because of the self-consistent field, the gyrokinetic theory is, in fact, a many-particle theory. However, the conventional derivation scheme[11] based on the Lie transform, considers rather a single-particle motion of guiding centre in a gyro-dependent self-consistent field. Formulated on the basis of the rigorous theory of guiding centre single-particle motion[12], gyrokinetic theory remains semi-phenomenological in the treatment of many-particle effects. A systematic first-principle approach to the many-particle formulation of gyrokinetic theory[13] has been developed. Starting with a system of N charged particles in a strong external magnetic field and using the Lie transform technique[14], the fast gyro-motion has been separated from the dynamics of the system in a way which is analogous to the conventional derivation of the single-particle gyrokinetic theory. The many-particle Hamiltonian function resulting from the Lie transform is used to derive the generalized gyro-

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kinetic equation with the collision term in accordance with the well-established Born-Bogoliubov-Green-Kirkwood-Yvon (BBGKY) methodology. Finally, the microscopic expression for the self-consistent potential and the polarisation density is obtained. New terms appear in the gyrokinetic polarization which can not be derived in the conventional approach. An expression for the collision term is obtained in the Landau approximation.

Global ITG modes in stellarators

Global linear simulations of the electrostatic gyrokinetic equation with adiabatic electrons were performed in three-dimensional geometry using the particle-in-cell code EUTERPE. It has been possible to simulate ITG instabilities for Wendelstein 7-X with β=4.8 %. Decomposing the growth rate of the mode into contributions from different drive mechanisms it was concluded that it is mainly slab-driven, although its complicated spatial structure shows a high degree of poloidal localisation. To take into account the influence of the ubiquitous neoclassical radial electric field present in stellarators, simulations have been performed including an external electric field employing a simple model for its functional form. In this model, the radial field is, assuming a constant density, proportional to the pressure gradient. Two configurations have been investigated: Wendelstein 7-X and the LHD standard configuration with $\beta\approx$1 %.[15] In both cases increasing the electric field leads to a decrease of the growth rate, which reaches about 40 % when the field is fully switched on. This is accompanied by a change in mode structure such that the spectrum of the mode becomes more localised in Fourier space, indicating a more slab-like structure. For the LHD configuration also the mode number of the mode maximum in Fourier space decreased significantly. In collaboration with the Garching Computing Centre EUTERPE has been optimised with respect to single processor performance and parallel scalability. Especially the concept of domain cloning, which allows a decoupling of grid resolution and number of processors has been implemented after modifying the iterative matrix solver accordingly. It has been demonstrated that the code scales nearly optimal with processor number for up to 512 processors.

Predictive Simulations of Microinstabilities for Optimized Stellarators

The following effort has been carried out in close collaboration with the Helmholtz-University Young Investigators Group ‘Theory and ab initio simulation of plasma turbulence’ at Garching. In the context of computational studies of small-scale turbulence in magnetized toroidal plasmas, the nonlinear gyrokinetic equations are frequently used as a starting point where using field-aligned coordinates is important to minimize the number of necessary grid points. Usually the magnetic configuration is assumed to consist of a set of nested flux surfaces, and Clebsch-type coordinates are chosen where one is a flux surface label. However, deviations from this standard scenario can occur. For example, it has long been known that stellarators (as well as tokamaks) tend to exhibit fairly large ergodic regions which can affect the plasma turbulence in a significant fashion. Under such conditions the usual procedure breaks down and a new way had to be found for embedding useful – and ideally still field-aligned – coordinate systems[16]. On this basis, the linear characteristics of two key microinstabilities in the core plasma of the stellarator experiment W7-X, namely ITG modes and TEMs have been investigated [17]. This study revealed a unique feature for the stellarator configuration, namely a coexistence of unstable ITG modes, differing in their parallel mode structure. This holds for both the adiabatic electron approximation and full electron dynamics.
Substantial differences between the stellarator and tokamak configurations are also revealed through the investigation of TEMs. For the W7-X configuration, the relative decoupling of regions with bad magnetic curvature and those with a large trapped fraction has a stabilizing effect. TEMs are thus expected to play a smaller role in W7-X than in a tokamak. On the other hand, their linear growth rates are by no means negligible, and their critical gradients are relatively small.

Intermittent turbulence in VINETA

In the linear VINETA device, the plasma density fluctuations exhibit a different character across the radial plasma background density profile. In the gradient, edge, and far-edge region the plasma fluctuations exhibit coherent, intermittent, and increased intermittent character, respectively. For the simulation of turbulence in the VINETA device, the adapted version[18] of the three-dimensional gyrofluid code GEM3[19] is used. Gyrofluid equations for the density and parallel velocity of electrons and ions, taking into account the effect of the outflow of atoms (neutral wind), are solved in a cylindrical annulus. Electrostatic computations are performed for a background density profile observed in VINETA. The results[20] exhibit fluctuations across the radial background profile similar to that observed in the experiment, see figure 4.
The effect of the neutral wind on the character of the fluctuations seems negligible for the VINETA device, but a full, quantitative comparison still needs to be done.

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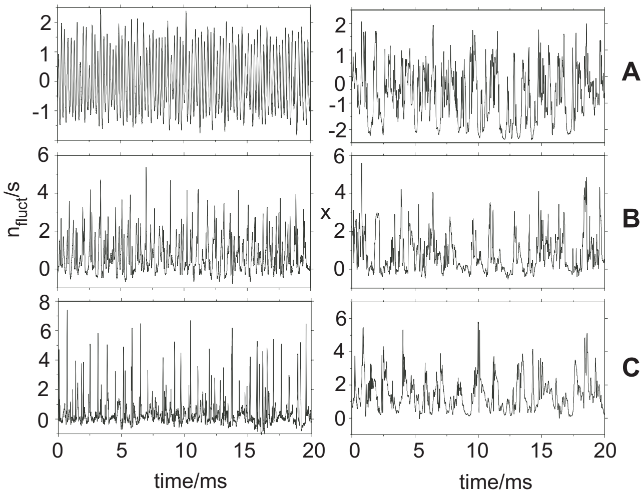

Figure 4: Electron density fluctuations (normalized to standard deviation) in the gradient (A), edge (B), and far-edge (C) region from experiment (left) and simulation (right)

Development of Stellarator Concept

Results of an optimization toward quasi-isodynamicity for a stellarator with a comparatively large number of periods, N=12, have been obtained. The following set of physics properties to be achieved has been used: 1) good long-time collisionless confinement of α-particles; 2) small neoclassical transport in $1/\nu$ regime; 3) small bootstrap current; 4) high stability β-limit. It was shown that these conditions are not in strict contradiction with each other. Preliminarily[21], the simultaneous achievement of low equivalent ripple and very high β appears to be most difficult; for example, for N=12 and A=36, $<\beta>\approx 20$ %, $\beta_0\approx 50$ % at $\delta_e\approx 0.05$ (with conditions 1) and 3) satisfied).

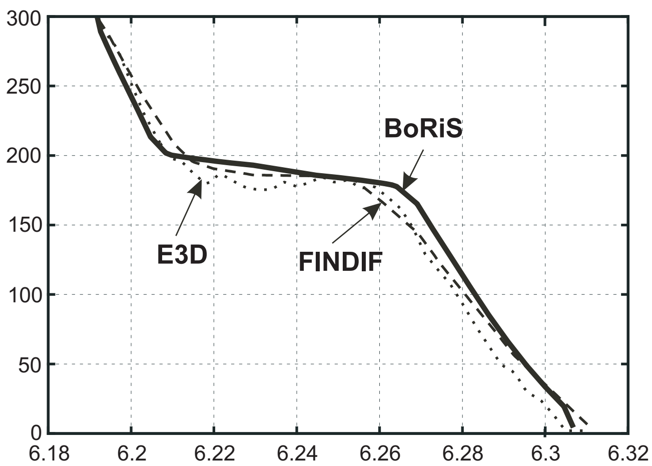

Figure 5: Electron temperature from 3D W7-X limiter calculations using BoRiS, FinDif and E3D in a 1D cut through an island in the midplane of the bean-like toroidal cut (at 0° toroidal angle). The island appears as a plateau-like structure.

[21] *M. Mikhailov et al: AIP, CP871, 388 (2006).*

Plasma Edge Physics

Benchmarking of 3D fluid codes for edge modelling

The problem of 3D transport in the periphery of modern fusion devices requires the development of appropriate theoretical models. In the stellarator theory division, there are three codes under development: a finite-volume code BoRiS based upon magnetic (Boozer) coordinates and two codes using a concept of local magnetic coordinates – a fluid Monte-Carlo code E3D and a finite-difference code FINDIF. In figure 5, a benchmark of these codes for a test geometry (vacuum configuration of W7-X without divertor plates) including the full 3-D metric variations is shown. Very good agreement between the different numerical methods is found.

BoRiS

A computational grid consisting of seven sub-grids has been constructed, thereby reflecting the magnetic field topology of the W7-X stellarator. The different sub-grids represent the different regions of closed magnetic field lines, the plasma core, five magnetic islands and the outer region. These regions/sub-grids have been properly connected with adequate interpolation between them. Heat conduction in W7-X geometry served as a test case for benchmarks with the Monte-Carlo code E3D and the finite-difference code FinDif (see figures 4 and 5).

The flexibility of the BoRiS code was demonstrated by solving incompressible Navier-Stokes problems in different 2D geometries.

Scientific Staff

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Max Planck Junior Research Group "Turbulence in magnetized Plasmas"

Head: Dr. Wolf-Christian Müller

Turbulent convection

Turbulence driven by mean temperature gradients is dynamically important in fusion plasmas as well as in terrestrial and astrophysical systems. Effects of buoyancy forces on nonlinear turbulent dynamics in electrically conducting fluids are studied by means of high-resolution numerical simulations; two-dimensional (2D) as well as three-dimensional (3D). The set of nonlinear magnetohydrodynamic (MHD) equations in Boussinesq approximation is solved on an equidistant Cartesian grid using a previously developed pseudo spectral code.

The nonlinear dynamics of two-dimensional turbulent magnetoconvection is found to depend strongly on the mutual alignment of velocity and magnetic field. The system exhibits quasi-oscillations in time between two regimes of turbulence with different properties. In time intervals of high alignment the inertial range dynamics is strongly influenced by buoyancy and the turbulence can be described by a Bolgiano-Obukhov-like phenomenology. During periods of small correlation of velocity and magnetic field, nonlinear MHD interactions are dominant and buoyancy effects are negligible at inertial scales. This regime can be described by the Iroshnikov-Kraichnan phenomenology. Dynamical alignment is directly related to the cross-helicity, which plays a prominent role in 2D turbulent magneto convection.

Results from a simulation of 3D magnetoconvective turbulence indicate that the investigated system operates in a Kolmogorov-like regime of turbulence and that temperature fluctuations are passively advected by the velocity field. Buoyancy forces are negligible at inertial scales since computational limitations prohibit going to higher Rayleigh numbers. Nevertheless, the often assumed direct and local nature of turbulent spectral transfer could be verified in this case. The level of intermittency of the turbulent vector fields agrees with numerical results of isotropic MHD turbulence.

Lagrangian statistics of turbulence

The Lagrangian viewpoint is particularly suited to investigate the diffusive characteristics of turbulent flows. For the investigations, a fully parallelized pseudo spectral code is employed which has been extended to tracking passive tracer particles. A first comparative study of Navier-Stokes and macroscopically isotropic MHD turbulence has shown that the relative dispersion of passive tracer particles is delayed in the MHD case relative to the Navier-Stokes case due to the influence of the local magnetic field.

To investigate the structure of turbulence Lagrangian structure functions based on numerical data have been analysed. Contrary to the Eulerian structure functions the Lagrangian scaling exponents show a lesser degree of intermittency in the MHD case compared to the Navier-Stokes case. This is explained by the characteristic differences of tracer particle trajectories in the neighbourhood of structures of high dissipation. In the Navier-Stokes case spiralling trajectories around vortex filaments are found whereas in the MHD case the trajectories are V-shaped around vortex sheets. However, even the existence of an inertial range for the Lagrangian structure functions remains an open question. In addition, a code for tracking fluid particles in 2D MHD turbulence has been developed permitting considerably higher Reynolds numbers and therefore a larger inertial range of turbulent fluctuations. A comparison with existing predictions from percolation theory is intended.

Compressible turbulence

Compressible, thermodynamically isothermal hydrodynamic and MHD turbulence is investigated in direct numerical simulations with large-scale forcing using the parallel FLASH finite-difference code which was previously modified to include turbulence-specific enhancements. The studies focus on the dependence of the intermittent turbulent structure on the sonic Mach number. A significant change of topology is found at the transition from subsonic and basically incompressible flow to strongly compressible supersonic turbulence. The increasing importance of dilatational velocity components and the associated emergence of shocks and shocklets in the flow lead to a decreasing prominence of dissipative small-scale structures in favour of large coherent and basically 2D vorticity sheets. The sheets are generated in "collisions" of large-scale fluctuations and evolve dynamically on the long time-scale of the largest eddies. These structures are accompanied by small-scale vortex filaments (hydrodynamic case), micro current- and vortex-sheets (MHD case) as well as shock-fronts of limited extent (shocklets). The major influence of the magnetic field seems to be the change of shape of the small scale structures of solenoidal dissipation (1D-filaments to 2D-sheets) as was shown before in simulations of incompressible MHD turbulence.

Homogeneous MHD turbulence

The investigation of anisotropic cascade dynamics and small-scale structure formation in 3D MHD turbulence with and without a strong mean magnetic field is continued. Special attention is paid to the verification of new phenomenological turbulence models which recently appeared in the aftermath of publications by our group.

Monoscaling of the two-point probability density functions of spatial increments in MHD turbulence has been found for the first time in numerical simulations. This follows the recent finding of such behaviour in the turbulent solar wind. The monoscaling property is shown to be linked to the existence of a cascade process for the respective turbulent field.

Scientific staff

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Helmholtz University Research Group "Theory and ab initio simulation of plasma turbulence"

Head: Priv.-Doz. Dr. Frank Jenko

The main goal of this project (a collaboration with the Institute for Theoretical Physics at the University of Münster) is to attack the important unsolved problem of plasma turbulence in an interdisciplinary way. To this end, we apply and extend ideas from fluid turbulence, nonlinear dynamics, and statistical physics. Spanning a wide range of approaches, from simple analytical models to simulations on massively parallel computers, we strive for a deeper understanding of the fundamental processes in turbulent magnetoplasmas. Beyond this, we hope that this project helps to improve the general dialogue and cross fertilization between plasma physics and the related fields.

