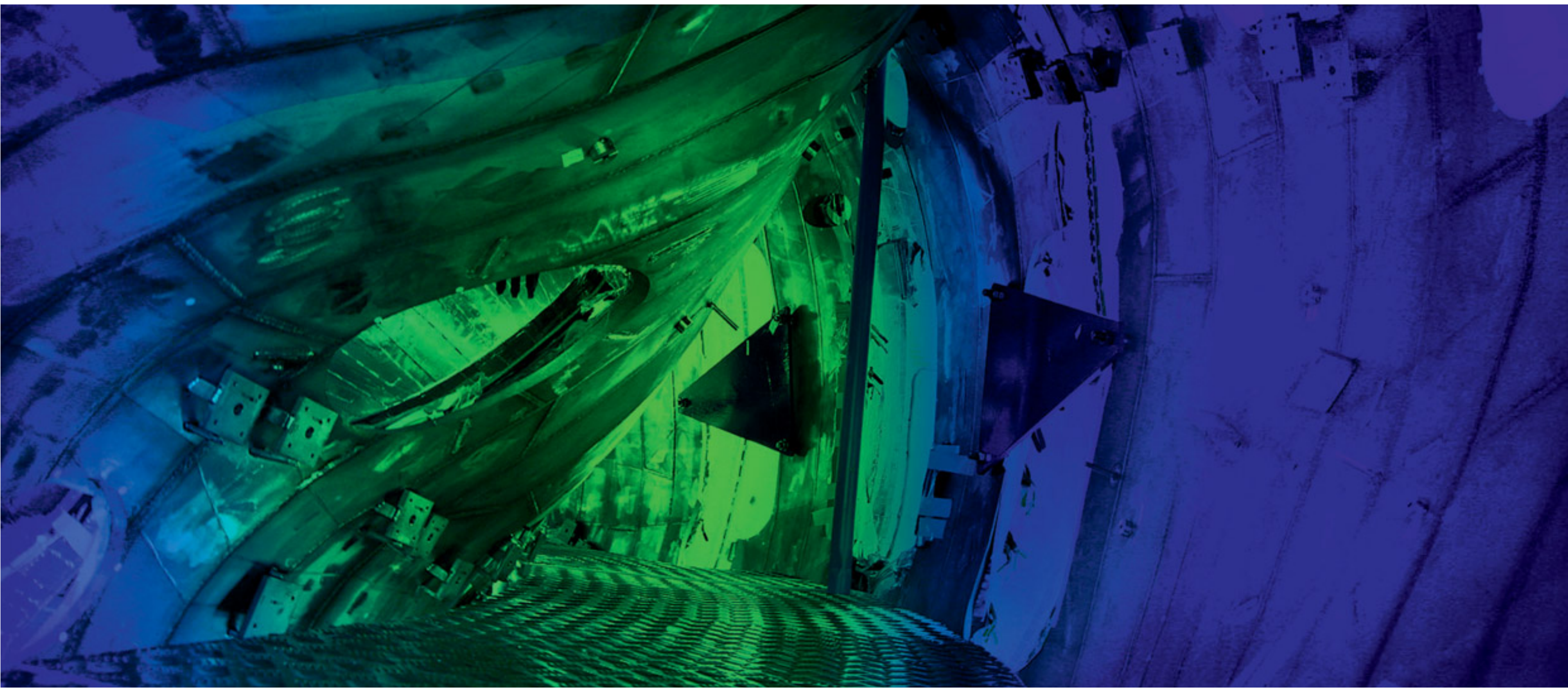
Max-Planck-Institut
für Plasmaphysik

Annual Report 2009



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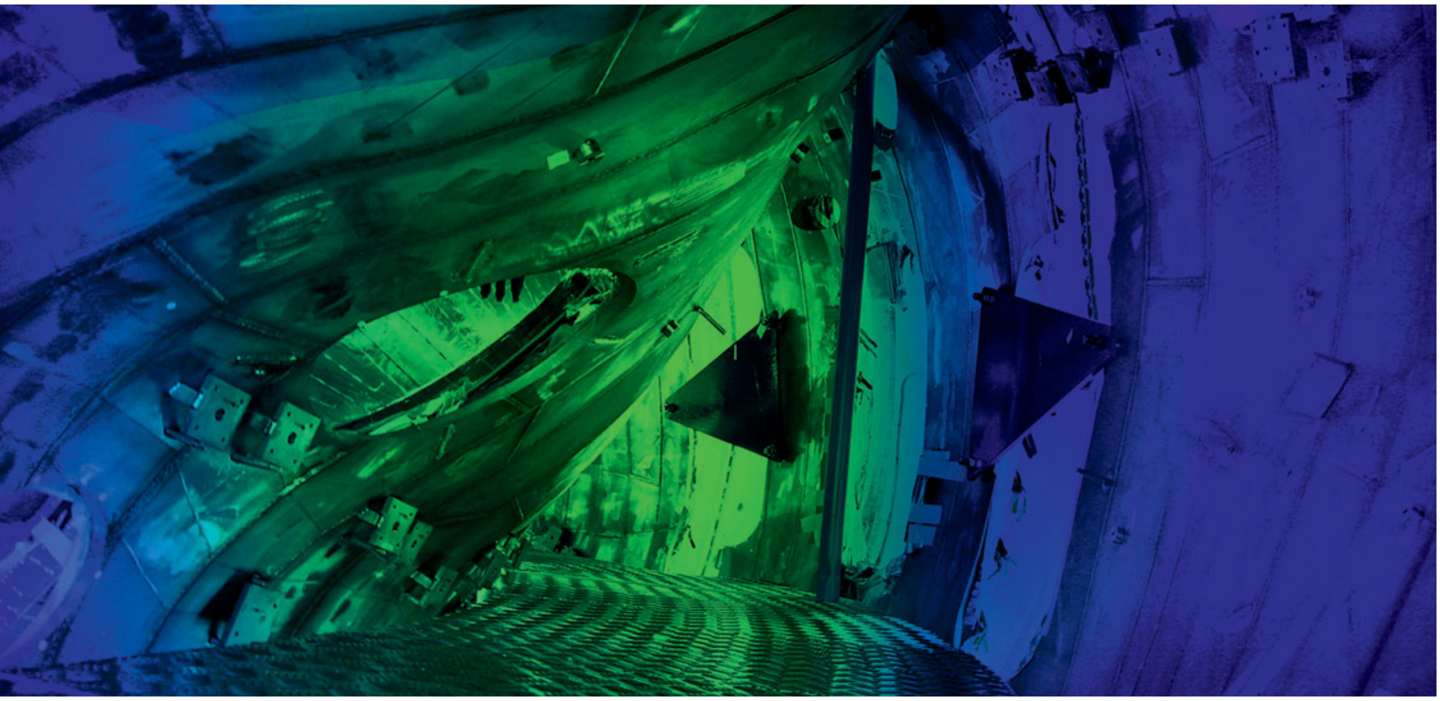

View into the plasma vessel of Wendelstein 7-X currently under construction at IPP Greifswald.

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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.

Foto: Christoph Mukherjee

In 2009, the Max Planck Institute for Plasma Physics (IPP) took important steps towards the future. The international scientific advisory board ranked IPP's scientific output at the top of its class among the world's fusion and plasma laboratories. This year also saw completion of the major review in which the programme-oriented funding of the Helmholtz Association has been defined for the next five-year period. Thanks to an excellent scientific evaluation result, fusion research – and thus IPP – will enjoy a small budget increase for the first time in about a decade. On the other hand, 2009 was a particulary difficult year for ITER and the funding of the accompanying European programme. The public outreach component of IPP has been strengthened through the formation of a "Friends of Fusion" circle of high-ranking scientists and industrial representatives, dedicated to helping improve the public image of fusion.

Manufacture and delivery of the main components for Wendelstein 7-X were also completed this year. The last coils were successfully tested at CEA in Saclay and delivered to Greifswald. The last two of the ten sections of the outer cryostat vessel were delivered to Lubmin, where the thermal isolation is being mounted prior to the installation of the magnet modules inside the lower and upper shells of the vessel. Meanwhile, work is progressing simultaneously on all five modules: the first magnet module has already been placed inside the cryostat vessel in its final position on the machine base. Starting in spring 2010, the next major assembly step is the installation of the ports. Altogether 254 ports will give access to the plasma vessel for pumping, cooling, heating and diagnostics. The other modules are at different levels of assembly. Significant progress was made in 2009 with the installation of the cryo-pipes, the superconducting bus and the superconducting joints of the second and third modules. The two half-modules of the fourth module were put together at the end of the year. Work on the last two half-modules started in December with the threading of the non-planar coils. The completion of the assembly of Wendelstein 7-X is foreseen for 2014. To prepare the approaching operation of Wendelstein 7-X, an internal seminar was held last year to define the scientific programme for the first operation phase.

Experiments on ASDEX Upgrade continued to explore the extension of the operational space with the all-tungsten covered wall. With the EZ4 flywheel generator back in operation from October 2009 onward, H-mode operation was extended to higher currents and also higher triangularity, confirming the favourable influence of nitrogen seeding on the plasma performance. Discharges were heated with up to 20 MW of heating power, showing good confinement and acceptable power load to the divertor and first wall. New experiments making use of the much improved temporal and spatial diagnostics resolution explored the dynamics of the H-mode edge transport barrier, giving new insight into this complex transport phenomenon. Also, fast-particle-driven instabilities could be studied with unprecedented diagnostics coverage, yielding details of the mode structures and the fast-ion losses caused by them. Moreover, it was demonstrated how plasmas prone to disruptive terminations can be ended safely by applying ECRH to counteract instabilities, a technique that could be of vital importance to ITER. All in all, ASDEX Upgrade continues to make important contributions to the detailed design of ITER as well as to the preparation of ITER operation.