Computational gyrokinetics

Much of the work done in this group is based on the nonlinear gyrokinetic code GENE which has been developed over the past years. In the GENE code, the distribution function for each particle species is represented on a fixed grid in phase space. A combination of finite difference and spectral methods is employed to discretise the underlying gyrokinetic equations. The time stepping is done via a higher order explicit Runge-Kutta scheme. The equations solved by GENE have been extended to include the following effects:
(1) fully kinetic ions and electrons [passing and trapped]
(2) beam ion and impurity species [passive and active]
(3) collisional scattering in pitch angle and energy
(4) electromagnetic effects
(5) general toroidal geometry or simple model equilibria.
Moreover, GENE runs on several parallel platforms and has been shown to scale almost linearly up to 4096 processors on a Cray XT3 architecture. It is thus suited for high resolution runs containing most of the physics which is currently considered important for turbulence and transport in the core of magnetised fusion plasmas.

Trapped electron mode turbulence

Inspired by experiments, e.g., at ASDEX Upgrade, we investigated systematically the nature of trapped electron mode turbulence. In particular, we were able to show that the nonlinear saturation of trapped electron modes is not due to zonal flows, but to turbulent decorrelation of the particle trajectories by the perpendicular E×B drift. This effect can be described in the framework of renormalized perturbation theory, yielding dressed test modes which still resemble the corresponding linear microinstabilities but are made neutrally stable by the presence of small-scale turbulent vortices. Based on this result, we were able to establish a close link between direct numerical simulations with the GENE code and a phenomenological transport model which has been used successfully in the past to provide a fast and efficient way to recover key nonlinear results.

Interaction of fast ions with turbulent fluctuations

In future burning plasma experiments like ITER, there will be a sizeable fraction of fast ions in the plasma. Usually, it is assumed that their interaction with the background turbulence is negligible Recent experimental results from ASDEX Upgrade, however, indicate that this common assumption might be wrong. This conjecture is confirmed theoretically by both simple two-dimensional models of passive tracers in turbulent or pseudo-turbulent fields as well as by direct three-dimensional simulations with the GENE code. Using this combination of descriptions, we were able to show that under certain, rather generic conditions, the diffusivities of fast particles resemble those of the main ions. The underlying physical mechanisms could be identified and explained. Extrapolations to ITER are currently underway.

Turbulence and transport in the core of Wendelstein 7-X

We have conducted a gyrokinetic numerical investigation of ion temperature gradient modes – considering both adiabatic and full electron dynamics – and trapped electron modes for the stellarator Wendelstein 7-X. The employed flux tube geometry is based on Clebsch-type coordinates which are generated by a realistic magnetic equilibrium. Linear studies reveal substantial differences with respect to the axisymmetric geometry which can be attributed to the relative separation of regions with a large fraction of helically trapped particles and those of pronounced bad curvature. The effects of both zonal flows and secondary instabilities have been examined as a possible mechanism for the turbulence saturation. The transport levels are found to be rather low.

Non-Gaussian transport in physical systems

The anomalous (i.e. non-Gaussian) dynamics of particles subject to a deterministic acceleration and a series of "random kicks" have been studied. Based on an extension of the concept of continuous time random walks to position-velocity space, a new fractional equation of the Kramers-Fokker-Planck type could be derived. The associated collision operator necessarily involves a fractional substantial derivative, representing important nonlocal couplings in time and space. For the force-free case, a closed solution has been found and discussed. This rather conceptual work is likely to be applicable to such diverse areas as condensed matter physics, biophysics, physical chemistry, astrophysics, and turbulence research.

Scientific Staff

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Helmholtz Junior Research Group "Computational Material Science"

Head: Dr. Ralf Schneider

This research group was initiated together with the physics department of the Ernst-Moritz-Arndt-University Greifswald and is funded by the Helmholtz-Associaton. It was started in 2005. The group studies effects on materials in contact with plasma, either with fusion or low-temperature plasmas. The major objective is the development and application of computational physics tools.

Development of a multi-scale model for the interaction of hydrogen with graphite

On the atomic scale the movement of hydrogen atoms in crystallites is studied using molecular dynamics (MD). Parameterisation of this movement with kinetic Monte Carlo allows a very efficient description of the processes within granules, including trapping and de-trapping and surface diffusion. The transport calculations within the granules can be parameterised as effective diffusion coefficients for the studies of macroscopic processes combining kinetic and diffusive Monte Carlo. These calculations show the effect of the 3D porous structure of graphite on the diffusion of hydrogen: the size of the voids determine mostly the diffusion.
Extending this multi-scale model by including the formation and destruction of hydrogen molecules shows very good agreement with experiments. Temperature and 3D structure (mostly void fraction) determine whether atoms or molecules are formed: at temperatures below 900 K mostly atoms are formed, with higher temperature more and more molecules are re-emitted. This behaviour is drastically affected by the structure (changing of the void fraction).

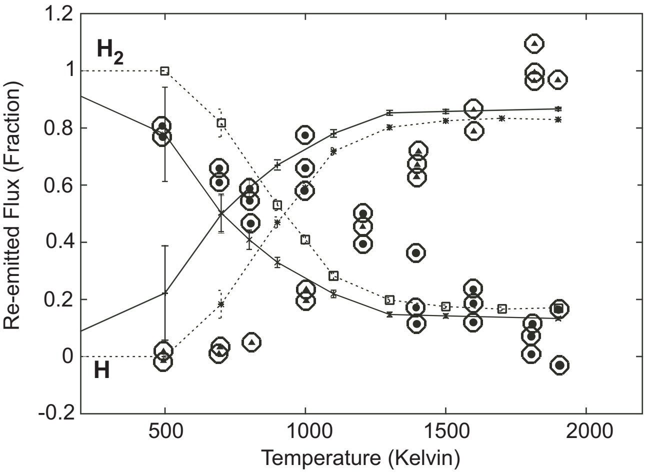

Figure 6: Re-emitted flux of hydrogen atoms and molecules as a function of temperature. Experimental values are shown as symbols, simulation results as lines. For the simulations a 3D porous structure was used with 5% voids and two different trap concentrations.

Atomistic description of the plasma-wall interaction using ab-initio methods

Analysis of hydrocarbons is of interest not only for fusion (co-deposition and chemical erosion), but also in astrophysics (in the interstellar medium and in star formation regions).
To do ab initio molecular dynamics one needs potential energy surfaces of these molecules with high accuracy. This parameterisation is done using a cluster expansion. First results for $C_2H_3^+$ show high accuracy of the fitted potential energy surface with the full quantum calculations and agreement with experimental frequencies within several cm^{-1}.
Using empirical potentials for the interaction of hydrogen and carbon, reflection coefficients of hydrocarbon molecules with a co-deposited hydrocarbon layer were calculated. These data are important for the erosion modelling in fusion using kinetic or fluid models.

Improvement of collisional cascade models

Collisional cascade models are being extended to study 2D and 3D surface structure changes.

Kinetic modelling of complex plasmas

Kinetic modelling of plasmas with PIC (Particle-in-Cell)-methods in close collaborations with experiments at the Ernst-Moritz-Arndt University in Greifswald within the Transregio TR-24 is a key element for accurate plasma description. This method was successfully applied to RF-discharges with oxygen, where the creation of negative ions and the distribution functions within the sheath were studied. The combination of PIC with MD allows the fully self-consistent inclusion of dust particles resolving properly the micro sheath in front of such dust particles and the charging processes. The full dynamics of the RF discharge as well as the dust particles and their interactions are included.

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EURYI Research Group "Zonal Flows"

Head: Dr. Klaus Hallatschek

The start of the research group is planned for the beginning of 2007. Funds for five years from the EURYI Award of ESF/DFG were approved in October 2006. The research will target the impact of the turbulence type, geometry, and higher nonlinearities on zonal flows.

During a Rosenbluth-award supported collaboration with the fusion theory division of General Atomics, San Diego, computational turbulence studies using the GYRO-code[1)] targeting the tokamak edge have been carried out. The gyrokinetic method is geared towards the rather collisionless and weakly turbulent conditions of a tokamak core. A priori, it is not clear whether the approximations inherent in the gyrokinetic approach allow an application to edge regions, because of the relatively large collision rates there, and the rather limited resolution - considering the strong nonlinear interactions in edge turbulence. On the other hand, the approximations on which existing edge fluid codes are based assume even higher collision numbers than are typical for the edge. Earlier fluid results on edge turbulence levels should thus be cross checked with the gyrokinetic code.

Two approaches were pursued. On one hand, comparison runs with GYRO for earlier published ITG mode results from the fluid code were carried out, and on the other, GYRO runs for realistic DIII-D edge parameters and geometry under L and H conditions were carried out, to test the possibility of runs at more extreme conditions.

Comparison of gyrokinetic and fluid turbulence runs

The fluid runs were carried out with NLET (which has been checked in local operating mode to yield transport values identical to PARTURB by A. Zeiler and a fluid code by B. N. Rogers). In the relevant regimes, the dissipation coefficients for magnetic pumping and parallel heat conduction were reduced to account for the collisionless flux limit.

The parameters were in the ITG regime, with s=1, q=4.6, η_i=2.5, ε=0.3, for either core or edge typical conditions with ε_n=0.9 and ε_n=0.085, respectively. The collisionality was varied from zero to values corresponding to a drift parameter α_d=0.1. For adiabatic electrons, reasonable agreement (with respect to the uncertain amount of effective dissipation in the fluid code) between the resulting transport values was observed for all collisionalities.

With kinetic electrons, at higher collision numbers – low α_d<0.3 – there was also rather accurate agreement in turbulence level between the fluid and the gyrokinetic code. At lower collision numbers, α_δ>0.6, the gyrokinetic code produced much higher transport levels than the fluid code, even considering the fact that the collisional dissipation in the fluid equations is adjustable. It is at the present stage not clear whether the difference is a convergence problem in the gyrokinetic setup (due to cost considerations GYRO needs to run with rather low resolution compared to the fluid code), or whether it is an intrinsic kinetic type of turbulence that is missing in the fluid code.

Gyrokinetic runs for realistic edge conditions

Regarding the modelling of nearly transitional discharges with the GYRO-code, the strongest restriction turned out to be due to the fact that realistic L and H-mode conditions in DIII-D are relatively close to the ideal ballooning boundary. Since turbulence codes can necessarily only model a thin region around the relevant flux surfaces, with the ignored plasma volume replaced by artificial boundary conditions, the stability against macroscopic ideal ballooning modes is not represented reliably. In fact, for the H-mode test cases, the code results did not converge for this reason. Lowering β or switching to purely electrostatic dynamics resulted in convergence. Nevertheless, overall the heat diffusivity was found to be a strongly rising monotonous function of the gradients. An intrinsic turbulence mechanism for the L-H-transition at the chosen parameters is thus rather unlikely, in agreement with earlier fluid turbulence runs in the same regime.

[1] *J. Candy, and R. E. Waltz: Journal of Computational Physics* ***186****, 545 (2003).*

Supercomputing and other Research Fields

Computer Center Garching

Head: Dipl.-Inf. Stefan Heinzel

A major task has been the optimization of complex applications from plasma physics, materials science and other disciplines. In data acquisition development, the implementation of the control and data acquisition system of W7-X has been started on a smaller existing system (WEGA) to prepare for pilot runs. For the FP6 EU project DEISA, especially plasma physics and the establishment of a global file system at European scale have been supported.

In the mass storage area, a new automated tape library Sun SL8500 has been installed to replace the old ADIC AML/E library. Both LTO3 and LTO2 tape drives are supported. Nearly 4 PB of compressed data can be stored in the actual configuration of the new system, which can, however, be expanded in the future.

Introduction

The Rechenzentrum Garching (RZG) traditionally provides supercomputing power and archival services for the IPP and other Max Planck Institutes throughout Germany. Besides operation of the systems, application support is given to Max Planck Institutes with high-end computing needs in fusion research, materials science, astrophysics, and other fields. Large amounts of experimental data from the fusion devices of the IPP, satellite data of the MPI for Extraterrestrial Physics (MPE) at the Garching site, and data from supercomputer simulations are administered and stored with high lifetimes. In addition, the RZG provides network and standard services for the IPP and part of the other MPIs at the Garching site. The experimental data acquisition software development group XDV for the W7-X fusion experiment and the current ASDEX Upgrade fusion experiment operates as part of the RZG.

Furthermore, the RZG is engaged in several large projects in collaboration with other, partly international scientific institutions. One of these projects is a bioinformatics project dealing with genome research, another one the ATLAS project, which is part of the LHC experiment of CERN and in which the RZG together with the MPI for Physics, the LRZ and the Physics Department of the LMU forms a Tier2 centre. And finally, the RZG has a leading task in the European DEISA project which is a collaboration of large European high-performance computing centres with the aim to provide infrastructure and resources for a common, distributed high-performance computing network. All these projects are based on new software technologies, especially so-called Grid-Middleware tools. Grid computing is about to become a standard and establishing broad competence in this field will be fruitful for future interdisciplinary collaborations.

Major Hardware Changes

The compute server landscape, essentially consisting of the IBM pSeries 690 based supercomputer, the IBM p575 based cluster of 8-way nodes, and a series of Linux clusters with Intel Xeon and AMD Opteron processors, has been further extended in the area of AMD Opteron based Linux clusters with Infiniband. Besides the generally available systems, dedicated compute servers are operated and maintained for: IPP, Fritz-Haber-Institute, MPI for Astrophysics, MPI for Polymer Research, MPI for Quantum Optics, MPI for Extraterrestrial Physics, MPI for Biochemistry, MPI for Chemical Physics of Solids, MPI for Physics and MPI for Astronomy.

Developments for High-End Computing

The application group of the RZG gives support in the field of high-performance computing. This includes supervising the start-up of new parallel codes, giving advice in case of software and performance problems as well as providing development software for the different platforms. One of the major tasks, however, is the optimization of complex codes from plasma physics, materials sciences and other disciplines on the respective, in general parallel high-performance target architecture. This requires a deep understanding and algorithmic knowledge and is usually done in close collaboration with the users/authors from the respective disciplines. In what follows two selected optimization projects are presented in more detail.

EUTERPE Code

The RZG is giving close support for the Stellarator Theory Division on the subject of gyrokinetic particle-in-cell (PIC) simulations. In 2006, the focus has been on the performance optimization of the EUTERPE code which solves linear electrostatic gyrokinetic equations for ions in full three-dimensional geometry such as for the stellarator W7-X. The code has been originally developed at CRPP-EPFL (Lausanne) and has been further enhanced over the past years at the IPP. However, the code had still two main obstacles, namely a relatively poor single-processor performance of just 230 MFlop/s and a rather small maximum total number of parallel processors of not more than 32 or 64, respectively.

After a detailed measuring of the performance of the code with the performance library "perf" of the RZG, the following steps have been taken. On the one hand, the code was altered to make it more "compiler-friendly" in order to tap the full potential of internal compiler optimizations. On the other hand, modifications on the algorithmic level such as the implementation of a specific sorting of the Monte-Carlo particles to improve the cache efficiency have been done. As a result, the overall MFlop rate has increased by a factor of two. The flowchart of the algorithm could be tightened by using a more flexible communication pattern to distribute the equilibrium data of the VMEC code inside the EUTERPE code. As a result, the number of processors for the domain decomposition could be increased by a factor of two for a typical run. Furthermore, an additional layer of parallelism was introduced into the code by applying the approved "domain cloning" concept for PIC codes. This is a supplement to one-dimensional domain decomposition which gives the opportunity to decouple the "toroidal" grid resolution from the total number of processors used for parallelization. As a result, for the first time the EUTERPE code could be executed efficiently on as much as 512 processors of the "IBM Regatta" of the RZG. Thereby, the weak scaling property of the EUTERPE code showed up to be nearly optimal by achieving an efficiency of 98 % (see figure 1).

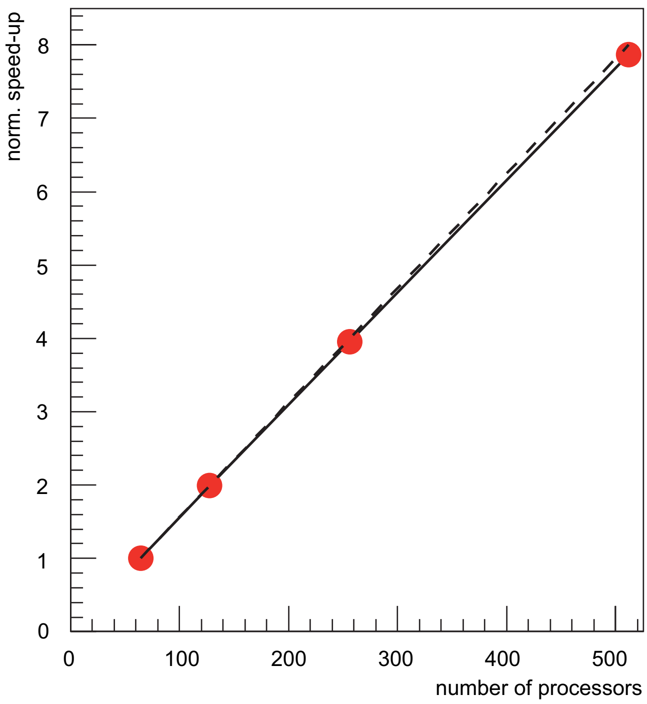

Figure 1: Scaling (weak scaling) of the EUTERPE code (circles) in comparison to optimal scaling (dashed line).

The distributed memory of such a 512-processor job is large enough to use more than one billion (2^{30}) Monte-Carlo particles for the PIC simulation. Thus, it is possible now to gain the necessary particle resolution for nonlinear turbulence simulations in global geometry. Corresponding code modifications to enhance the code from linear to nonlinear simulations are under way.

GENE Code

The GENE code from the IPP plasma theory, department Günter, is a so-called continuum or Vlasov code for turbulence simulations. Nonlinear gyrokinetic equations are solved on a fixed grid in five-dimensional phase space. All differential operators in phase space are discretised by fourth-order (compact) finite differences. GENE can deal with arbitrary toroidal geometry (tokamaks or stellarators) and retains full ion/electron dynamics as well as magnetic field fluctuations. At present, GENE is the only plasma turbulence code in Europe with such capabilities.

The version 9 of the GENE code was limited to 64 as the maximum number of MPI tasks for parallel execution. By this, the efficiency limit of scalability was 256 to 512 CPUs on supercomputers based on large SMPs (with 32 processors in a node), on supercomputers with one processor per node the limit was 64. For future big runs on state-of-the-art supercomputers, a much higher number of supported MPI tasks are required. To achieve this, a new version 10 of the GENE code was developed, in which the y-direction, formerly treated serially, was parallelized via domain decomposition. Consequently, the 2-dimensional FFTs in the xy-plane had also to be carried out in parallel on the decomposed coordinate giving, however, rise to additional, expensive transpositions. To reduce the number of FFTs and with that the number of transpositions in xy-direction a complete restructuring of the code connected with major changes in the overall data structure was carried out in close cooperation with the authors of the code: The principal parts of the calculations in y-direction are now carried out in the k-space and only single quantities are transformed back to the configuration space if required.

With these measures, the limit of 64 parallel processes could be extended by two orders of magnitude. The scalability of the GENE code has been significantly enhanced (see figure 2), so that it can now efficiently be used on up to several thousands of processors. In the GYROKINETICS project of DEISA at IPP e.g., the code now exploits successfully the power of 4096 processors of LRZ's SGI Altix.

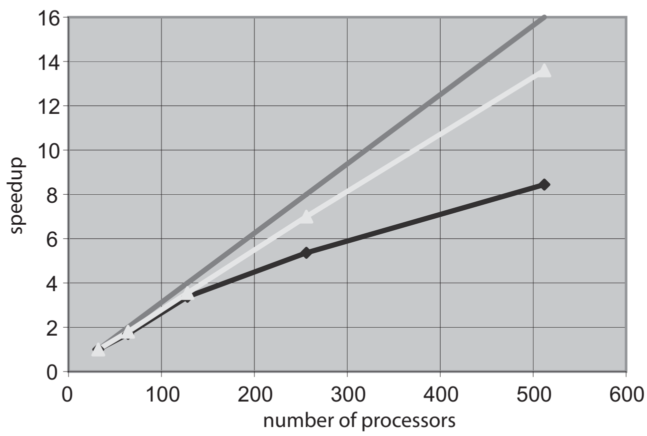

Figure 2: Scalability curves of GENE code for original (circles) and improved code version (triangles), linear scaling: unmarked solid line.

Bioinformatics

In the context of an interdisciplinary consortium joined by several Max Planck Institutes, the RZG has established a soft and hardware infrastructure for computational biology applications called MIGenAS (Max-Planck Integrated Gene Analysis System). The RZG hosts dedicated computing and storage facilities for the consortium, operates various services for project-internal and public use, offers application support on various levels (including participation in research projects), and also contributes original software development. For these tasks, two scientific positions are currently provided by the Max Planck Society.

The core of the MIGenAS platform is comprised of a comprehensive pool of bioinformatics and systems biology software tools together with local copies of the relevant biological databases. The latter need to be automatically updated at least once a week owing to the enormous growth rates of publicly available genomic sequence data. Depending on the type and scale of the project researchers can choose between different entry points – or interfaces – to the platform: Large-scale and high-throughput applications, which are emerging for example from metagenomics projects, are typically performed by direct (batch-)submission of custom-made scripts to RZG's computing facilities. For less data-intensive applications (involving hundreds to thousands of individual tasks or queries) the MIGenAS web toolkit offers a comprehensive and integrated web interface to all relevant tools and data. It allows to seamlessly chain individual tasks into pipelines enabling the biologist to conveniently process complex workflows interactively over the Internet (www.migenas.org) with only a minimum of technical effort.

Initially focusing exclusively on microbial genome research the MIGenAS platform has been substantially extended and generalized in the course of 2006. This, for example, allowed a team of scientists to utilize the MIGenAS infrastructure for conducting high-throughput analyses of ancient DNA which was isolated from a Siberian Mammoth fossil. The corresponding "Science" publication reports on the identification of 13 Millions of base pairs of mammoth DNA plus a huge number of so-called "environmental" genomic sequences from other (mostly microbial) species who shared the Mammoth's habitat. The analysis of the latter provided interesting insights into the bio-diversity of that age.

Videoconferencing (VC)

The VC infrastructure was rather heavily used again in 2006. The Gatekeeper was available on 365 days, with scheduled shut-downs due to power supply work. The number of registered endpoints is ≈250, a plus of 60 % compared to 2005. The number and length of conferences is constantly increasing (12800 connections with 4800 h, which means ≈20 % plus compared to 2005). Conferences with presentation sharing have become standard. The new DFN Codian MCU pushed this even more. Two High-Definition Systems (LifeSize) have been installed, allowing 30 frames/sec and 720 p (720×1280 pixel) resolution over moderate bandwidth (1-2 Mb/sec). A new booking system has been developed and given free in July 2006. So far (January 2007) some 500 bookings of rooms, point-to-point and multi-point conferences have been entered.

Data Networking

IPP's data network infrastructure was planned with a cabling structure in mind that can easily be adapted to future technologies. The network realized is therefore based on the concept of a "collapsed backbone", consisting of high-level switches at a few central locations which directly connect to all endpoints via links based on copper or fibre – eliminating the need of limiting switches at workgroup or story level. This structure greatly enhances overall network performance, for all connections between centralized switches are at a speed of 1 Gigabit/s (Gigabit Ethernet technology) with the option of implementing even more powerful trunks. Due to the availability of both multi-mode and mono-mode fibre optic cables between the premises it is also possible to adopt upcoming new network technologies such as 10 or 40-Gigabit Ethernet. With this structure we also improved security and integrity of data because eavesdropping is almost impossible.

For logical security based on the functionality of the internet protocol suite TCP/IP a packet filter firewall at the access point to the internet (a new Cisco 6509) is implemented, where all the incoming/outgoing packets are checked against a set of blocking or granting rules. Additionally all incoming electronic mail is scanned for viruses and only clean and unobjectionable data (based on known problems) will be passed to the internal network, the rest gets quarantined. Spam mail marking is also active. Based on a level of probability users can define and set filter threshold values at their PCs. In addition, the individual activation of "greylisting" drastically reduces the incoming of unwanted emails.

After having successfully relocated the core node of the German research network X-WiN to the new building, the old building of the computer center was renovated. As frequent reorganizations within the center can be anticipated, a very flexible passive network structure with fixed and hidden loose cables was planned and installed. The active part of the data network will be made up of a state-of-the-art high-performance switch-router Foundry MLX, where all the supercomputer and server nodes get attached with the highest performance available.

Data Acquisition and Data Bases for Plasma Fusion Experiments

The W7-X experiment of the IPP is at the moment under construction in Greifswald. The XDV group at the Computer Centre Garching is responsible for the development of the data acquisition and data storage system for this experiment. This work is done in close cooperation with the experiment control group, the data analysis group as well as the diagnostic and physics department.

Especially the close collaboration between the control group of W7-X and the XDV group leads to a combined design of the data structures used for describing the operation of the experiment. This collaboration was strongly intensified during the course of 2006. The result is now a generally agreed structure for all data describing the configuration of the experiment as well the sequential information necessary to operate the long-running discharge. These data structures are persistent in the object-oriented data base Objectivity, which is commercially available. To guarantee access to this information from all participating stations a TCP/IP portal and a proxy server were developed. This portal allows especially the VxWorks real-time operating systems of the control stations a read-and-write access to the data base.

The data base schema has been extended to allow a more functional description of the experiment and to give the physicists a more simplified view of the necessary definitions of operational parameters. The scheduling of the long discharges of W7-X will be done by predefining operational parameters in segments and scenarios, where a scenario is a fixed sequence of segments with a special physical background. To hide the specialized information contained in the basic parameters from the experiment leader or physicist, an abstraction layer was introduced that only shows physically interesting information. An executable segment will be generated after verifying the consistency of the high-level parameters by using a transformation function for every basic parameter used.

The work on the editor (Confix) for the data structures in the data base was started in 2005 and was further intensified in 2006. At the end of 2006 the basic functionality for dealing with all kinds of objects in the data base are available. The implementation of object life cycles, object states and user access rights on objects was started. Future releases of the editor will extend the functionality to defining and editing of configurations, segments and scenarios in a user-friendly way.

A model for message exchange between all active components of the experiment was developed together with the control group. The standard set of messages to pass control and status information has been defined and message receivers and senders were implemented for PLCs, control stations and data acquisition stations.

The final assembly of the W7-X fusion experiment is delayed to some extent; it was therefore decided in the middle of 2006 to implement the complete control and data acquisition system of W7-X on an already existing and functional older device (WEGA). This gives the opportunity to show and prove the principles of long-pulse control and data taking in a prototype environment. All features like segmented operation, long pulses and continuous data taking and storage as well as using the tools developed for defining operational parameters will be tested. Furthermore, the interaction between all parts of the system, the exchange of messages, the real-time network and its performance as well as the overall performance of the system can be demonstrated. Another important point is the response of the users to tune the tools for handling the system. The work on this prototype has started in the 4th quarter of 2006 and will last for at least another year.

For measuring the magnetic fields of W7-X a new diagnostic has been implemented. This so-called WDIA diagnostic is interesting, because for the first time a user-defined real-time analysis function has been incorporated in the data acquisition software to recover magnetic signals from the raw input data streams in a fast continuous sampling environment. The recovered data is stored in the data base together with the raw input streams.

In cooperation with the analysis group of W7-X we worked on the model of data analysis for a long-pulse experiment, where data and parameters are related by time only. A first application programming interface was defined and implemented to extract data with corresponding parameters and insert analyzed signals into the data base.

Staff

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**IPP Greifswald*

Energy and System Studies

Head: Dr. Thomas Hamacher

As in the year before it is asked for a new, more sustainable energy supply. The problems are manifold: the ongoing political chaos in the Middle East, a new role of Russia as oil and gas supplier with new or better old political ambitions, high electricity and gas prices. System analysis shouldn´t be misunderstood as infallible central planning tool, it should just offer insight and foresight beside the numerous claims of interest groups.