The financial future of JET was uncertain at the beginning of 2009, but with the support of the associations the situation has been resolved for 2010/11. With the end of the 2009 campaigns and the beginning of the shutdown for the installation of the ITER-like wall, JET has begun a new era. For 26 years JET has been a predominantly carbon-walled machine. Now it is on its way to becoming a new device with the same wall materials as ITER. With this change to a carbon-free environment JET takes a step, which ASDEX Upgrade has already taken. Based on the success of ASDEX Upgrade operation with a full-tungsten inner wall, the IPP is best suited to take a leading role in the scientific exploitation of JET. With the appointment of an IPP scientist to become the leader of the JET Task Force E1, which will be responsible for the development of plasma scenarios compatible with the new wall, the first step to an enhanced IPP involvement in the future JET programme has been taken.

The theory effort at IPP is directed toward the understanding and ab-initio modelling of physics processes in fusion plasmas, guided and substantiated by measurements on present-day experimental devices. The ultimate aim is the capability to make reliable predictions for Wendelstein 7-X, ITER and future fusion reactors. Major achievements in 2009 were, for example, the development of global gyrokinetic electromagnetic turbulence codes, the understanding of the observed consequences of fast-particle-driven instabilities in ASDEX Upgrade, as well as new insights into transport processes in stellarators. As the physics processes relevant to fusion plasmas are very similar to many astrophysical plasmas, in 2009 the two theory divisions started a collaboration with the Max Planck Institute for Solar System Research to exploit synergies between the two communities. In Garching a high-level support team was established in collaboration with the Max Planck Society Computing Centre in order to support the EFDA high-performance computing initiative.

The ITER cooperation project at IPP passed two major milestones in 2009. Firstly, a service contract between F4E and IPP was signed for the establishment of ELISE, a test rig for a half-size ITER source for negative hydrogen ions, and subsequent experiments. Secondly, the CYCLE Consortium for the ITER ICH antenna was signed and received a grant. Also, progress can be reported from the ITER bolometer project, which is currently supported by national funds but still awaits the call from F4E for R&D tasks. Furthermore, IPP is contributing to various heating systems, diagnostics and, in particular, the preparation of the physics basis through a number of tasks within the EFDA work programme.

The "Plasma-facing Materials and Components" project constitutes a field of competence at IPP. The close cooperation of researchers in tokamak edge plasma physics from ASDEX Upgrade and from the materials research department makes it possible to respond to newly emerging plasma-surface interaction issues resulting from new operational scenarios. Systematic investigations accompanying the transition of ASDEX Upgrade from a carbon-dominated to a tungsten-dominated device in the period from 1999 to 2007 resulted in a good agreement of gas balance measurements during machine operation with posterior surface analysis of retrieved tiles. High-heat-flux tests, combined with metallographic investigations of pre-series elements for the Wendelstein 7-X divertor targets, led to significant improvement in the production process and higher reliability of the components. The activities in this field are concerned with the EU Task Force on Plasma-Wall Interactions. Scientists from IPP have participated in the leadership of this EU Task Force and its subcommittees since 2002. Furthermore, the project coordinates the large EU-integrated EXTREMAT project with 37 partners and manages the EU coordination action FEMaS (Fusion Energy Materials Science).

On behalf of the Directorate and the Scientific Board I would like to take this opportunity to thank our staff for their dedication and the excellent results achieved in all divisions. The coming year 2010, having been dedicated to "The Future of Energy", will see a series of highlights for IPP, commencing with Federal Chancellor Dr. Angela Merkel's visit to IPP and culminating in Garching's 50th anniversary celebrations and the 10th anniversary of the opening of the institute building of IPP's Greifswald branch.

Scientific Director Günther Hasinger

Content

Tokamak Research

ASDEX Upgrade

Head: Dr. Otto Gruber

The ASDEX Upgrade programme supports design and operation of ITER and DEMO. Highlights of 2009 were the operational extension of improved H-modes with an all-tungsten wall using Nitrogen seeding, reliable ITER like discharge operation using ECRH, disruption avoidance and progress in the physics of energetic particles, H-mode edge barrier and SOL transport. Technical extensions (ICRF antennas, ECRH, in-vessel coils for ELM control) are proceeding.

1 Overview

1.1 Programme and Operation

The fusion experiment ASDEX Upgrade (AUG) is a medium size divertor tokamak (major radius R=1.65 m, minor radius a=0.5 m, plasma current I_p up to 1.4 MA, toroidal magnetic field B_t up to 3.1 T) with a 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 (PF) coils outside the B_t 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 ITER equivalent power fluxes to the wall and divertor. Even the P/R ratio, relevant for divertor similarity, is close to ITER values.

The scientific programme gives priority to support the design (heating, fuelling, first wall material) of ITER, to prepare the physics basis and reliable operation of ITER, and to explore regimes beyond the baseline scenario of ITER, the ELMy H-mode, and even of DEMO. These studies were coordinated by four Task Forces (TF)

- Improvement of the H-mode and integrated advanced scenarios beyond the ITER baseline scenario,
- H-mode pedestal physics and Edge Localized Modes (ELMs) mitigation and control,
- Magnetohydrodynamic (MHD) stability, active control of limiting instabilities, as well as avoidance and mitigation of disruptions,
- Scrape-off layer and divertor physics to optimize power exhaust and particle control, as well as qualification of tungsten as high-Z wall material.

The configuration similarity of AUG with JET and ITER at absolute length scaling 1:2:4 is the basis for extrapolation of plasma scenarios developed at AUG as well as core and edge physics results towards ITER (step-ladder approach). AUG is particularly well suited to test control strategies for shape, plasma performance and MHD modes. The operation of AUG has continued in 2009 in close cooperation with the EU fusion associations and the JET programme, and has contributed to both the high priority physics research areas and the joint experiments at all major tokamaks as proposed by the ITER team and ITPA Topical Groups. Thereby, the AUG programme is embedded in a framework of national (see e.g. section 9 on Stuttgart University contributions) and international collaborations (see section 10).

The AUG Programme Committee (PC) established in 2001 enables the Associations to take responsibility for our programme. This PC defines the TFs 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. With this structure, we have achieved a compromise between the international involvement and the flexibility that has so far been typical for the AUG programme. For the 2009 experimental campaign out of the 164 proposals 56 were from outside IPP from 14 EURATOM Associates, the US and universities. Correspondingly, the fraction of AUG related publications in referred journals with an external first-author stays at 35 %.

The heating and current drive systems of AUG include all three day-one systems foreseen for ITER. These consist first of the neutral beam heating (NBI) with 10 MW at 60 keV and 10 MW at 93 keV including 5 MW tangential off-axis deposition. The ion cyclotron resonance system (ICRF) was capable of routinely coupling up to 6 MW compatible with type I ELMs using 3dB-couplers, but is presently restricted with tungsten (W) walls by W sputtering caused by ICRF accelerated light impurities. The electron cyclotron injection system (ECRH) can couple 1.6 MW (2 s pulse length), and a new 1 MW gyrotron works at two frequencies (105 and 140 GHz) allowing pure electron heating and current drive.

The large installed heating power allows the exploration of pressure limiting MHD phenomena over a large parameter range and provides high flexibility for heat deposition, current drive and torque input. 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 fast integrated control and data acquisition system (CODAC) 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 with integrated data analysis.

The re-installation of the flywheel generator EZ4 (which supplied some of the poloidal field coils and heating systems and which was damaged in 2006) was completed end of September this year together with substantially improved safety installations for all three generators. Additional electrical brakes for generators EZ2 and EZ3 were built in 2007/8. The operation of AUG with the remaining generators EZ2 (for the TF coils) and EZ3 (all poloidal field coils and heating systems) was improved during the last three years to accommodate acceptable restrictions by optimizing the generator power consumption with reduced inductive loads and new shape and scenario evolutions to allow better PF coil interactions.

The full installed power and energy is now available again for AUG operation and was used in plasma discharges starting 1st October.
In 2009, the AUG programme continued to explore reliable operation and the extension of the operational space with a fully W covered first wall as well as the compatibility of high performance plasma scenarios with such a wall. This topic is at present only possible at AUG and represents an outstanding position in the world-wide fusion programme. The campaign restarted in April for the third time without using boronization for wall conditioning, thus proving that this type of operation is no major obstacle. Plasma operation was accomplished from April to July and September to December. We conducted 74 long shifts at high availability with a total of 1700 pulses (technical tests, diagnostic calibrations and plasma discharges).