Global Energy Models

The energy system is a global system. Many problems and issues can only be understood on a global level and if technical, political and social problems are combined. A prominent example are speculations about the most recent decrease in the oil price. While Iran and Venezuela would like to cut global oil production to keep the oil price high, Saudi Arabia resists this plans. One explanation is that Saudi Arabia tries to punish Iran for its role in Iraq, especially for the suppression of the Sunnites in Iraq. While it is certainly difficult to prove this example it highlights the complexity of the overall system.

Global Gas Model

While gas is certainly the most handy primary energy carrier for the end-user – at least in stationary applications – it is definitely more expensive to transport and distribute gas than oil, coal and uranium. This is the reason why gas is not traded globally but in four distinct regional markets. To understand the future development of the gas markets and a possible creation of one single world market a special model was designed. The model was made up by two different models: a general global energy model and a special global gas transport model. First results of the analysis are ready and indicate that also in the future not all gas markets will converge. A much stronger role of unconventional gas resources is expected.

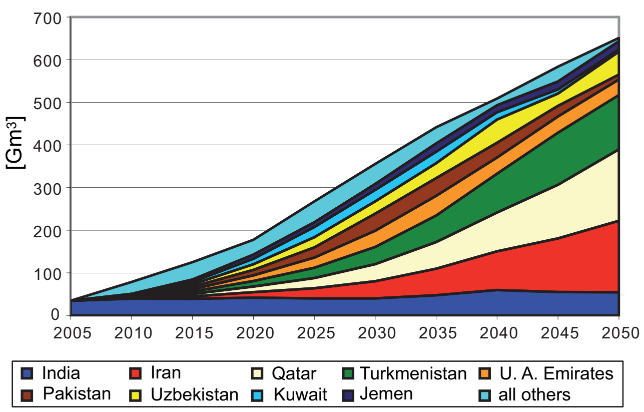

Figure 1: Natural gas supply in India calculated from the ProToG model

EFDA model

The development of the EFDA Times model turns out to be more complex than anticipated in the beginning. This is in parts due to the fact that the software supplied by EFDA did not work in the expected manner. Beside this it turned out that a complete revision of the technology data is necessary and that in parts the structure of the model is well suited for a short term more prognosis type of work, but that it is not suited for long term discussions which are in any case very uncertain. For such a work a more schematic approach seems wise.

The IPP contributed and will contribute in three directions: a better description of the heating sector and a discussion of future global gas markets. Currently the IPP works on a better description of the traffic sector. The special challenge of all these tasks is to represent not only technologies in Western Europe and the US, but in all parts of the world.

Networks

The capacity of individual fusion power plants will be between (1-2) GW. A capacity of this magnitude can only be operated smoothly in a power network of considerable size. In case of an unforeseen failure of the fusion power the remaining power plants need to balance the missing power. If we assume that each individual power plant can not deliver more than (2-5) % of its maximal power, the remaining operating power has to be in the order of (20-100) GW. This is often quoted as an obstacle for the future deployment of fusion, since some people expect for the future that the supply system will be more decentral and the size and strength of the electricity network will decrease. The motivation of this project was to analyse the benefits of an enlarged electricity network. The results indicate that a larger network shows certainly benefits in many aspects. Less expensive peak power needs to be supplied, the demand curve is smoother and renewable technologies can be easier integrated into the network. Certainly integration of fusion power into a European-Russian electricity network is without any problem.

Urban Energy Systems

Urban energy systems remained to be one focus of the group for energy and system studies. The part of the global population living in cities is now bigger than the rural population and a strong push for further urbanisation is expected in the decades to come. These urban areas are hot spots of energy demand which can in most cases not be supplied just by local sources. The whole architecture of the energy system is challenged by these systems. In contrast urban areas offer a unique opportunity to optimise demand and supply in a holistic approach.

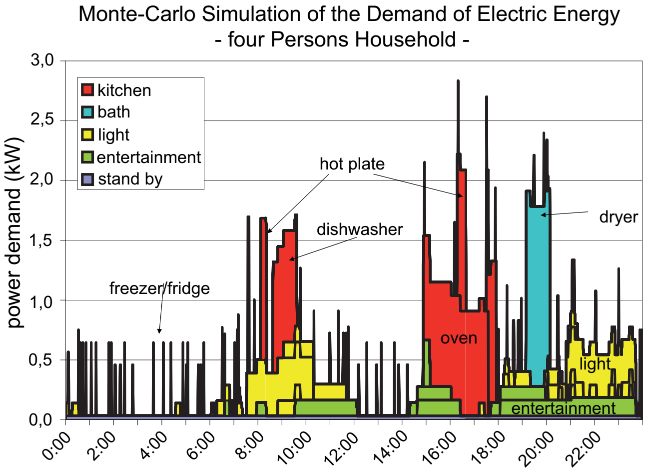

Figure 2: The electricity demand of a typical household. The picture shows the result of a Monte Carlo programme to simulate household demand patterns. A detailed knowledge of the pattern is necessary to analyse the performance of small combined heat and power plants.

ESCOBALT

ESCOBALT is a INTEREG IIIB project which tries to spread the idea of Corporate Social Responsibility (CSR) to energy companies and the energy field in general. The IPP developed greenhouse gas emission balances which can in the future be used to monitor emission targets of municipalities or city utilities. One result was a CO_2-emission report for the city of Grevesmühlen in Mecklenburg-Vorpommern.

The Vienna Project

The Project with the city and city utility Wienstrom in Vienna was successfully finished in the year 2006. The background of the project was the EU directive on energy savings. The project tried to identify measures necessary to fulfil the directive within Vienna and possible impacts of these measures on the city utility. The results indicate that a reduction of the overall energy demand can not be achieved in the next years, but a reduction of the increase seems possible.

The measures indicated by the project partners were ratified by the Vienna city council and will be applied in the next years.

Ungerhausen

A new project was launched to understand the possibilities to supply a village with local energies, especially bioenergy. The background is to become a better understanding of real bioenergy potentials and to discuss in parallel the opportunities for rural areas to develop a new income opportunity. In the project a very detailed mapping of the available land is done and combined with another detailed analysis of the local energy demands.

Greifswald

The IPP tries to develop together with the city of Greifswald a programme to reduce greenhouse gases. Due to various reasons the process turned out to be much more complex than anticipated in the beginning. Especially the city administration has no contact person who is at least part time responsible for the programme. First signals from the city administration indicate that this will change in the future.

Energy and Economy

Energy is one of the central production factors for modern economies. This is only partly reflected in the energy prices. The total expenditure on energy of modern economies is in the range of (5-10) %. A review of different theories and analysis of historical data was performed. The work was done in cooperation with the University of Augsburg and the EASAC.

Cooperations with Universities

The group of energy and system studies has strong links with the university of Augsburg here especially with the chair of plasma physics and the Wissenschaftszentrum Umwelt (WZU). In Greifswald the group cooperates with institutes in the geography department. Also a cooperation with the Fachhochschule Stralsund exists.

With the WZU a study about the energy supply of mountain huts was performed. The work focused on the life time of batteries. The lifetime depends strongly in the battery treatment.

In a diploma thesis with the university of Greifswald a model of the German energy system was designed. The model is based in the model generator TIMES. In the cooperation with the Fachhochschule Stralsund a diploma thesis investigated the possible conflicts between combined heat and power and wind energy. The investigation was done for the city of Greifswald. It is rather likely that in future electricity from off-shore wind parks will come on land close to Greifswald, beside this Greifswald has a large district heating network.

Acknowledgement

The group for energy and system studies likes to thank the Schiedel-Stiftung for financial support of the guest scientist.

Scientific Staff

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Electron Spectroscopy

Head: PD Dr. Uwe Hergenhahn

Photoelectron spectroscopy is a valuable tool for the investigation of fusion relevant materials. As an extension to conventional electron spectroscopy techniques, we have developed in recent years a set-up for coincident detection of two electrons emitted in the same ionization event. The gain of state-dependent information by this method is demonstrated here, using inner shell ionization of small molecules as an example.

Photoelectron – Auger electron coincidence measurements

Auger spectroscopy is widely used as an element-specific probe in material science. More information, e.g. about potential curves of the final state and about dynamics in the intermediate state, is contained in principle in the Auger spectrum, but is difficult to extract because the number of dicationic final states is typically large, and because an Auger spectrum, conventionally recorded, is composed of a convolution of all accessible intermediate states. A technique that can overcome this natural barrier is two electron coincidence spectroscopy. In the last two years, we have greatly improved our coincidence spectroscopy apparatus based on an in-house design. After this preparatory work we were able to record the coincident emission probability for inner shell photoelectron-Auger electron pairs for several small molecules with good statistics and unprecedented energy resolution. An example recorded in 2006 is shown in figure 1.

The instrumental broadening for these data corresponds to 200 and 300 meV for the photoelectron and the Auger electron, respectively. At that resolution, the vibrational structure in the dicationic X state (the least energetic singlet state of CO^{2+}) can be clearly resolved around an Auger energy of 255 eV. For the B state, transitions between pairs of vibrationally resolved intermediate and final states are clearly separated as well.

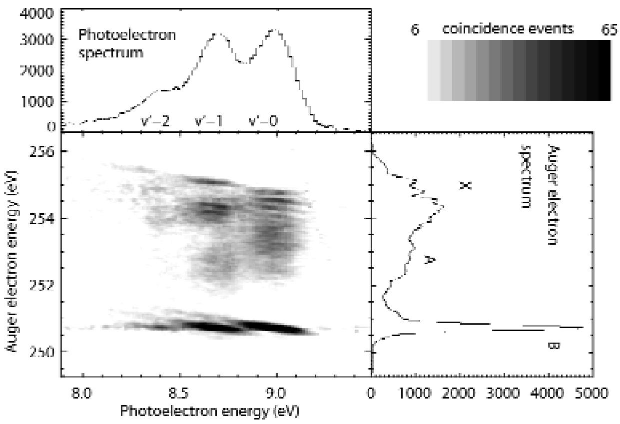

Figure 1: Intensity map of photoelectron-Auger electron pairs for C 1s ionization of carbon monoxide. The ionization energy was set to 305 eV. The joint emission probability for each combination of kinetic energies of the two electrons detected in coincidence is presented in the two-dimensional map. Spectra shown in the top and righthand panel pertain to summation over all Auger electron energies or all photoelectron energies, respectively, and agree with non-coincident spectra presented in the literature.

As they appear at practically identical Auger energy, it can be concluded that the potential curves of both states are parallel. In the carbon monoxide example discussed so far, the intermediate state (CO^{+} $C1s^{-1}$) is bound, and the final states of CO^{2+} shown here possess local minima in their potential curves as well (although asymptotically they are dissociative). A different regime of coincident photo + Auger emission is shown in figure 2, which shows the coincident two-electron intensity for F 1s ionization of CF_4.

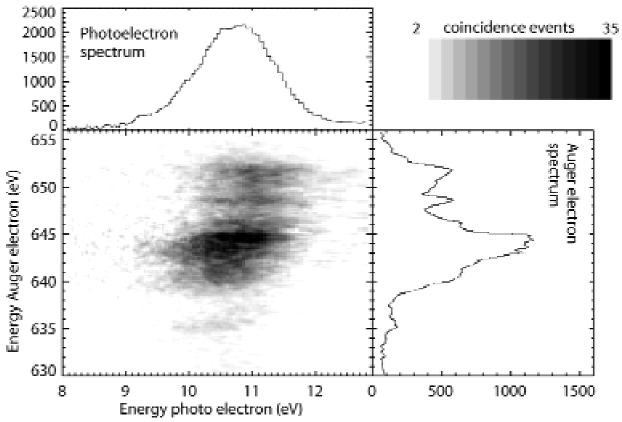

Figure 2: Intensity map of photoelectron-Auger electron pairs for F 1s ionization of carbon tetrafluoride.

The intermediate state thus reached is strictly dissociative, and no vibrational structure is observed in the F 1s photoelectron spectrum. Nevertheless, strong propensity rules seem to exist that allow the population of most Auger final states only at certain energies of the photoelectron. This behaviour can be seen as the analogue to the "core hole clock" effect in resonant Auger decay, where the time dependence of the decay within the lifetime of the core hole is well established.

Cluster electron spectroscopy

Our source for water clusters was greatly improved with respect to the degree of condensation by changing to a more extended, conical nozzle. This allowed the valence photoelectron spectrum of water clusters for different mean cluster sizes to be recorded, and to follow the energy shift for the least strongly bound peak as a function of cluster size.

Scientific Staff

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University Contributions to IPP Programme

Cooperation with Universities

Author: Dr. Axel Kampke

Many important goals in plasma physics and materials science have to be met on the way to a fusion power plant. Since this process will last another generation, IPP attaches great importance to the training of young scientists. The close interaction with the universities in teaching and research is therefore an important part of the mission of IPP. It has also borne fruit in recent years. Moreover, the joint projects, which exist with several universities, form an integral part of the IPP research programme.

Since fusion-relevant physics and engineering are not the most prevalent subjects in Germany's academic landscape, sparking student's interest in high-energy plasma physics and other fusion-relevant fields is a duty and delight. Teaching at universities therefore has a sound tradition at IPP. In 2006 there were 147 contact hours at German universities and 6 contact hours in neighbouring countries (table 1).

Univertsity	Contact hours
Augsburg	23
Bayreuth	27
Berlin, HU	16
Bochum	7
Greifswald	21
Munich, LMU	4
Munich, TUM	28
Tübingen	4
Ulm	17
Ghent	2
Padua	2
SCK/CEN	2

Table 1: Number of contact hours – 153 in total – served at universities by IPP staff in 2006

Lecturing at universities is supplemented by the IPP's "Summer University in Plasma Physics": one week of lectures given by IPP staff and lecturers from partner institutes providing detailed tuition in nuclear fusion. For this the 21st time 65 students enrolled at Garching in 2006 – more than 55 per cent from abroad.

The international character of fusion research is also reflected in the countries of origin of graduate students at IPP: A third of the postgraduates and half of the postdocs are from abroad, half of them from Central and Eastern Europe (table 2).

In addition IPP uses specific instruments developed by the Max Planck Society, the Helmholtz Association and the Deutsche Forschungsgemeinschaft (DFG) for more intensive networking with universities on a constitutional basis:

- the "International Max Planck Research School on Bounded Plasmas" at Greifswald in cooperation with Greifswald University,
- a "Helmholtz Virtual Institute" together with the Universities of Stuttgart and Karlsruhe and Karlsruhe Research Centre,
- two "Helmholtz Young Investigators Groups" – "Computer-aided Materials Sciences", headed by Dr. Ralf Schneider, and "Theory and Ab Initio Simulation of Plasma Turbulence", headed by Dr. Frank Jenko – in cooperation with the Universities of Münster and Greifswald, respectively,
- participation in the DFG Collaborative Research Centre Transregio 24, "Fundamentals of Complex Plasmas", at Greifswald University.