1.2 ITER Relevant Results in 2009

The experimental programme in 2009 continued to address key ITER needs, particularly, the enlargement of the operational space with fully W-covered wall. Even without boronization stationary ITER baseline H-modes (H_{98}~1, β_N~2) with ITER compatible W concentrations below $3 \cdot 10^{-5}$ were routinely achieved up to plasma currents of 1.2 MA. The tungsten concentration is controlled by central heating (from NBI and the upgraded ECRH system) to increase the turbulent outward transport, and by ELM pacing forced by gas puffing. ICRH can only be used after boronization, which began again in October to reduce the W influx from the antennas and to achieve lower plasma densities.
In 2008, enhanced performance of Improved H-mode discharges with modest triangularities of $\delta \leq 0.3$ was achieved with energy confinement times more than 20 % above the ITER baseline values (H_{98}~1.2) and β_N up to 2.7. This was obtained with Nitrogen seeding, used after boronization, to protect the divertor tiles. In 2009 the compatibility of the improved H-mode scenario with H_{98}~1.2 (which forms the basis for the long pulse ITER hybrid scenario) with a full-tungsten wall was confirmed, and then extended to higher densities and plasma currents, and was also demonstrated with an un-boronized W wall. This improvement is due to higher core temperatures often resulting from higher edge pedestal temperatures together with profile stiffness, and increases with the Nitrogen content. Discharges were heated with up to 20 MW showing H-mode confinement and acceptable power load to the first wall and divertor.
The density cut-off limits the application of X2-absorption with 140 GHz ECRF at a toroidal field of 2.5 T. Using X3 absorption at a lower field permits ECRF at significantly higher densities, where the incomplete first-path absorption is balanced by a X2 resonance at the high field side (HFS). H-mode discharges at q_{95}~3 were achieved with H_{98}~1 and β_N~2 as planned for the ITER standard Q=10 operation. O2 absorption at 2.5 T, permitting even higher densities, was demonstrated using a holographic mirror at the HFS to allow for a second-path absorption.
The AUG programme in 2009 also addressed other urgent ITER research needs. ITER q_{95}~3.5 discharge scenario tests achieved an ITER compatible range of plasma internal inductance during plasma current ramp-up, flattop and ramp-down. The plasma start-up and current rise at toroidal electric fields down to 0.25 V/m (ITER design value: 0.33 V/m) using ECRF assist was extended to ECRF injection angles up to -20° from perpendicular as is foreseen in ITER. Disruption avoidance by suppression of (2/1) tearing or neoclassical tearing modes at higher β, using ECRH deposition at the q=2 surface allowed safe landing of discharges prone to disruptive termination. Routine disruption mitigation by massive gas puffing was demonstrated. Additional fast massive gas injection valves will be installed and may allow a more uniform particle deposition and electron densities needed to suppress runaway electrons in ITER.
The ITER physics basis was extended in the areas of transport, stability and exhaust by making use of the much improved temporal and spatial diagnostics. The neoclassical impurity ion transport across the pedestal was further confirmed by the dynamics of ELMs. Insight into energetic particle physics was gained by measuring the distribution function of confined fast particles (Collective Thomson Scattering, Fast Ion D-Alpha spectroscopy) and the losses of fast ions in the presence of multiple Alfvénic instabilities. Small-scale fluctuations and transport of filaments in the scrape-off layer show strong poloidal flow reversal of blobs and electron temperature fluctuation gradients outside the separatrix measured both by reciprocating probes and Doppler reflectometry.
The new results reported here form the basis to further enhance the operational space of AUG with the full tungsten wall, especially towards lower densities and collisionality, and strongly support tungsten as a first wall material solution.

1.3 Technical Enhancements and Programme in 2010

In order to achieve AUG's programmatic goals and to maintain a leading position parallel to the ITER construction, it is necessary to continuously upgrade the AUG diagnostic and technical systems. The next operating diagnostic enhancements, partly with support from other EU Associations, are for simultaneous core and edge Thomson scattering, bolometer cameras, poloidal edge velocity (CXRS), poloidal distribution of fast ion losses (FIDA), a reciprocating probe at the X-point, and a retarding field analyzer.
The compatibility of ICRF with a tungsten wall (light impurities accelerated by induced sheath voltages sputter limiter material) will be tested in 2010 by installing a newly designed antenna with modified straps and toroidally extended limiter structures in the next shutdown (Jan – Aug 2010). EM code calculations indicate a reduction of the sheath voltages by a factor of 2.

The AUG ECRF system will be upgraded to a total installed power of 6 MW (after 2011) with 4 gyrotrons of 1 MW each (pulse length 10 s) operating at 2 frequencies. Avoidance of impurity accumulation by central heating, and, together with the installed fast steerable antennae, feedback control of performance limiting NTMs and diagnostic support are the main issues. The first new gyrotron failed in May this year and was replaced in November. The next two 2-frequency gyrotrons will be delivered mid 2010.

The step-wise installation of 24 in-vessel coils from 2010 to 2012 will allow physics studies of the suppression of ELMs by Resonant Magnetic Perturbations (RMP) – up to a toroidal wave number of n=4 – and toroidal rotation control. Such a system is foreseen for ITER with a coil geometry very close to that chosen for AUG. The first 4 top and 4 bottom coils will be installed beginning 2010. Later-on, a conducting shell close to the plasma could enable studies and control of pressure limiting Resistive Wall Modes which hamper steady state tokamak operation. These coils will be a unique tool in the EU fusion programme.

For the 2010 AUG campaign the call for experimental proposals will be initiated in April 2010 and the resulting programme will be conducted by five task forces, the four current ones mentioned above and one "cross" task force on transport. The restart of AUG is planned for September 2010. The main emphasis will be the application of the internal coils for ELM control, where inconsistent results have been found at other devices, and of the increased ECRF power for W control as well as MHD and disruption control. The programme will benefit from availability of the full generator power again, opening up the possibility to boost the operational space even further towards ITER relevant conditions, namely plasma currents with up to 1.6 MA and, either with low triangular shapes and 20 MW heating power, or with high triangularity (δ>0.35) and 10 MW heating.

In summary, the success and the expected future contributions of the AUG programme are of very high importance for the detailed design of ITER as well as for the preparation of ITER operation and even for the future DEMO device. AUG will support ITER well into the next decade and even longer unless a similar device would become available to the fusion programme.

2 Fluctuations and Turbulent Transport in the SOL

Turbulent transport is responsible for a significant particle and energy loss in tokamaks. It is related to confinement and momentum transport as well as energy and particle transport to the wall and into the divertor. Also an interplay of turbulence and shear flow at the plasma edge is expected. Nevertheless, the underlying physics is not well known. Turbulence can form small scale fluctuations, filaments in between ELMs or large ELM filaments. In 2009 we continued investigating the turbulent transport in the SOL using reciprocating probes at the outboard side. These studies are discussed in the context of previous observations. Ion saturation current (I_{sat}) measurements in ohmic discharges show negative fluctuations (density holes) inside the separatrix and positive ones (density blobs) outside. The blobs propagate radially outward. Blobs and holes are born in the plasma edge. Indications for blobs and holes exist also in L- and H-mode discharges. The generation mechanism of blobs and holes is still unknown.

The poloidal velocity, $v_{pol,cc}$, of blobs and holes was determined by performing a cross correlation (CC) of two I_{sat} measurements of poloidally separated Langmuir pins. A strong shear with an abrupt flow reversal outside the separatrix was detected by probes in ohmic, L- and H-mode discharges. The radial $v_{pol,cc}$ profile measured by the CC of I_{sat} measurements show a good agreement with the $v_{pol,d}$ deduced from Doppler reflectometry. The Doppler reflectometer employs the microwave V-band (50-75 GHz) to detect the movement of turbulent density fluctuations using the Doppler radar principle. The frequency of the backscattered signal is $\omega=k_\perp u_\perp$, where $u_\perp=v_{E\times B}+v_{ph}$, from which the radial electric field $E_r=-u_\perp B$ is extracted assuming the turbulence phase velocity v_{ph} is small. Direct measurements of the plasma potential V_{pl} or E in tokamaks are hard to perform and rare. Therefore it is a common technique to measure the floating potential V_{flt} in the SOL with Langmuir probes to determine E. The relation of V_{pl} and V_{flt} is given via the electron temperature T_e: $V_{flt}=V_{pl}-\alpha\ T_e$ with $\alpha\approx2.8$. Accounting for the time averaged background T_e profile $\langle T_e\rangle$ it is assumed that T_e fluctuations can be neglected and the electric field is approximated by E=-grad $(V_{flt} - \alpha \langle T_e\rangle)$. Using radially staggered Langmuir pins to determine E_r from V_{flt} and calculating $v_{pol,E\times B}\sim E_r/B$ deliver a significantly different radial $v_{pol,ExB}$ profile than $v_{pol,cc}$ measured simultaneously. Recently a ball pen probe (BPP) was adapted for AUG. In a ball pen probe the pins are shielded against particle flux parallel to B. Experiments in smaller machines showed that this arrangement allows to measure V_{pl} directly. In AUG a comparison of the radial profile of E_r=-grad V_{pl} from the BPP data and the Doppler E_r show good agreement (see figure 1). This indicates that also in AUG the BPP can be used to measure V_{pl} directly; it also supports the hypothesis that the $u_\perp$ of the density fluctuations is dominated by the E×B velocity.

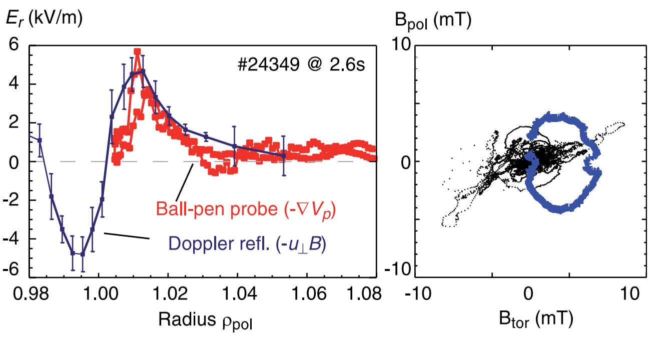

Figure 1: Left: Comparison of E_r measured by Doppler reflectometry and BPP. Right: Hodogram during one current filament (blue, closed loop) and in between (black).

Finally, this result shows that close to the separatrix gradients of T_e fluctuations are not small compared to V_{pl} gradients in the fluctuations. First investigations on this were performed. When measuring V_{flt} and V_{pl} at the same time the fluctuation power spectrum showed a much higher level for V_{flt} at frequencies above 30 kHz. This is in line with modelling results showing the spatial size of T_e fluctuations is about half size of V_{pl} structures while the fluctuation levels are 10-20 % and 10-30 % respectively. This also points in the direction that T_e fluctuations cannot be neglected with respect to V_{pl} fluctuations. A corresponding observation was made measuring v_r of ELM filaments. Also for ELM filaments the most reliable method to determine v_r is the CC of radially staggered I_{sat} measurements. Deriving v_r from E×B using V_{flt} is affected by the spatial arrangement of the probe pins and their size since turbulent (sub-)structures and the diagnostic are of comparable sizes.