In 2006 IPP was successful within the "Excellence Initiative" of the German government. The proposals for "Munich Centre for Advanced Photonics" and "Origin and Structure of the Universe" – both in cooperation with LMU and TUM – were accepted as "Clusters of Excellence", the latter to be located at IPP.
As another highlight Dr. Klaus Hallatschek won a "European Young Investigator Award" for his work in the field of plasma turbulence. The prize money of one million euros gives him the opportunity to set up his own young investigators group.

Country	Postgraduates	Postdocs
Austria		1
Canada	1	
Czech Republic	1	
France		1
Georgia		1
Germany	28	13
Greece		1
India	3	
Italy	1	1
Kazakhstan	1	
New Zealand	1	1
Poland	2	
Romania		1
Russia		2
Spain		1
Ukraine	2	3

Table 2: Countries of origin of the 40 postgraduates and 26 postdocs at IPP

University of Augsburg
Lehrstuhl für Experimentelle Plasmaphysik

Head: Prof. Dr. Kurt Behringer

The fields of research are focused on development and application of diagnostic methods for low temperature plasma physics, negative ion sources, and plasma edge physics. The work is carried out in close collaboration with several divisions of the Max-Planck-Institut für Plasmaphysik.

Low Temperature Plasmas

In order to use the non-invasive optical emission spectroscopy (OES) as a simple standard diagnostic tool in hydrogen plasmas, the analysis methods should be benchmarked in a wide parameter range. Therefore, different diagnostic techniques such as microwave interferometry, Langmuir probe and double probe were applied together with OES in low temperature plasmas. To compare line integrated signals with local probe measurements, a specially designed, spatially homogeneous ECR plasma was used with electron densities from 1×10^{16} to 5×10^{18} m^{-3} and temperatures from 1.5 to 10 eV. The electron energy distribution function (EEDF) was measured directly by the Langmuir probe using the Boyd-Twiddy modulation technique. The EEDFs are Maxwellian in good agreement with results of the conventional Langmuir probe technique (second derivative of the V/I characteristic).

Using an absolutely calibrated spectroscopic system and using effective rate coefficients from collisional radiative models (ADAS, YACORA), the degree of dissociation, the electron temperature, and the electron density can be determined from the measured line emission. For these investigations, argon and helium were added as additional diagnostic gas to the hydrogen plasma (5%Ar/95%He).

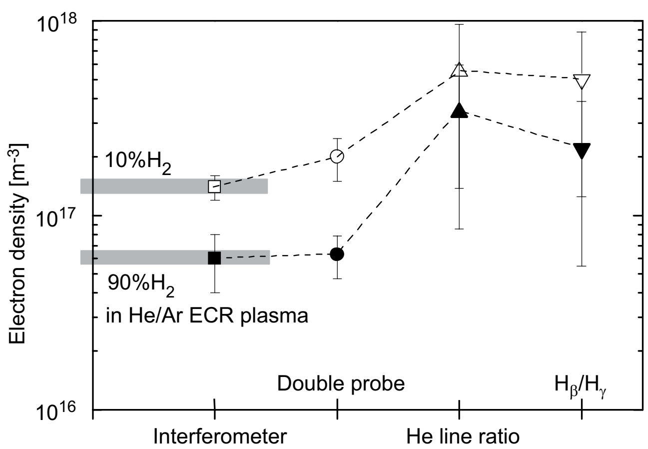

Figure 1: Comparison of different diagnostic methods for the determination of n_e in hydrogen plasmas at 0.5 Pa

In figure 1 the electron densities of 10 % and 90 % hydrogen in He/Ar ECR plasmas were determined by interferometry as the most reliable method. The results of the double probe are in good agreement with interferometry, whereas the line ratio methods, i.e. the He line ratio (singlet system 667/728 nm) and the Balmer line ratio (H_β/H_γ) show higher densities. Since the line ratio methods starts to be sensitive above several 10^{17} m^{-3}, the uncertainty is quite high. Detailed studies have started with focus on Balmer line emission in hydrogen and deuterium plasmas in a wide parameter range of power and pressure.

Negative Ion Sources

The diagnostic methods for hydrogen plasmas, developed and proven in the University laboratory, are being used as standard diagnostic tools for the high power RF ion sources at IPP, i.e. the negative hydrogen ion source testbeds for neutral beam injection systems. Besides determination of plasma parameters with optical emission spectroscopy (e.g. diploma thesis S. Riegg), cavity ringdown spectroscopy (see PhD thesis M. Berger) and laser detachment are now routinely used for determining negative hydrogen ion densities. Clear correlations with extracted negative ion current densities are obtained in hydrogen and deuterium plasmas, allowing for extrapolations to expected current densities in testbeds without extraction system, where only negative ion densities are measured. Systematic studies of plasma homogeneity (diploma thesis S. Hilbert) indicate a plasma asymmetry, i.e. close to the extraction grid more Balmer line intensity is observed in the upper half of the plasma than in the lower half. The dependencies on the amount of negative ions, on the strength of the magnetic filter field and on the applied bias voltage indicate an $E\times B$ drift, where the electrical field in the complex plasma sheath plays a dominant role.

The experimental investigations are accompanied by modelling (diploma thesis R. Gutser). One of the topics was the calculation of the extraction probabilities of negative ions starting at the plasma grid. Using the real 3D geometry of the plasma grid, the extraction probability was calculated to be 20 %, depending slightly on the starting energy of the particles. About 40 % are lost by particle collisions and by collisions with the surface of the plasma grid. Systematic parameter studies are the basis for optimisation of the grid geometry. A second task deals with the simulation of the extracted beam using a commercial code (Kobra3D), which was adapted to the geometry of the present extraction system including the magnetic field structure. Trajectories of extracted negative ions and electrons have been calculated for relevant parameters (applied potentials, experimentally achieved current densities, perveance), showing clearly the correlation between the shape of the meniscus at the plasma boundary and the beam profile. The electrons, which should be forced to flow into specially designed pockets by permanent magnets in the extraction grid, hit the surface of the extraction grid;

a fact observed experimentally by melting traces in these areas. The code has also been applied to an optimisation of Faraday cups, which are needed for local extraction at the large testbed RADI being presently without extraction system. Figure 2 shows the trajectories of negative deuterium ions and electrons with the plasma grid (aperture:A1) on ground potential, the extraction grid (A2) and the cup (A3) on high potential. In order to prevent backstreaming of secondary electrons created in the cup, a negative bias is applied to the additional aperture A4. Similarly to the situation mentioned above, the extracted electrons hit the surface of the extraction grid (A2). The beam itself is slightly shifted downwards, however, flow into the cup is ensured in a wide parameter range. On the basis of these optimisations, the Faraday cup is now in the construction phase and will be tested on RADI in summer 2007.

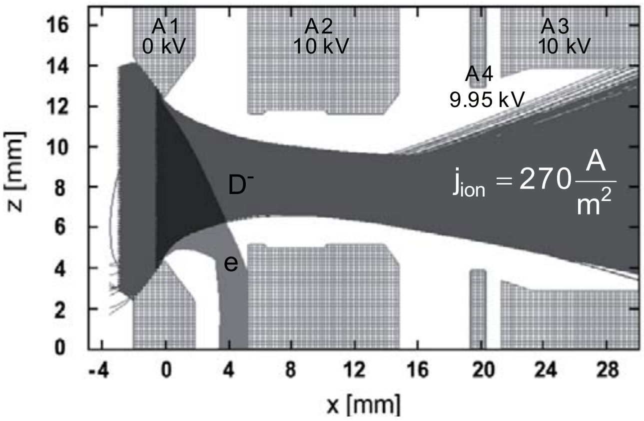

Figure 2: Negative ion (D-) and electron trajectories in an optimised Faraday Cup for local extraction at the IPP testbed RADI

Plasma Surface Interaction Studies

The work on chemical erosion of different carbon materials has now focused on doped materials. Doping of carbon (for example with various carbides) leads to a reduction of the effective carbon surface area and thus a reduced erosion yield. In strong cooperation with the materials research group of IPP, titanium-doped carbon fibre composite materials (CFC) and amorphous carbon films with atomically disperse titanium distribution (a-C:Ti) were investigated in low pressure hydrogen plasmas (ICP discharges). For both materials the concentration of the dopand has been varied. The incident ion flux towards the surface was measured using an energy resolved mass spectrometer in combination with a Langmuir probe. The absolute value of the carbon flux was determined by weight loss; time resolution was achieved by measuring the CH and C_2 band emission. Hence, fluence resolved erosion yields were obtained. For the CFC materials, the yields show only a weak decrease with fluence and a weak dependence on the dopand concentration due to particle and matrix loss. As expected, the erosion yields shows an isotope effect of roughly a factor 1.3 between deuterium and hydrogen. The erosion yields of the a-C:Ti films strongly depend on the titanium concentration and the fluence. With increasing dopand concentration the process of carbidization of the whole surface (proved by AFM measurements) accelerates. Thus the resulting yields reach values below 0.5 %, which is the detection limit of the diagnostic system. Figure 3 shows the results for a surface temperature of 300 K and incident ion energy of 30 eV in deuterium plasmas.

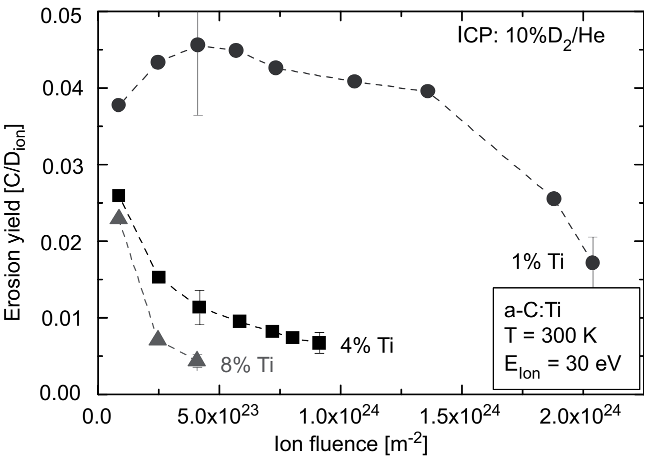

Figure 3: Erosion yields of amorphous carbon films with atomic disperse distribution of titanium (different concentrations of the dopand) in deuterium plasmas

Diploma and PhD Theses

Berger, M.: Cavity-Ringdown-Spektroskopie an Wasserstoff-Niederdruckplasmen. (PhD)

Gutser, R.: Rechnungen zur Extraktion von negativen Wasserstoffionen aus einem HF Plasma. (Diploma)

Hilbert, S.: Messungen zur Plasmahomogenität großer HF angeregter Ionenquellen. (Diploma)

Riegg, S.: Erste Messungen von Plasmaparametern mit optischer Emissionsspektroskopie in Quellen für negative Ionen (H-,D-). (Diploma)

Scientific Staff

U. Fantz, P. Starke, M. Berger, S. Dietrich, R. Gutser, S. Hilbert, S. Riegg, T. Wunderlich, S. Baur, F. Botzenhart, J. Herrmann.

University of Bayreuth
Lehrstuhl für Experimentalphysik III

Head: Prof. Dr. Jürgen Küppers

Elementary reactions of hydrogen atoms with adsorbates and solid surfaces

Cooperation between IPP and the University of Bayreuth is concentrated on investigating fusion-relevant plasma-wall interaction processes. Accordingly, the hydrogen atom surface chemistry on possible reactor wall materials is the primary research topic.

A considerable fraction of the species impinging on the first wall of a fusion experimental vessel are neutrals and ions in the energy range below a kinetic energy of about 10 eV. These particles are not capable of causing physical sputtering, but can induce several processes, such as chemical erosion, abstraction etc, which contaminate the plasma. Since low-energy ions are neutralised in the immediate vicinity of a substrate by resonance neutralisation, it is sufficient to study the low-energy atom-surface interaction. For experimental reasons, the present work utilised only thermal atoms with energies in the range of a few tenth of an eV.

The interaction of thermal H atoms with the basal plane of graphite, C(0001), leads to H adsorption in a bonding scheme which is unique and only observed on that surface, the C_{gr}-H bond. Unlike the sp^n C-H bonds, eg sp^3 C-H in CH_4, methane, sp^2 C-H in C_2H_4, ethene, sp C-H in C_2H_2, ethyne, the C_{gr}-H bond is relatively weak, only 0.7 eV binding energy, and requires an activation energy (0.3 eV) for its formation. This activation energy is needed for lifting the C atom to which H eventually binds by about 0.4 Å out of the basal plane.

Intuitively one expects that lifting of a C atom affects the geometrical arrangement of the neighboring C in such a way that a "hill" occurs with the center C atom on the hill top providing the adsorption site for H. If this expectation is correct, the sticking coefficient of H on graphite should increase with increasing coverage at very small coverages – which was confirmed experimentally – and H atoms should display clustering on the surface.

Scanning tunneling microscopy (STM) is currently the only technique which is capable to monitor arrangements of atoms on a surface with sub-nm resolution and, as we have shown recently, STM is capable to monitor H or D on graphite via bright dots in height profiles. As the thermal desorption spectrum in figure 1 illustrates, at extremely small coverages, due to the lack of neighbors, adsorbed D desorb as atoms. At higher, but still small coverage the STM profile in figure 2 shows small adsorbed D clusters of various types on an otherwise uncovered surface.

Upon close inspection of figure 2 one observes that the distances between adsorbed D atoms are not random multiples of a C-C distance but exhibit regular features. For example, ortho-pairs – nearest neighbour pairs – exist, but meta-pairs – NN neighbour pairs – do not. Even if D atoms located in different C rings are considered, there is a selection for allowed D-D distances apparent from figure 2: clustering occurs not random.

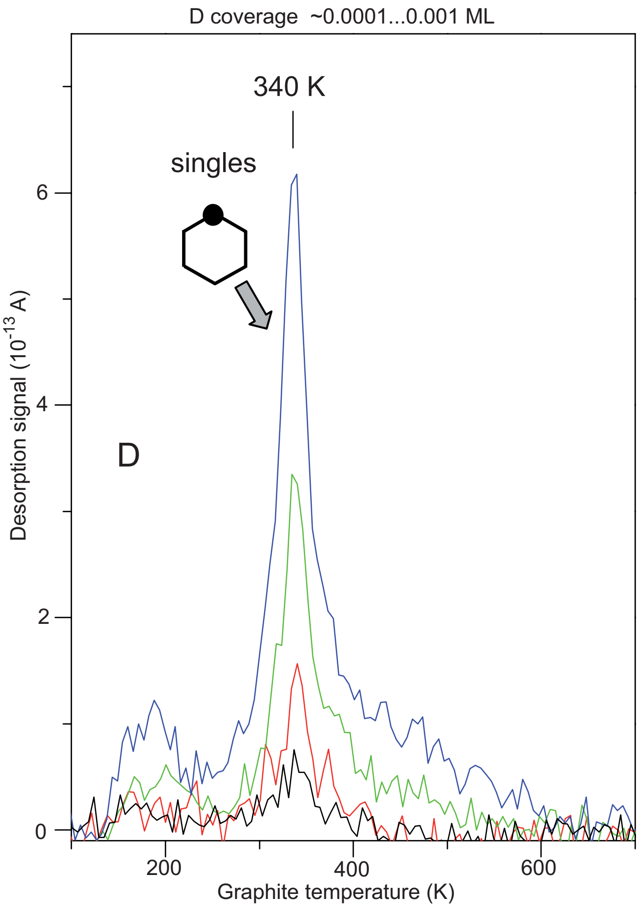

Figure1: Deuterium atoms thermal desorption spectra of D coverages between 0.0001 and 0.001 monolayers on graphite (HOPG) surfaces

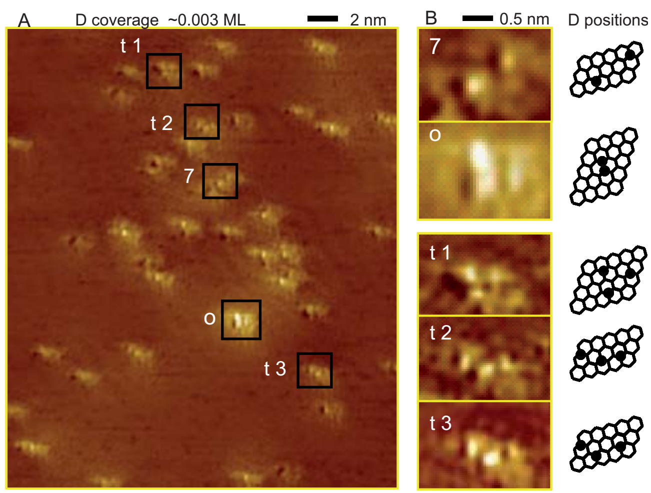

Figure 2: Scanning tunneling microscopy profile of graphite covered with D at 0.003 monolayers with detailed cluster geometries

The TD spectra shown in figure 3 correspond to the coverage regime of 0.001 to 0.02 monolayers. D_2 molecules desorb recombinatively from different cluster configurations. The STM profile in figure 4 displays the clustering phenomenon at even higher coverage, 0.03 monolayers. Note the atomic resolution of the underlying graphite lattice seen on the patches of the bare surface.

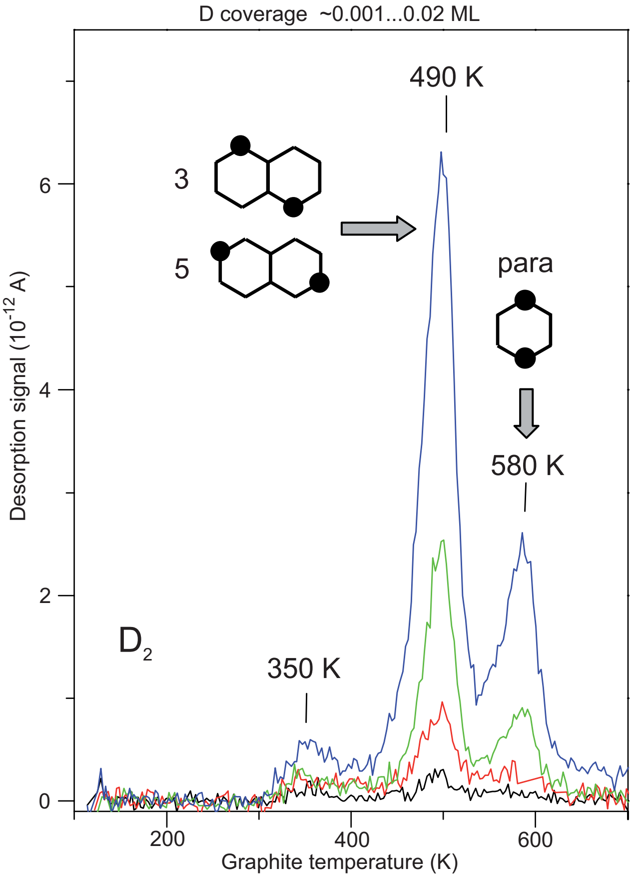

Figure 3: Deuterium molecules thermal desorption spectra of D coverages between 0.001 and 0.02 monolayers on graphite (HOPG) surfaces

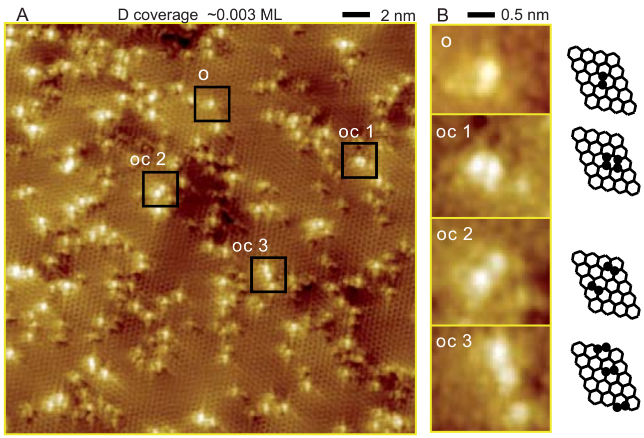

Figure 4: Scanning tunneling microscopy profile of graphite covered with D at 0.03 monolayers with detailed cluster geometries

The combination of the STM and desorption data shown above confirm the expectation that D atoms cluster on the graphite surface. Furthermore, the variety of cluster geometries apparent in STM explains why the structure of the desorption spectra is so complex which is unexpected for covalently bonded species on a surface with a simple surface geometry.

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A. Andree, M. Le Lay, T. Zecho, and J. Küppers: Pair formation and clustering of D on the basal plane of graphite. Chemical Physics Letters. 425, 99 (2006).

P. Hoffmann, S. Wehner, D. Schmeisser, H. R. Brand, and J. Küppers: Noise-induced spatiotemporal patterns in a bistable reaction-diffusion system: Photoelectron emission microscopy experiments and modeling of the CO oxidation reaction on Ir(111). Physical Review E 7305, 6123 (2006).

S. Wehner, P. Hoffmann, D. Schmeisser, H. R. Brand, and J. Küppers: The consequences of anisotropic diffusion and noise: PEEM at the CO oxidation reaction on stepped Ir(111) surfaces. Chemical Physics Letters. 423, 39 (2006).

Conference contributions

S. Baouche, G. Gamborg, T. Zecho, V. V. Petrunin, L. Hornekaer, A. C. Luntz, T. Kuzuya, and A. Baurichter: Adsorption and desorption dynamics of hydrogen on HOPG graphite. Symposium on Surface Science 2006 (3S'06), St. Christoph am Arlberg, Austria, March 5-11, 2006.

S. Baouche, V. V. Petrunin, A. C. Luntz, T. Zecho, L. Hornekaer, and A. Baurichter: Dynamics of Hydrogen interacting with Graphite Surfaces.The International Conference on Carbon (Carbon 2006), Aberdeen, Scotland, July 20, 2006.

T. Zecho, A. Andree, M. Le Lay, and J. Küppers: Identification of adsorption structures of D on the basal plane of graphite.24th European Conference on Surface Science (ECOSS 24), Paris, France, September 4-8, 2006.

Seminars

T. Zecho: Chemical reactions of thermal hydrogen atoms with graphite surfaces. Seminar, Materials Research Division, MPI for Plasmaphysics, Garching, Germany, September 28, 2006.

T. Zecho: Chemical reactions of thermal hydrogen atoms with graphite surfaces. Seminar, FOM Rijuhiuzen, Nieuwegein, Netherlands, November 30, 2006.

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The plasma physics group at the Humboldt University operates the plasma generator PSI-2 and an electron beam ion trap (EBIT). The research activities comprise basic plasma physics, plasma-material interactions and highly charged ion processes relevant to present and future fusion test devices. Further effort is dedicated to the study of plasmoids produced on water surfaces at atmospheric pressure.

PSI-2 Plasma Generator

In 2006, the following topics were covered by the PSI-2 group: (i) Generation and decomposition of hydrocarbons. In the framework of a collaboration with the EFDA group in Garching, the process of decomposition of hydrocarbons (CH_4, C_2H_6 and C_2H_4 gas) injected into the PSI-2 plasma was investigated. The decomposition products were measured with high spatial resolution by optical emission spectroscopy. As a general observation we found that the decomposition of the hydrocarbons to CH_x radicals proceeds on path lengths that are much shorter than those predicted by theoretical calculations. The decomposition path lengths are calculated using cross sections listed in the atomic data package by Janev and Reiter. In order to identify ion-induced processes as contributing to hydrocarbon decomposition, further measurements were made in which the nozzle of the gas injector was biased with respect to ground potential. Operation with positive bias voltage shifts the CH emission away from the nozzle compared to the case without biasing. This suggests that the hydrocarbon decomposition is not only an electron-induced process, but is also influenced by the presence of ions.

(ii) Shadow phenomena in magnetized plasmas. This item is connected with the question of how, and at what rate, charged particles are displaced perpendicularly to a magnetic field. Although shadows in magnetized plasmas are a well-known phenomenon and can be seen when, for instance, a Langmuir probe is inserted into the plasma column of the PSI-2 generator (see Annual Report 2004) the underlying physics is still largely unclear. Using Langmuir probes and different plasma spectroscopic techniques, a survey of electron temperature and density behind diaphragms of various shapes could be conducted. Particularly significant in these measurements was the conservation of the hollow density profile in the non-shadowed plasma region. The density in the plasma halo was found to decrease slowly as a function of radial distance. To provide an explanation for the density distributions in the shadowed and non-shadowed regions, modelling calculations were carried out with a newly developed transport model that takes volume ionisation into account. The measured profiles could be best described by relying on $D \approx 1.6\ m^2\ s^{-1}$ for the perpendicular diffusion coefficient. This D value is larger than the classical diffusion coefficient by a factor of 100. The reason for this large enhancement of D is so far not fully understood and we are investigating this topic further.

(iii) Plasma flow in front of a target. Earlier investigation of the flow behaviour of plasmas in contact with a material surface was complemented. Information about the flow behaviour is essential for the interpretation of probe measurements, but it is also of great relevance for nuclear fusion plasmas in contact with limiters or divertor plates. Using a modulated CW diode laser and an improved optical detection system, we have measured the ion velocity distribution function (ivdf) of Ar^+ ions by scanning the narrow band width laser radiation over the excitation threshold of a metastable argon level while observing the intensity of fluorescence light perpendicular to the excitation beam as a function of wavelength. Compared to our first measurements of the ivdf (see Annual Report 2003), the spatial resolution of the present experiment was enhanced by a factor of 100 to $\Delta z \sim 0.5$ mm. Figure 1 shows distribution functions obtained at eight different intervals from the target. Since an absolute wavelength calibration of the spectrometer was not available at the time of going to press, the ivdf is plotted as a function of relative velocities. With the absolute wavelength calibration, a statement about the streaming velocity and the shape of the distribution function at the sheath edge will be possible.

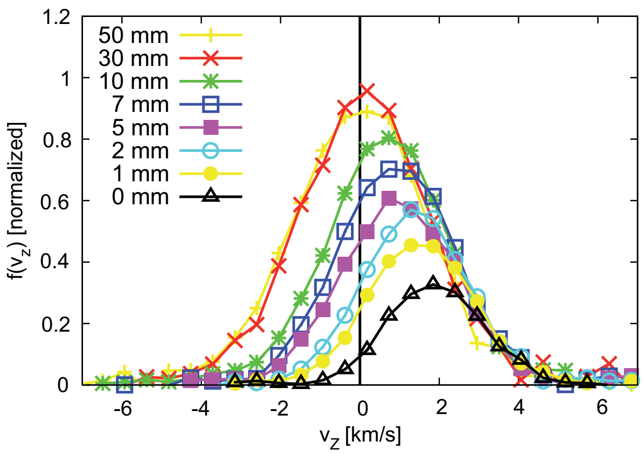

Figure 1: Ion velocity distribution function at certain distances from the target

Electron Beam Ion Trap (EBIT)

Research at EBIT focussed on x-ray spectroscopy of charge exchange (CX) reactions between highly charged Ar^{q+} ions (q=17, 18) and neutral argon atoms. Charge exchange is a significant contributor to line radiation in the x-ray range and has become an area of increased interest in the fields of astrophysics and controlled nuclear fusion. In the experiment, highly charged argon ions were extracted from the EBIT and directed via a deceleration setup onto a gas target where the x-rays emitted following charge exchange collisions were detected (see Annual Report 2005). The deceleration setup was used to retard the extracted ions (from 5000q down to 10q eV) and gain control over the angular momentum-sensitive capture in CX collisions. In the CX interaction of $Ar^{17+, 18+}$ ions with argon atoms, electron capture into Rydberg states with n=8 dominates. The highly excited ions relax by cascading transitions of the electron down to ground energy thereby producing a relaxation spectrum with x-ray lines in the energy range from 3 to 4.5 keV. This spectrum is particularly important since it provides a measure of how ion relaxation is divided into different radiative decay paths. From this information one can infer the probability of capturing electrons into high-n levels with either low (one-step decay) or high (multi-step decay) angular momentum ℓ.