In previous experiments the reciprocating probe was observed by an infra red (IR) camera (time resolution about 100 µs) which allowed to measure the heat flux q onto the reciprocating probe head in parallel to the Langmuir probe measurements. In ELM filaments the I_{sat} fall off length λ_{Isat} and the heat flux fall off length λ_q were both about 2.5 cm in the far SOL. The identical λ for q and I_{sat} can be expected only when the energy loss is mainly convective. This requires T_i<100 eV, $n_e \sim 10^{19}\ m^{-3}$ and T_i/T_e>2.6 where T_i denotes the ion temperature. From q and I_{sat} an $n_e = 4 \cdot 10^{19}\ m^{-3}$ and T_i=30-60 eV were calculated. In L-mode, analysing the I-U characteristics of the BPP showed $T_i > T_e$ in the SOL, but this result still needs to be validated in ELM filaments. New measurements with a retarding field analyser (RFA) showed ion energies exceeding 160 eV during ELMs. This is in line with RFA studies at JET and MAST where ion energies of several 100 eV were found in ELMs. Such ions can cause significant sputtering of the first wall.

In 2009 investigations were made on fast T_e measurements resolving ELM filaments. Single probes with a fast swept bias voltage were used to determine n_e and T_e from the probe characteristic. The bias sweep frequency was 50-100 kHz allowing a 5-10 µs time resolution. In ELM filaments we found 4.5 cm outside the separatrix n_e and T_e peaks of $n_e = 1\text{-}2 \cdot 10^{19}\ m^{-3}$ and T_e=30-40 eV at the probe. Due to the acceleration of the ions towards the probe the background plasma n_e is about twice the probe n_e. Smoothing the T_e data to 25 µs time resolution to smear out individual filaments (as in the IR measurements) reduces the measured T_e to 10-15 eV. The measured peak n_e is well in line with the values determined in the IR experiments and the plasma parameter from the single probe support the existence of conductive heat transport in ELM filaments in the far SOL.

ELM filaments are thought to be related to current filaments. Magnetic measurements with pick up probes at the outer wall and on the reciprocating probe showed strong magnetic fluctuations during ELMs but are not well correlated with I_{sat} measurements nearby. Modelling showed that bidirectional rotating modes as well as bidirectional current filaments in the SOL can account for the observed magnetic fluctuations. The current densities j_{sat} required to generate the observed amplitude have to be 6 MAm^{-2} for the modes in the pedestal and about 1 MAm^{-2} for filaments in the far SOL, which is much higher than the observed j_{sat} of about 0.1 MAm^{-2}. Therefore, it is concluded that the magnetic signature is caused by mode structures in the confined plasma.

In a new probe head combining Langmuir probes with a very small triaxial coil nearby (much smaller than the coils used before) ELMy H-mode discharges were investigated. The degree of polarisation showed that during ELMs the magnetic signals are not caused by plane waves, like in between ELMs. Hodograms reveal closed loops in ELMs indicating the existence of current filaments (see figure 1). These filaments are aligned with B and a monopolar current was found opposite to previous observations. The required current densities are up to 6 MAm^{-2} similar to the values determined before. The minimum distance between current filament and pick up coil can be determined by assuming a propagation velocity. For a typical velocity of 1 km/s the distance is smaller than the distance to the separatrix. Again the required current densities are much higher than j_{sat} measured. A possible explanation are current carrying filaments which move into the SOL while still being connected to the confined plasma allowing for high currents. Such filaments cannot be detected by Langmuir probes since the probe acts like a wall and inserts a current density limiting sheath.

3 ELMs and Transport inside ETB

3.1 Characterisations of the Edge Transport Barrier in H-modes

In the narrow region of the edge transport barrier (ETB) transport coefficients for electrons are reduced but still anomalous, while ion temperature profiles in H-modes can be modeled under the assumption of neoclassical transport for ions. In the following, results are presented which confirm the assumption of validity of neoclassical transport for ions. Regarding electron transport, new temporally highly resolved measurements indicate the existence of different transport regimes during the pedestal recovery after an ELM crash.

3.2 Profile Alignment

In the following, all considerations are done after mapping all measurements performed at various poloidal and toroidal positions to the outboard midplane. There the ETB is only ~10-20 mm wide and it is important to achieve a relative positioning of the various diagnostics to better than 3 mm. In H-modes, where steep gradients allow an accurate relative positioning, the profiles of the various diagnostics are selected temporally relative to the occurrence of ELMs (ELM synchronized). For modeling transport in the transition region of closed flux surfaces to the scrape off layer (SOL), the determination of the separatrix position is essential.

The separatrix temperature can be estimated with a simple two-point model for the power flux to the divertor and depending on the heating power of the discharge T_e^{sep} lies between 70 and 140 eV for H-modes. For relative alignment of all diagnostics we start with setting T_e from Thomson scattering (TS) to fulfill the condition for T_e^{sep}. The ECE data are then aligned to the TS data in the upper ETB region, where second harmonic X-mode emission is optically thick. n_e profiles from the Lithium beam (LIB) are then aligned to the measurements of TS, the latter building the connection between T_e and n_e profiles.

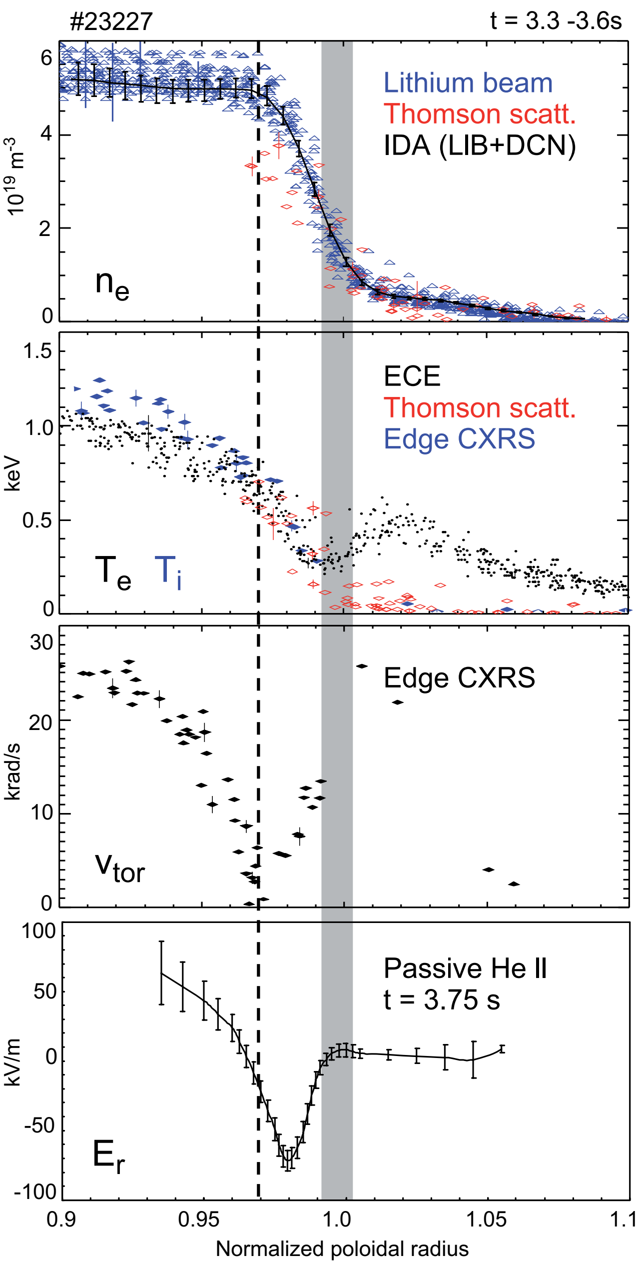

Figure 2: ELM synchronized profiles of n_e, T_e, T_i, v_{tor} and E_r taken during a radial shift of the plasma (# 23227, 3.3-3.6 s).

Relative positioning of edge CXRS data with an accuracy of 2-3 mm is done such that the steep T_i gradient region coincides with that of the T_e measurements. v_{tor} profiles stem from the same diagnostic as T_i, so that both profiles have fixed positions relative to each other. E_r profiles are reconstructed with a set of n_e and T_e profiles as input and consequently have a fixed radial position relative to these.

Figure 2 shows an example of well aligned ELM-synchronized profiles for n_e (TS and LIB), T_e (TS and ECE: Note the strong shine-through from relativistically downshifted emission from the plasma core, which is not reabsorbed in the SOL because of its low optical depth.), T_i and v_{tor} during a radial shift of the plasma by 2.5 cm in discharge # 23227. Only data which lie in the time window of -3.5 to -0.5 ms before an ELM are chosen. The inter-ELM E_r profile is derived from data at t=3.7 s averaged over 100 ms, which is a phase in the discharge without radial shift but still the same plasma conditions. The grey bar denotes the uncertainty in the separatrix position. With all profiles aligned we can make several observations: 1) The ETB width is narrower for n_e than for T_e and T_i. 2) T_e and T_i barrier widths are similar. 3) The position of the minimum in v_{tor} corresponds to the position of the 'knee' at the pedestal top in the n_e profile as indicated by the dotted line, i.e. we find evidence for strong inversed shear of toroidal rotation in the region with steep gradients in the n_e, T_e and T_i profiles. 4) The position and magnitude of the minimum in E_r corresponds to the maximum of $\nabla p_i/n$. Neoclassical theory predicts E_r to be of the order of $\nabla p_i/n$ with a correction depending on collisionality and ∇T_i, which for this case is small.