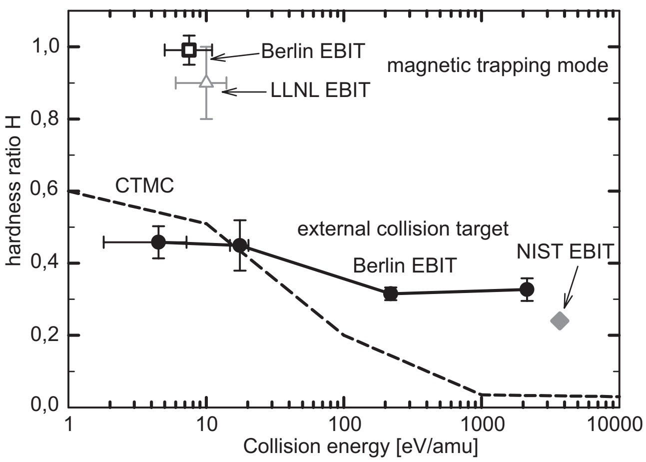

Figure 2: Hardness ratios for capture to Ar^{18+} ions as a function of collision energy. Solid shapes represent extraction measurements. Hollow shapes represent the results for charge exchange in magnetic trapping experiments. Measurements from other groups are labelled. The dashed line represents a calculation using the classical trajectory Monte Carlo (CTMC) method.

The data from the CX measurements can be summarized by calculating hardness ratios, defined as the ratio of x-rays from $n\geq3\rightarrow1$ to $n=2\rightarrow1$ transitions. The resulting hardness values are plotted as a function of collision energy in figure 2. A larger hardness ratio indicates electron capture into a lower angular momentum state. This is because high energy decay directly to the ground state is more accessible to electrons captured into lower ℓ states, whereas electrons captured into higher ℓ states favour decay in Δn=-1 and $\Delta\ell$=-1 steps. From the data points for the extraction experiments it can be seen that hardness ratios increase with decreasing collision velocity. This shows that electrons are transferred into progressively lower ℓ states as would also be expected from consideration of angular momentum conservation. In addition to the data points for the extraction experiment, figure 2 presents results for Ar^{18+}/Ar charge exchange from magnetic trapping experiments. In this in situ investigation EBIT's electron beam is switched off periodically for 20 s during which the EBIT operates as a Penning trap. There, trapping conditions limit the collision energy to a small but undetermined value. The hardness ratios for CX in magnetic trapping mode are much larger than any of those measured in the extraction experiments or predicted by the CTMC calculations. This suggests a significant difference in the population mechanism and/or the relaxation process for high-n capture states in the EBIT environment versus the controlled conditions of an external gas target experiment.

Study of Plasmoids at Atmospheric Pressure

Luminous plasmoids with diameters of about 0.2 m and a lifetime of up to 0.3 s are produced by high voltage discharges across a water surface. To this end, a capacitor bank charged to 5 kV is switched to a central electrode that is surrounded by a ceramic tube and protrudes from the water surface. The counter electrode is placed at the bottom of the water-filled vessel. Figure 3a shows as an example a discharge 15 ms after ignition at a current of 70 A. Some milliseconds later, a plasmoid develops that ascends with a velocity of 1-2 m/s. It continues to radiate even when the current is shut off (figure 3b). The plasmoid has a sharp boundary and emits luminous jets as can be seen in the image of figure 3b. To study the physical nature of that autonomously long living object spectroscopic and probe measurements are in progress. So far, calorimetric data on the discharge as a whole have been obtained.

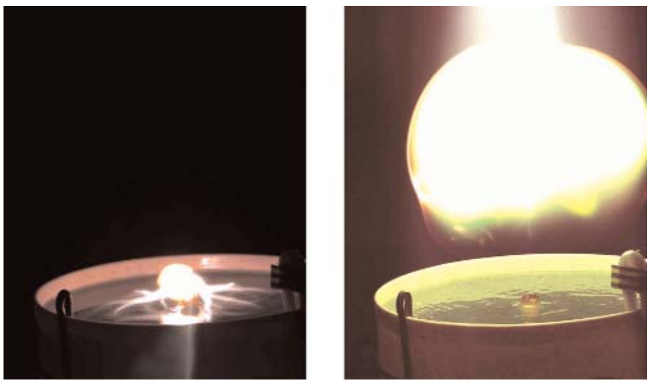

Figure 3: (a) Water discharge 15 ms after ignition. (b) Plasmoid 30 ms after current zero

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The joint program between IPF and IPP on ECRH systems for ASDEX Upgrade, W7-X, and ITER can be found on the respective pages of this annual report. The part of the program carried out at IPF are the development of new mm-wave components and investigations of plasma waves and turbulent transport. Experiments are carried out on the torsatron TJ-K, which is operated with a magnetically confined low-temperature plasma.

Investigations of microwave material properties in a three-mirror resonator configuration

The three-mirror resonator configuration for measurements of different material samples was further improved. The technique is based on the comparison of the quality factor of a 2-mirror reference resonator with the quality factor of a 3-mirror resonator, which has identical dimensions and includes the sample to be tested. The resonator measurement equipment (sample holders, resonator for curved samples and for simultaneous E- and H-plane measurements) was optimized. It is now ready for detailed investigations as i) the microwave-specific characterization of the in-vessel components for future fusion experiments (W7X and ITER), ii) the characterization of plasma-exposed mirror samples to enlarge the data base on ohmic losses of launcher mirrors and iii) the characterization with respect to absorption and reflection of microwaves as well as ohmic damping due of parts used in transmission-line components like mitre-bend mirrors, corrugated waveguide walls.

Experiments with a narrowband waveguide diplexer

In the framework of the FADIS-project (development of a FAst DIrectional Switch, see also 6.1.5), a waveguide diplexer based on the Mach-Zehnder interferometer and the Talbot effect in rectangular waveguides was investigated. The numerical calculations resulted in an efficiency of more than 99 % (see IPP annual report 2005). A prototype was build using recycled parts from a remote-steering launcher mock up, and measurements were done. Figure 1 shows the output fields at 2 different frequencies. The results confirm the basic principle of frequency controlled switching. However, the mode purity is only about 80 % for both output channels. This value is confirmed by transmission measurements yielding losses in the main mode in the order of 18 %. Optimizations of this design would include more precise machining of the waveguide parts, which is mandatory for interferometric devices, as well as improvements of the mitre-bends and other optical components.

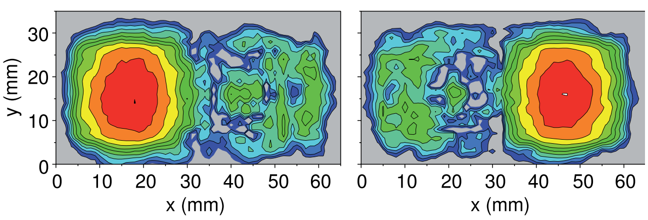

Figure 1: Output field of the diplexer at 140.735 GHz (left image) and 140.650 GHz (right image)

Simulation of reflectometry measurements

The Finite-Difference-Time-Domain code for wave propagation (IPF-FD3D) has been further improved. The code works now on one, two, or three dimensional grids. Wave propagation can be simulated in magnetised and unmagnetised plasmas, in materials with arbitrary ε and μ, and in metamaterials. The code can be used as well to model components for microwave applications as dense plasma, which allows the investigation of Ohmic losses. The major applications of the code for IPP are in the Doppler reflectometry on ASDEX Upgrade. To this end, 2D simulations of Doppler reflectometry were undertaken for different incident angles and plasma turbulence strengths. The goal is to find dependencies of received power and Doppler spectrum on these parameters. This is especially important for measuring the turbulent wave number spectrum, since this can only be achieved by varying the incident angle of the reflectometer beam. A preliminary investigation in slab geometry has been completed, and runs with ASDEX Upgrade geometry and plasma parameters are starting in 2007.

ECRH in over-dense plasmas

Heating plasmas by means of microwaves is a widespread tool in both fusion relevant and process plasmas. In the torsatron TJ-K, low-temperature plasmas are investigated in which the absorption coefficient at the cyclotron resonance is low. Possible heating scenarios are the absorption at the upper-hybrid (UH) resonance or the coupling to the Bernstein wave through OXB-conversion. The investigation of the heating process in TJ-K has been extended to two frequencies, 2.45 and 8.25 GHz. At 2.45 GHz the density saturates at a heating power of about 3 kW. Electron-temperature profiles are hollow and both cutoff and the UH layer are located at the plasma-edge. This indicates that the UH layer plays an important role in the heating process. This is further supported by measurements of the wave-electrical field, which has a maximum at the UH-layer.

The IPF-FD3D code was used to calculate the wave field inside a cylinder in the presence of an over-dense plasma. In figure 2, the rms-value of the electric field is plotted in the poloidal cut of TJ-K. A Gaussian density profile was used. The field enhancement at the plasma-boundary, where the UH-resonance is located, can be clearly seen. Using different antenna designs, improved heating in the plasma centre was obtained, which could point also to a contribution of the Bernstein wave in the heating process.

3D structure of plasma edge turbulence

For the first time, the parallel dynamics of turbulence has been studied in the plasma core. A finite parallel wavenumber of turbulent structures has been identified. As required for drift-wave turbulence, their parallel extension, which is about 15 m, is much larger than the perpendicular one of typically only 7 cm. The measured parallel velocity of the structures was found to be between the ion-sound and the Alfvén velocity. Five different and independently measured quantities, namely the parallel and perpendicular wavenumbers $k_{\|}$ and $k_{\perp}$, the displacement $d_{\perp}$ of the structure from the field line accumulated within the connection length L_c, and the drift parameter ρ_s could be combined for a comparison with the drift-wave dispersion relation. The characteristic parameter $d_{\perp}/\rho_s k_{\|} L_c$ agrees well with the value from the full dispersion relation, and lies below the one expected if the Alfvénic dynamics is neglected. Hence this is a first experimental evidence of the importance of the coupling of drift wave turbulence to the Alfvén wave. Using the GEM3 turbulence code, excellent quantitative agreement with the simulations has been obtained.

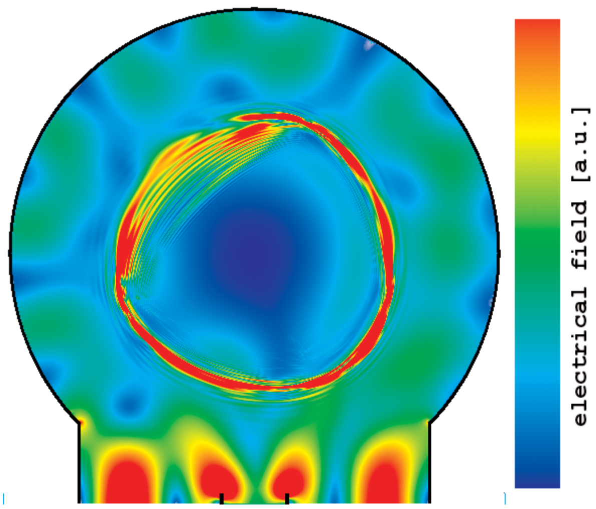

Figure 2: Contour plot of the microwave electrical field in the torus with over-dense plasma

The turbulent cascade

The investigation of the turbulent energy cascade has been continued using bispectral methods developed by Ritz et al. and Kim et al., which base on the model of three-wave interaction. Both methods are compared for capability and accuracy by a well known turbulence model, the two-dimensional Hasegawa-Wakatani equations. General properties of the Hasegawa-Wakatani turbulence are recovered, as the analytically known growth rate, dispersion relation, and the direction of the energy transfer. The growth rates and dispersion relations from an helium discharge in TJ-K shows a great structural similarity to those of the Hasegawa-Wakatani turbulence. This is consistent with the previous result that drift-waves are the driving instability for the turbulence in TJ-K. The density fluctuations, which are advected by the vorticity as a passive scalar, show free energy transfer in direction of smaller scales, while the E×B energy of the potential fluctuations is transferred as an inverse cascade to larger scales. This can be seen as experimental evidence on the dual cascade in magnetized plasma turbulence.

Plasma biasing experiments

The influence of strong poloidal E×B shear flows on the spatio-temporal structure of turbulence has been investigated in TJ-K. Strong shear flows were generated by core plasma biasing. Calculations of the particle flux from a particle balance have shown that during biasing, the particle confinement is improved by a factor of about 2.5. At the same time, the correlation lengths of turbulent density structures, as measured with an 8×8 probe array, increased. The poloidal structure of density fluctuations was measured with a poloidal probe array. It was shown that the poloidal mode structure changes from $m=4$ in the unbiased to $m=3$ in the biased state. This mode was found to become dominant even though strong shear was present. A low-frequency mode with signatures of the shear-driven Kelvin-Helmholtz instability was also detected. The enhanced particle confinement is understood as a consequence of changes in the cross-phase, by which the observed coherent large-scale structure causes inward transport.

Turbulent magnetic fluctuations

Next to electrostatic fluctuations, magnetic fluctuations are important for the investigations of plasma turbulence. To measure the magnetic component, a highly sensitive magnetic probe has been developed. The probe was aligned inside the plasma to measure the radial component of the magnetic fluctuations δB_r. The magnetic fluctuations turn out to be about 4-5 orders of magnitude smaller than the electrostatic ones and the magnetic contribution to the turbulent transport is negligible. However, the measured fluctuations are in good agreement with GEM3 simulations and are a clear hint to the parallel currents related to drift-wave turbulence. Furthermore, the β dependence of the magnetic fluctuation spectrum has been investigated. Theory predicts a scaling of the normalized magnetic fluctuations with respect to the electrostatic ones as $(\delta B/B_0)/\beta \sim e\delta\phi/T_e \sim \delta n/n$. A strong decrease of the measured magnetic fluctuations with increasing B_0 has been observed. The drop is a factor of 4 stronger than in the simulations.

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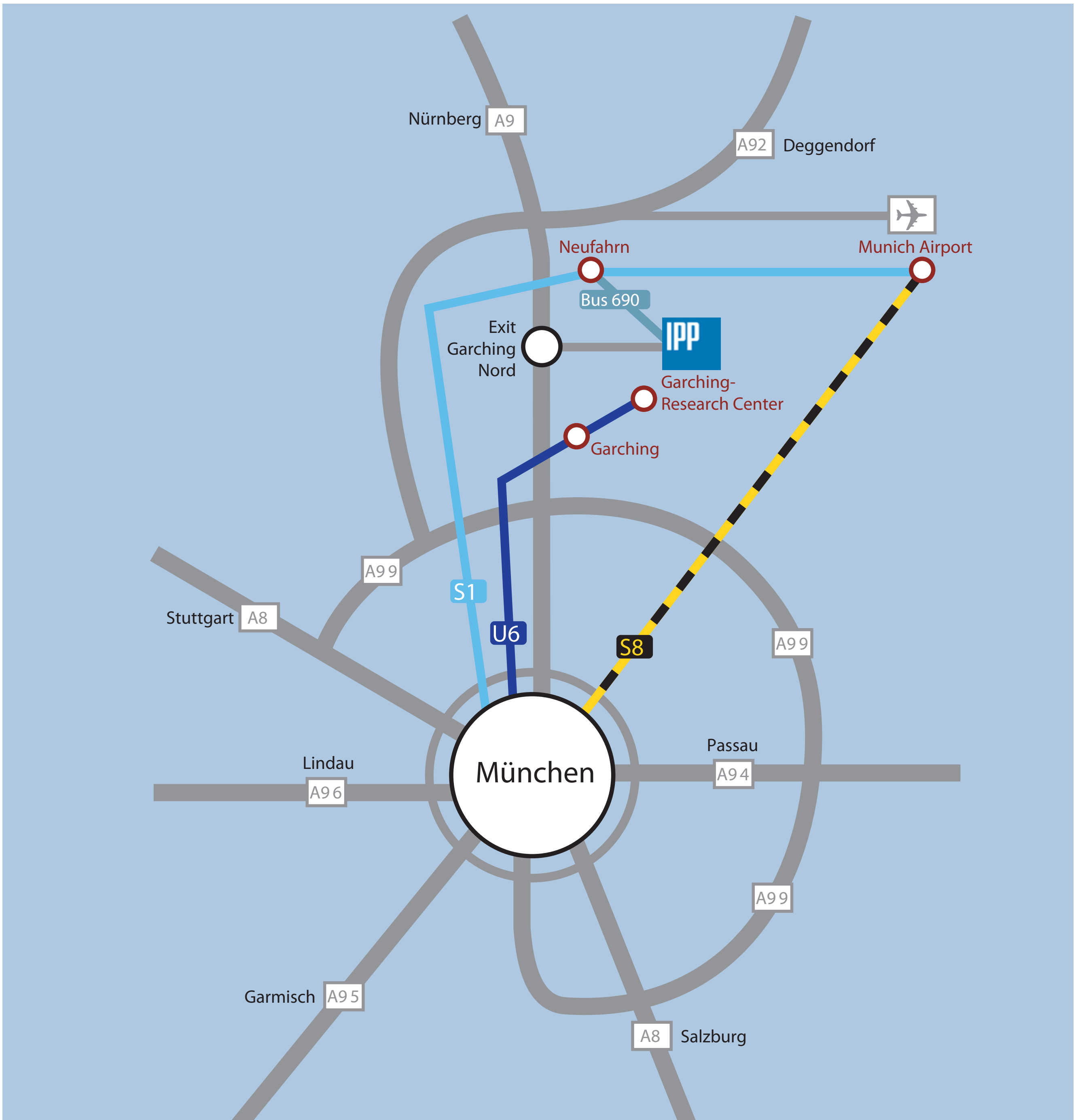
Appendix

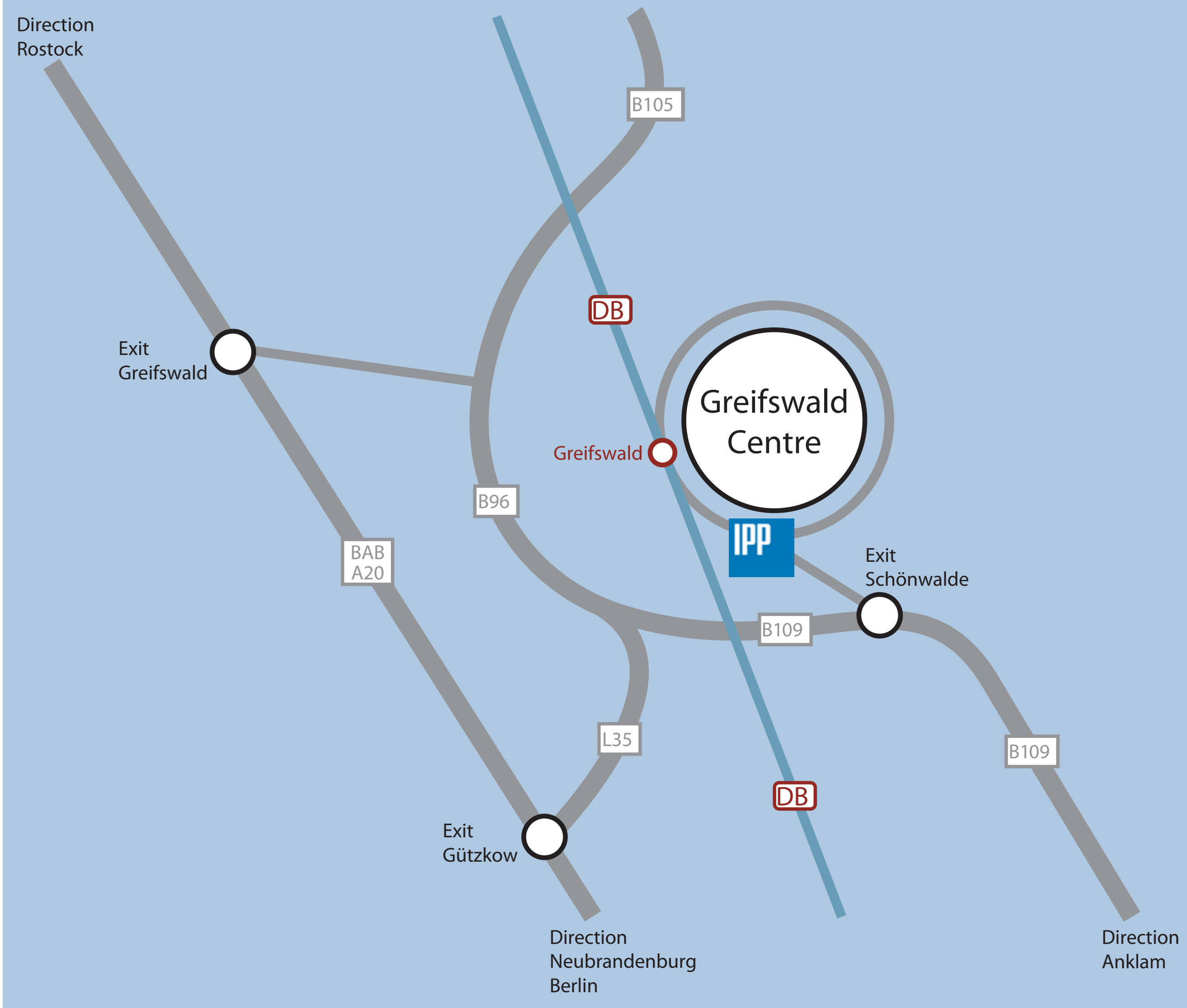
How to reach IPP in Garching



By car:
Exit Garching-Nord on the
Autobahn A9 München-Nürnberg,
then follow the signs “Forschungsinstitute”.

By public transport:
Any S metro from Munich Main Station to Marienplatz,
metro U6 to Garching-Forschungszentrum;
or from Airport Munich: S1 to Neufahrn, then bus 690
to "Garching Forschungszentrum" (only on weekdays).

How to reach Greifswald Branch Institute of IPP

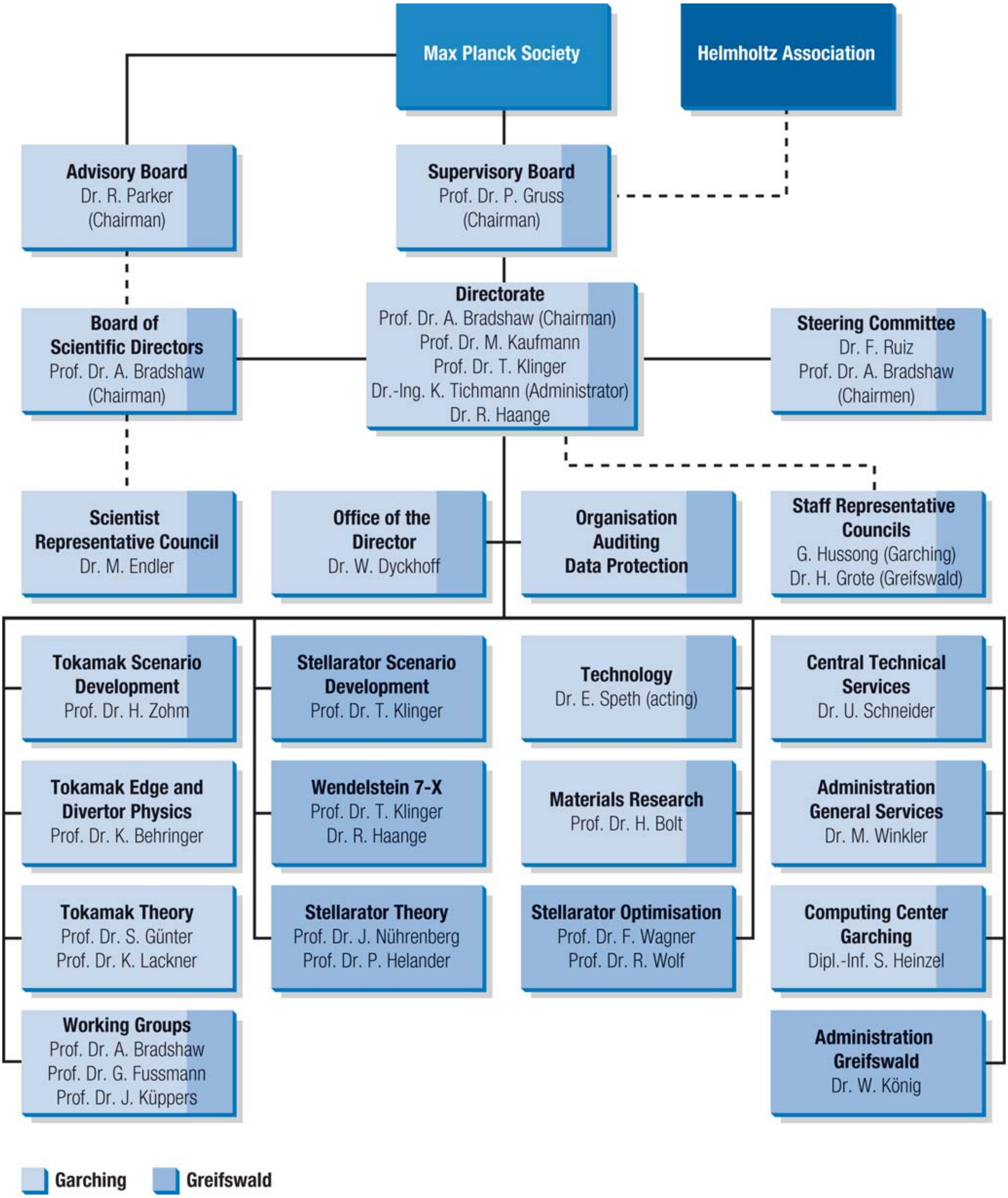


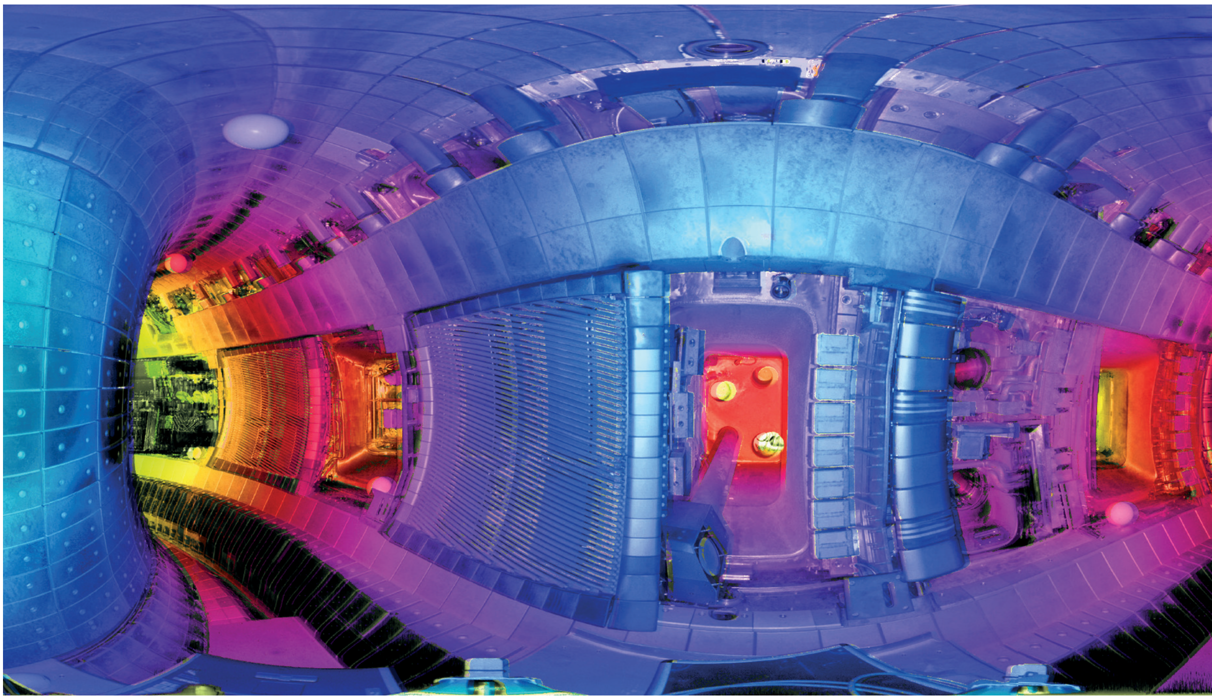
By air and train:
Via Berlin: from Berlin Tegel Airport by bus “JetExpressBus” to Hauptbahnhof (central station), by train to Greifswald.
Via Hamburg: from the airport to main Railway Station, by train to Greifswald main station.

By bus:
From Greifswald-Railway Station by bus No. 2 or 3 to the “Elisenpark” stop.

By car:
Via Berlin, Neubrandenburg to Greifswald **or** via Hamburg, Lübeck, Stralsund to Greifswald, in Greifswald follow the signs “Max-Planck-Institut”.

Organisational structure of Max-Planck-Institut für Plasmaphysik





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