3.3 Z-dependence of v and D

The impurity transport was studied in the inter-ELM phases using the aligned edge profiles of electrons along with the impurity density profiles as measured by the edge CXRS system. The impurity transport code STRAHL allowed for modeling the steep gradients at the ETB only if transport coefficients were used that exhibit a strong reduction of D and an inward pinch v.

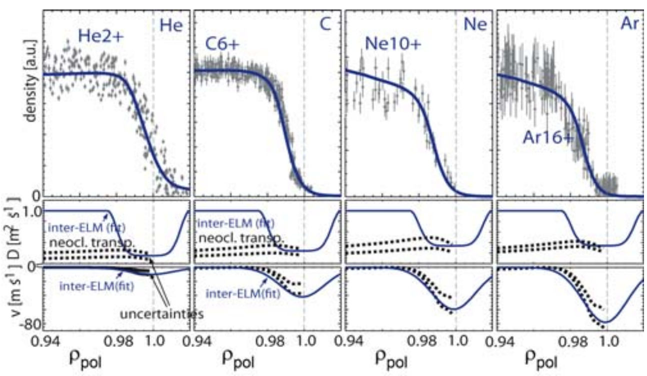

Figure 3: Analysis of impurity transport at the edge transport barrier. The measured data of He, C, Ne and Ar (upper half) from the inter-ELM phases are modelled by STRAHL using the depicted D and v (lower half).

In detail, the determined D and v at the ETB resemble the neoclassical values. The result of a Z-scan for investigations on impurity transport is depicted in figure 3.
In the upper most diagrams, the measured data are presented along with the modeling results (line) for He, C, Ne and Ar. Below, the determined transport coefficient profiles (solid lines) along with the neoclassical values (dotted) are shown. It should be noted that the neoclassical values are presented by two curves which represent the upper and lower border of an uncertainty interval due to the influence of other impurities and T_i. However, at the ETB the measurements agree well with the neoclassical values and the corresponding Z-dependence is observed.

3.4 Pedestal Recovery after ELM Crash

The availability of fast T_e measurements from ECE (up to 1 MHz) and integrated n_e profiles from Lithium beam and DCN (10-20 kHz) allows the detailed examination of the recovery of electron density and temperature profiles after an ELM crash. The data presented here use CLISTE equilibria with a temporal resolution of 1 ms. The maximal temperature gradient shows the same evolution as the T_e values in the pedestal region, but is not subject to possible inaccuracies in the equilibrium calculation.

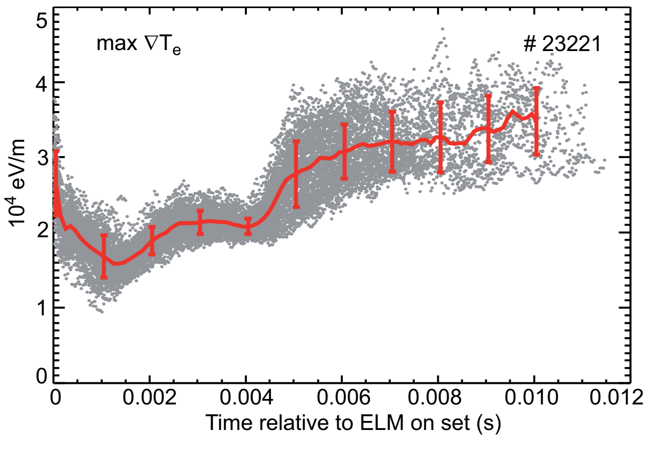

Figure 4: Maximal T_e gradient values plotted relative to the ELM onset time (grey dots). t=0 corresponds to ELM start time.

Figure 4 shows the recovery of the maximal T_e gradient in the ETB region after the ELM crash for discharge # 23221. For ~80 ELMs in a constant plasma phase the maximal T_e gradients are drawn on a scatter plot relative to the ELM onset time. The mean value and standard deviation were calculated for every 0.1 ms interval (red curve). Typically, the T_e gradient in the ETB region drops during an ELM and takes about 2 ms to recover to a steady value. While the T_e gradient stays steady, the n_e gradient rises and reaches an upper limit. This process takes about 2-3 ms. As soon as the n_e gradient has reached its limit a transition to a different transport phase can be observed: ∇T_e rises again with large amplitudes in the T_e values, probably indicating the occurrence of fluctuations or filaments. This is the first time that it is shown that density and temperature profiles recover on different time scales while influencing each other.

4 Fast-particle Physics

On the road to ITER, a basic understanding of burning plasmas represents a primary scientific challenge towards the demonstration of fusion as a commercial source of energy. In D-T plasmas, self-heating is provided by the 3.5 MeV α- particles born in fusion reactions. Furthermore, external heating systems such as the Neutral Beam Injection (NBI) and the Ion Cyclotron Heating (ICRH) allow a better control of the plasma through suprathermal particles with anisotropic distribution functions. All these fast-ions in plasma often constitute a major source of particles, momentum and free energy that under certain conditions may drive some unstable magnetohydrodynamic (MHD) fluctuations such as Alfvén Eigenmodes (AEs) or Energetic Particle Modes (EPMs). The interplay between these MHD fluctuations and the energetic particles may considerably affect the fusion performance as well as the safety of the vacuum vessel by concentrated heat loads on the first wall. In AUG, significant progress in energetic particle physics has been made by investigating the redistribution and loss of fast-ions in the presence of multiple Alfvénic instabilities as well as their stability.

4.1 Measurements of the Confined Fast-particle Distribution Function

The radial profiles of the fast-ion pressure and driven current can have a significant impact on macroscopic stability properties. Although dilute populations of fast ions often behave classically, intense populations with large gradients can drive instabilities that redistribute or expel the fast ions from the plasma. A number of existing techniques provide information about the confined fast-ion distribution function. In AUG, two techniques are being used to extract information about the local and global distribution function of the fast-ions; the Collective Thomson Scattering (CTS) and the Fast-Ion D-Alpha (FIDA) spectroscopy. The distribution function of on- and off-axis NBI sources has been investigated using both of these techniques.
The local fast-ion distribution function has been inferred from the scattered microwave emission measured by the CTS diagnostic (see section 10). Preliminary results of FIDA spectroscopy have given valuable information about the radial profiles of the fast-ion distribution functions. The FIDA diagnostic is based on the Doppler-shifted D- light emitted by the fast-ions that are neutralized as they pass through the footprint of an NBI beam. A novel technique for background subtraction without NBI modulation has enabled the study of the temporal evolution of the FIDA profiles without affecting the fast-ion distribution and consequently the plasma stability.

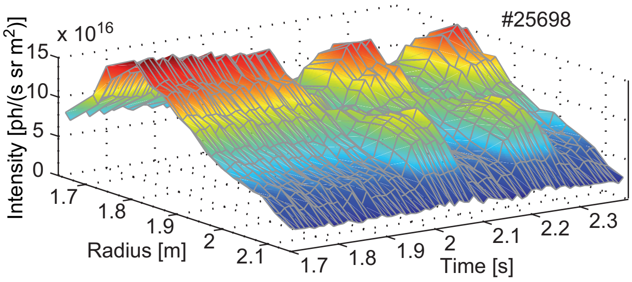

Figure 5: FIDA profiles of on- and off-axis NBI sources.

As a first proof of principle, figure 5 shows the measured FIDA profiles (photon fluxes) of modulated on- and off-axis NBI beams. As expected from their injection geometry, NBI source # 8 gives rise to a centrally peaked FIDA profile while NBI source # 6 produces an off-axis profile. To estimate the distribution function of fast-ions that are contributing to each FIDA profile, the neutral density profile as well as the ion weighting function must be taken into account. Simulations of the FIDA emission in quiescent plasmas are being performed to validate the measured profiles and evaluate the effect of different MHD fluctuations on the fast-ion population.

4.2 Fast-ion Losses Induced by RSAEs and TAEs

The non-linear evolution of Alfvénic instabilities driven by energetic particles and the subsequent redistribution of those particles has been the focus of exhaustive theoretical studies worldwide. Low amplitude AEs are expected to eject energetic ions in a convective process directly proportional to the fluctuation amplitude. So-called diffusive losses are predicted to occur if the amplitude of a single Alfvén mode exceeds a certain threshold, leading to overlapping several of wave-particle resonances. As this is a stochastic phenomenon, the fast ions losses are proportional to the square of the mode amplitude. Diffusive losses can also be induced by multiple modes if their spatial structures and wave-particle resonances overlap. The phase-space of convective and diffusive fast-ion losses induced by Reversed Shear Alfvén Eigenmodes (RSAEs) and Toroidal Alfvén Eigenmodes (TAEs) has been characterized using the fast-ion loss detectors (FILD). The RSAEs and TAEs radial structures have been reconstructed through cross-correlation techniques between FILD signals and the 1D Electron Cyclotron Emission (ECE) radiometer (see section 7.5). A more detailed knowledge of the AE radial structures has been gained with the recently installed ECE Imaging system (see section 7.8). Figure 6 shows the T_e fluctuation amplitude (left) and phase (right) induced by a NBI driven RSAE. The right panel (phase) clearly shows the upper part of the RSAE poloidal structure on the low field side.

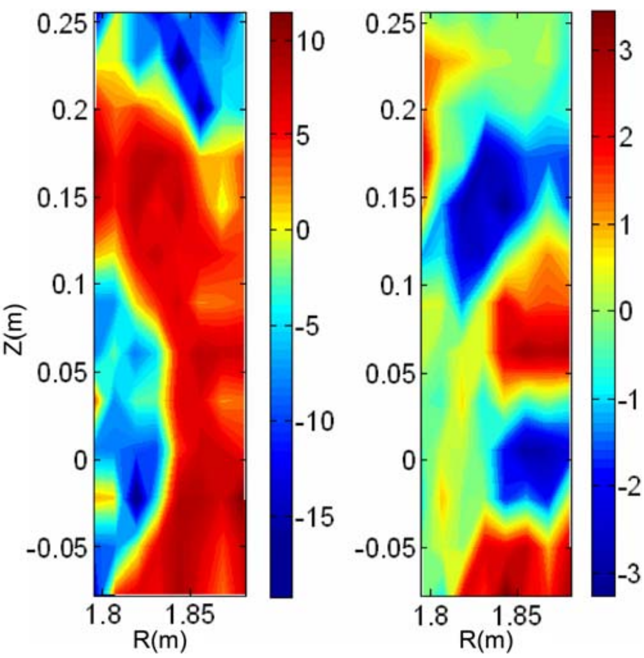

Figure 6: ECE-Imaging of an NBI driven RSAE. Left panel shows the amplitude of the T_e fluctuation. Right panel shows the phase of the fluctuation.

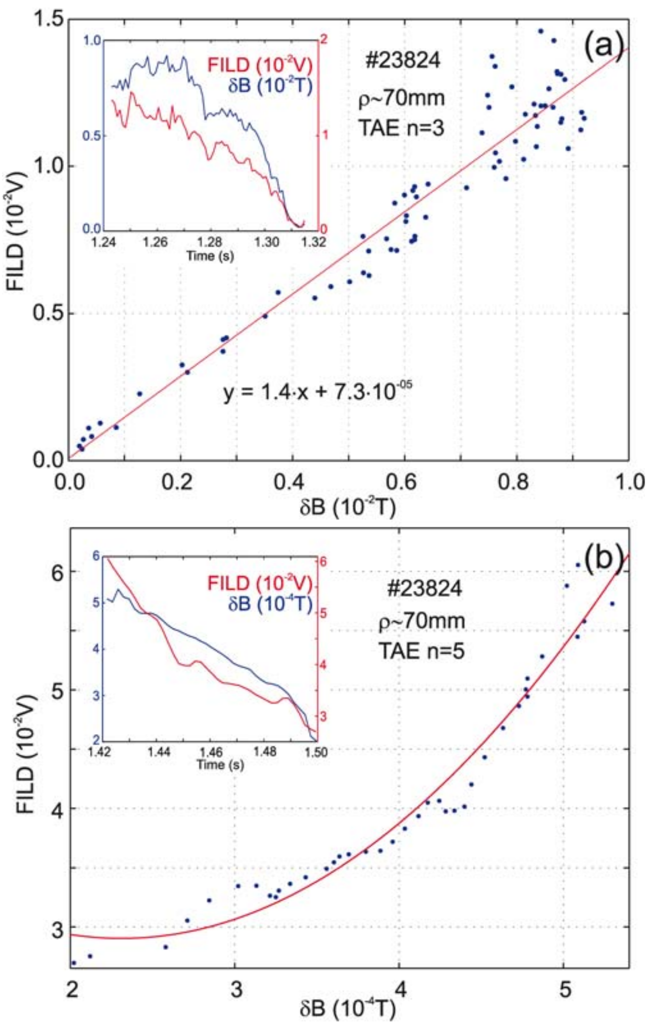

Figure 7: Convective and diffusive fast-ion losses induced by RSAEs and TAEs.

The combination of both FILD and ECE diagnostics have allowed experimental identification of the convective and diffusive character of the AE induced fast-ion losses due to single and overlapping eigenmodes. As expected in a convective process, a linear dependence of the fast-ion losses on the TAE fluctuation amplitude has been observed, see figure 7(a). For single TAEs, diffusive losses of fast-ions, scaling as $(\delta B)^2$, are observed for local radial displacements of the magnetic field lines larger than a certain threshold, figure 7(b).
Multiple overlapping TAEs and frequency chirping RSAEs cause an enhancement of the diffusive losses. A detailed theoretical analysis of the convective and stochastic fast-ion transport induced by RSAEs and TAEs is under way.

5 New ECRH Scenarios

With fully W covered plasma facing components, central ECRH turns out to be a crucial tool to control central tungsten accumulation in H-mode discharges. The commonly used X2-mode heating at 140 GHz restricts the toroidal field to 2.5±0.1 T with a cut-off approximately at the Greenwald density for a plasma current of 1 MA, which in fact limits the plasma current to 1.2 MA or below (for higher triangularity). Therefore, values of q_{95} below 4.0 cannot be achieved (ITER: q_{95}≈3). Together with IPF Stuttgart, new heating scenarios were developed either for lower B_t (X3) or higher I_p (higher cut-off, O2). O2-mode heating has the advantage of twice the cutoff-density of the X2-mode, but the single-pass absorption is poor (≈70-80 % at typical electron temperatures of 3 keV). Better absorption can be realized only with a second pass of the ECRH-beams through the plasma centre (>90 %). Therefore, two phase reconstruction mirrors for the new ECRH system were developed to reflect the beams in the correct direction and polarisation back through the plasma. Because of the plasma erosion the mirrors are conformed to the inner wall. Only holographic gratings can meet this challenge. It is important to ensure that the beams are well located on the mirrors. If the density peaking, and therefore the beam refraction, changes then the launching angles may need adjustment. To determine the beam position four thermo-couples are installed on the edges of each mirror to detect local temperature increases due to ohmic losses on the mirrors. Figure 8 shows a picture of one holographic mirror with the locations of the thermo-couples indicated by coloured crosses. The sensors are inserted through milled holes from the back of the mirror and fixed with graphite adhesive. The bottom of figure 8, shows time traces from two thermo-couples for a discharge during which the ECRH-beam was intentionally moved with the fast steerable launcher from above the mirror to the centre and back to the top. It can be seen clearly, that the two thermo-couples have nearly a linear increase of the temperature caused by the heating of the plasma. In addition the top thermo-couple (red) shows a steep temperature gradient in the phase of the launcher movement (indicated by the blue line) while the beam hits exactly the thermo-couple. The number of the thermo-couples will be enlarged in the next campaign for better resolution and to allow their use for real time control of the beam spot alignment.

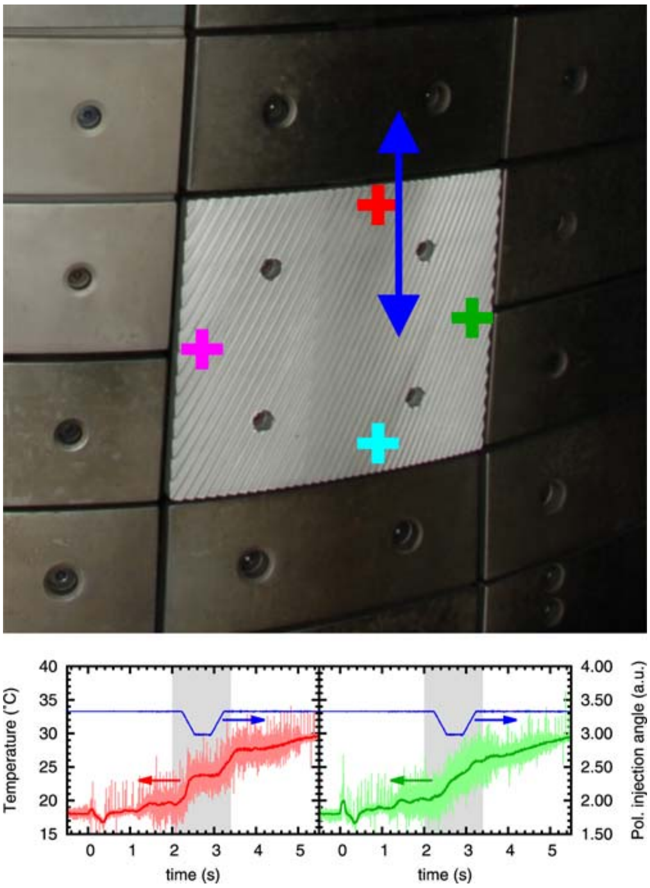

Figure 8: Holographic mirror mounted at the inner wall. The coloured crosses show the places of the thermo-couples, the blue arrow the movement of the beam spot caused by changing the launching angle. At the bottom, time traces of the temperature measured with the thermo-couples are shown during the discharge (red curve belongs to the top thermo-couple, and green curve to the right).

In the same discharge it was possible to detect the electron temperature response on the second pass of the ECRH beam. During the phases with the beam either on or beside the mirror the ECRH power was modulated at 30 Hz. It should be noted that the beam, when it is outside of the mirror, hits a standard tile, which acts also as mirror. But this "mirror" creates only a direct reflection in the wrong direction and polarisation, with resulting absorption concentrated mostly in the plasma edge. This effect is obvious in the amplitude of the modulated electron temperature and the cross phase between ECRH and the temperature modulation, which are shown in figure 9. In the case of a directed second pass from the holographic mirror (blue line), a high peak of the modulation amplitude and a small cross phase in the centre are seen. On the other hand, the non-directed reflection from the standard tile has a relatively flat cross phase with two minima, which indicates an absorption in the centre and edge. Also, the amplitude of the temperature modulation at the nominal deposition in the plasma core is smaller in comparison to the directed reflection and has a second smaller peak in the edge.

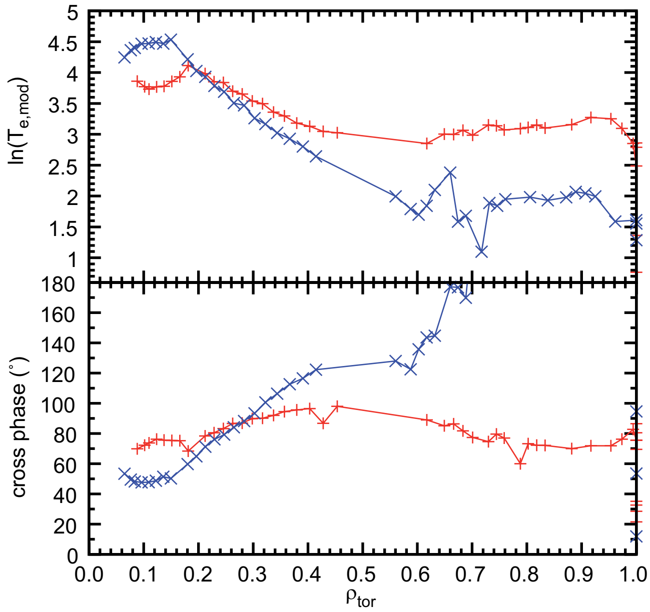

Figure 9: T_e modulation amplitudes and cross phase between the ECRH-modulation and the T_e response, while the beam is on the holographic mirror (blue curve) and above the holographic mirror (red curve).

For a toroidal magnetic field of 1.8 T, a stable ITER-relevant discharge with central ECR-heating and a plasma current of 1.1 MA (resulting q_{95}=3) could be demonstrated (# 25388). Here, the ECRH is launched in X-mode, and the 3rd harmonic is absorbed in the plasma core. The non-absorbed component (approximately 30 % at T_e=3 keV) is absorbed in the plasma edge at the X2-resonance. In some cases W accumulation could not be completely controlled, leading to reduced central T_e and less X3 absorption, which enhances W accumulation. Finally the H-mode degrades and the pedestal temperature drops below the value necessary for full X2 absorption. At this point non-absorbed ECRH power is a potential hazard for the machine (a similar chain of events is observed when the W accumulation cannot be controlled completely with O2 heating). As a measure for machine protection, ECRH stray radiation is now routinely monitored with three sniffer probes close to the gyrotron launchers. The interlock electronics switch-off the ECRH reliably in cases of increased stray radiation due to unexpectedly low T_e during O2 or X3 heating. Also for X2 heating, the interlock switches-off the ECRH safely when the plasma density exceeds the cut-off density in the plasma centre.

6 Technical Systems

In 2009, the experiments in a tokamak with a full W first wall were continued with an extended operational space due to the modified power supply and generator EZ4 coming into operation at the end of the campaign. The experiment was in operation for 86 days performing 1701 shots in total with 1080 shots useful for physics programme. 124 discharges were heated with more than 10 MW, 2 of them up to 17.5 MW. All target tiles of the outer strike line module with 200 μm thick W coating were replaced by tiles with 10 μm thick W coating during the 2008/09 opening. These tiles show no degradation during operation in 2009. The in-vessel inspection after the campaign reveals that the target tiles withstands the heat load and show no damages. A water leakage coming up in the outer divertor at the end of the campaign required 2 out of 16 divertor modules to operate without water cooling. Typically 250 MJ were deposited to the divertor during a shot day. At the end of an operational day the resulting target temperature was about 150 °C and the temperature of the support structure about 70 °C as shown in figure 10. These data have to be compared to the technical limits of 300 °C for the target equilibrium temperature and 150 °C bake out temperature, respectively.

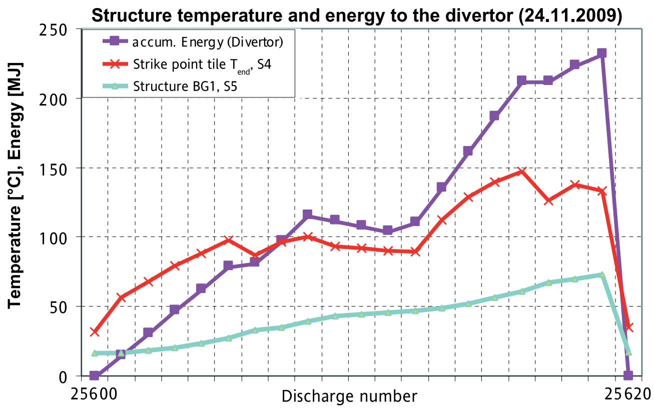

Figure 10: Temperature increase of the strike line tile and the divertor support structure with the energy accumulated to the divertor for an uncooled divertor segment at a typical shot day.

6.1 Experimental Power Supply

The main achievement of the experimental power supplies department was the successful re-commissioning of the flywheel generator EZ4. While the contract was initially let for the repair of the damaged EZ4, the safety reviews held after the incident led to many improvements in the control, instrumentation and protection as well as auxiliary systems of EZ4. This led to a protracted commissioning phase. Since September 2009 AUG can make use of the full power, again. In line with the start of EZ4 operation the new damping circuit of torsional resonances at the generator's shaft line has been commissioned.

Another main achievement is the letting of the contract for a mechanical braking system for EZ4 in August 2009 after 15 months of negotiations. It consists of a 7 MW hydraulic dynamometer and a 40 kNm disc-brake. By the end of year, the mechanical design has been completed.
Besides, during the last outage, the technical requirements for the installation of a central control room for all four generator plants have been established. In the future the centralised data acquisition and visualisation centre will help to early identify emergent faults and trends and to react faster and more efficiently on occurring failures.

6.2 Erosion in PF Coil Water Cooling Circuits

The poloidal field (PF) system consists of 17 coils (OH1, OH2, OH3, V1, V2, V3, CoI, CoA). All coils are wound up with rectangularly formed copper conductors with the cooling channels in the centre of the conductors. The coolant is deionized water. During plasma experiments the coils are warmed up quasi adiabatically. After every discharge the coils are cooled down to ambient temperature. The demanded cooling time of max. 15 min at maximum PF-currents is guaranteed by accordingly high flow rates with water speeds in the cooling channels of up to 5 m/s. During the last years a monotonic decline of the water flow rate in the cooling channels of the OH1 and V3 coils was ascertained. At a first visual survey of the in- and out-let tubes with an endoscope erosion has been detected in the OH1 coil. The cause of the decreased flow rate is probably the increasing surface roughness in the outlet tubes to ~0.2 mm. To avoid further erosion in the cooling channels, the water speeds have been reduced in all coils to 1.5-2 m/s. The cooling time of the authoritative OH1 coil at the given temperature change of T=40 °C (max. allowed T=60 °C) is thereby prolonged from 8 to 12 min, which does not degrade the plasma pulse rate. In 2010, the in- and out-let tubes of the OH1 and the V3 coils will be examined with an endoscope in more detail, in particular the brazed joints between the tubes and the cooling channels.

6.3 Manufacturing of In-vessel Saddle Coils

AUG will be enhanced with in-vessel saddle coils for ELM suppression, locked mode disruption avoidance and active feedback control of the resistive wall mode. The upgrade includes 24 coils, arranged in 3 rows of 8 coils each located at the outboard wall, at vessel midplane (A-coils), top PSL (Bu-coils) and bottom PSL (Bl-coils). Bu- and Bl-coils are manufactured under contract with Babcock Noell GmbH in Würzburg, Germany. The work has started in January 2009 with detailled drawings which involve a winding layout fitted to the space constraints in the AUG vessel, manufacturing of the various tools and moulds and deep-drawing of the inconel coil casing as well as ultra-high vacuum compatible laser welding qualification. Measurements of the complex coil impedance of the winding confirmed prior FEM calculations.

Alongside with the coils, current feedthroughs are presently being built which will be fitted into the C-ports. A prototype feedthrough has been installed and successfully tested througout the 2009 experimental campaign. The saddle coils will be supplied for DC operation with two grid-commutated converters already available at IPP. For AC operation, a new set of self-commutating switched inverters is in planning as a second step of the enhancement. This work is done in collaboration with Consorzio RFX (Padova, Italy). For extended and realistic tests in the AUG environment, one of the spare RFX saddle coils converters on loan from Consorzio RFX has been used for AC operations tests (oscillating JB forces, electromagnetic interference with diagnostics and control systems on AUG). The results are used for the specification of the new AC power converters.

6.4 Neutral Beam Heating

By providing heating during more than 85 % of all useful AUG plasma shots in 2009 Neutral Beam Injection (NBI) continued to act as the workhorse among the experiment's heating systems. With all of its 8 sources in working condition NBI was ready to deliver up to 20 MW of heating power. During the maintenance break preceding the 2009 campaign 3 prototype calorimeter target plates had been installed for testing under real conditions. These redesigned target plates are intended as future replacement for defective plates. No problems were experienced with them since. Furthermore, a new water-cooled wall shielding had been installed in the duct of NBI box II replacing its worn predecessor. The new shielding represents a design prototype for the W7-X NBI ducts. After the campaign it was found that some screw-hole plugs on the front side had started to come out, luckily with no adverse effect on beam operation.
The experimental campaign began with an unfortunate water leak at one of the ion dump plates that appeared during a test shot even before the first beam injection into a plasma. Repair by exchange of the defective ion dump plate was immediately begun and regular operation of the beam box could be started just three weeks after the incident. During the repair neutral beam heating was provided with the four sources of box I only. Later in the campaign NBI box I had to suspend operation for about a week after the failure of a high pressure cooling water connection that flooded parts of the high voltage housing.
Besides the regular overhaul of the Ti sublimation pumps and other in-vessel components the major task for the following break is an upgrade of the programmable logic controller units from SIMATIC S5 to S7 systems the preparations for which were already begun during the experimental operation. In addition, the so-called deceleration voltage safety interlock which so far has been a frequent source of erroneous pulse stops during modulated beam operation will be replaced by a new hardware-based solution. A prototype was already successfully tested.

6.5 Ion Cyclotron Heating

There are no spare tetrodes available for the 4 final stages of the AUG generators. At the beginning of the year, the oldest tetrode led to an unacceptable restriction in output power and was therefore send out for refurbishing. Transport damage to the container and the resulting insurance issue delayed tests with the refurbished tetrode for several months. AUG could therefore only use 3 RF-generators. With a change of connections between these generators and the 3-dB hybrids all four antennas could be powered up to 4.5 MW.

The connections of the 3 dB-hybrids to the antennas were further modified to increase the experimental flexibility. In the original configuration, the neighbouring antennas in sectors 2 and 4 are powered simultaneously by one 3 dB-hybrid (with a phase shift of 90 ° between them) and those in sectors 10 and 12 by the other. In such a configuration, the simultaneously powered antennas are connected to each other via magnetic field lines. This complicates studies of the impurity sputtering with the ICRF power. For specific studies in the past, two antennas were connected to the RF generators directly, but such a connection does not allow load-tolerant operation. To improve the flexibility of the ICRF system while keeping load tolerance, modifications to the transmission lines from the 3 dB-hybrids to the antennas have been made: the length of all lines were equalized and the connections can be rearranged on day-to-day basis to power the antennas in sector 2 and sector 10 by one 3-dB hybrid and those in sector 4 and 12 by the other. At sufficiently low q_{95} (typically ¾ 4) the frames (including limiters) of the antennas powered simultaneously do not connect to each other via magnetic field lines. This allows for better characterisation of impurity release during ICRF. With further modifications of the safety protection systems and by using the alternative phasing configuration of the ICCD studies, the new configuration of the transmission lines will allow changes of phasing of antenna straps (with some limitations and only when all 4 antennas are powered).

The ICRF group started with the HV-group of E1, the construction of a new HV-supply for a driver stage of a RF-generator. This stage can then be run at a higher power. Together with the ZTE, steps also were undertaken to bring the old ASDEX/W7-AS generators back into operation. These will be modified to use EIMAC 4CK2.500KG tetrode in replacement of the old, no longer available type. The detailed plans for the needed mechanical and electrical changes have been worked out in co-operation with the IPR, India, with the help of GA, San Diego and PPPL, Princeton. Mechanical adapters with diameters of up to 400 mm for the EIMAC tetrode have been manufactured in the ZTE workshop and a new filament transformer installed.

6.6 Electron Cyclotron Resonance Heating

The ECRH operated with the old system (40.4 MW, 140 GHz, 2 s) and one unit of the new system (0.8 MW at 140 GHz or 0.5 MW at 105 GHz, both for 10 s) until May. At this point the 10 s gyrotron had an air leak and was sent back to Russia for repair. As reported for 2008, the delivery of further new gyrotrons was delayed due to modifications of the output window. The first successfully brazed diamond disk was only ready in June. The respective gyrotron started plasma operation early December. The gyrotron could only be commissioned so far for 140 GHz, for which it delivers 1 MW for 10 s as specified. With this gyrotron 1 MW plasma heating for 8.5 s could be demonstrated (limited by the tokamak), a proof of the technical feasibility of the power transmission system. Three sniffer-probes for stray-radiation analysis have been purchased and installed close to the ECRH ports, preferentially supported by EFDA (WP-08-H&CD-01-03). They allow to study the dependence of stray radiation on polarisation and are successfully used for machine protection as well. On the inner heat shield, 22 tiles have been replaced by 2 holographic gratings to reflect non-absorbed power in case of O2-injection for operation above the X2 cutoff-density. Fast thermocouples to localize the ECRH beam have been implemented in these tiles (see section 5).

Sustainement of plasma breakdown often failed in the first months of the campaign. Under these circumstances ECRH was successfully used from 50 ms to 200 ms. With the readjustment of the vertical field at breakdown this start-up problem could be solved and early ECRH was no longer necessary. The completion of the new ECRH system is further hampered by problems with the gyrotrons. The gyrotron taken into operation in December has a poorly connected heater, which requires operation with rectified AC, with different polarity for 140 GHz and 105 GHz. The latter will be conditioned early 2010. A second gyrotron shall be delivered in April 2010 and the gyrotron which had the air leak in May 2009 is expected back at IPP in June 2010, such that three 10 s, 1 MW gyrotrons should be available for the next campaign. These are all 2-frequency gyrotrons. The fourth (and last) gyrotron for the new system is still planned to be a 4-f gyrotron. As detailed in the 2008 report, the problematic part is the diamond window of the gyrotron. The original Brewster-angle concept has been given up by the manufacturer, even for thicker disks. Actually a grooved disk solution is studied. If it is feasible, the gyrotron will be equipped with such a window, otherwise also the forth gyrotron will have only two frequencies. This gyrotron shall be delivered in 2011.

A major goal with the new ECRH system is the feed-back control of NTMs. In this context the following progress has been made: the ECRH deposition code Torbeam is now available as real-time diagnostic making use of the new real-time possibilities (see next section). A possible candidate scenario has been identified, which allows simultaneously central heating to suppress W-accumulation and heating at half radius for NTM suppression. For this scenario several discharges have been run to optimize the determination of the ECRH position with the ECE system. The determination of the NTM position with ECE is described in section 7.5. On the basis of these components the NTM feedback control algorithm can be detailed and dry-tested on the existing data before the start of the next campaign.

6.7 Data Acquisition and Computer Infrastructure

Main focus of the CODAC group was the conversion of existing diagnostics into real-time (RT) systems (see table 1) and the integration of these systems with the control system. Two real-time communication networks and a software framework to synchronize the workflow and to interface diagnostics and control system has been developed.

diagnostic	analysis	sytem type	chan.	sampl.rate	MB/s
MAC	RT	LabView	16	100 kHz	3.2
MAG	RT	LabView	80	10 kHz	1.6
Bolo	RT	LabView	128	2 kHz	0.5
RT-Video	RT	2x Linux	15	25 Hz	188
DCN	RT	SolSparc SIO	5+5	50 kHz	1
ECE	RT	SolSparc SIO	60+4	1 MHz	2x64
MSE	RT	SolSparc SIO	26	250 kHz	8
DTM	(RT)	SolSparc SIO	16	1 kHz	0.032
XVR	-	SolSparc SIO	128+64	500 kHz	128+64

Table 1: Diagnostics turned into real-time systems including analysis and control communication capabilities (incomplete list, work carried out in cooperation with resp. diagnosticians).

Closing the loop from control system commands over heating, fuelling and magnetic actuator systems to the plasma, and via RT diagnostic measurements back to the control system, this activity facilitates advanced feedback control schemes. Radiation feedback control is based on this structure and is routinely used to ensure high confinement operation in a full tungsten machine. Density profile feedback with a sliding mode controller has lately been commissioned.

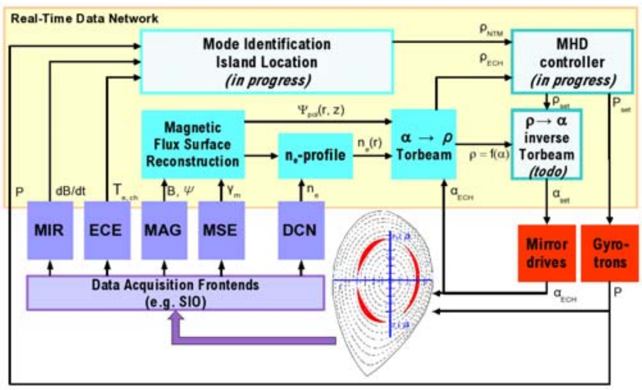

Figure 11: Schematic of the MHD activity control loop depicting real-time diagnostics, analysis and control processes, and actor system.

Also major parts of the MHD feedback loop (see figure 11) have been completed. It was shown that the Torbeam analysis diagnostic using various online processed quantities can provide the ECRH beam deposition location to the control system. The next steps will be to complete the MHD controller and to close the feedback loop.

7 Core Plasma Physics

7.1 Confinement Enhancement in Improved H-Modes with N_2 Seeding

Fusion reactors are likely to be operated with W as first wall material. Such a W wall is tested in AUG. Investigations of its compatibility with various tokamak scenarios are on-going, in particular hybrid scenarios envisaged for extended pulse duration. These scenarios require high heating power, thus raising the question of the tolerability of the heat load on the divertor.

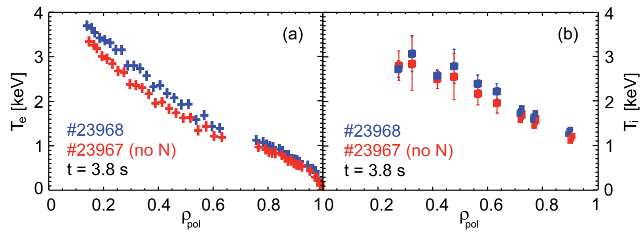

Figure 12: T_e profile with 3 % N_2 (blue) and without (red).

Radiative cooling at the plasma edge with N_2 seeding proves to be effective, even with a low contamination of the core plasma. Surprisingly, a confinement enhancement is observed, with H_{98} factors up to 1.28, even higher than those achieved in a C dominated device in the years 2002-2006. The improvement is very reproducible and it has been observed in freshly boronized as well as in unboronized conditions. The higher plasma energy (at the same input power) compensates the loss in neutron yield due to the higher impurity content in the case with N_2, yielding a similar neutron rate. Core transport is analysed, to identify the causes of the high confinement. Density peaking, which would be detrimental in a W device, can be excluded as a dominant contributor to the confinement improvement, as neither a higher density gradient nor W accumulation is observed. The main contribution is the increase of temperature profiles, in the core and in the edge of the plasma (see figure 12).

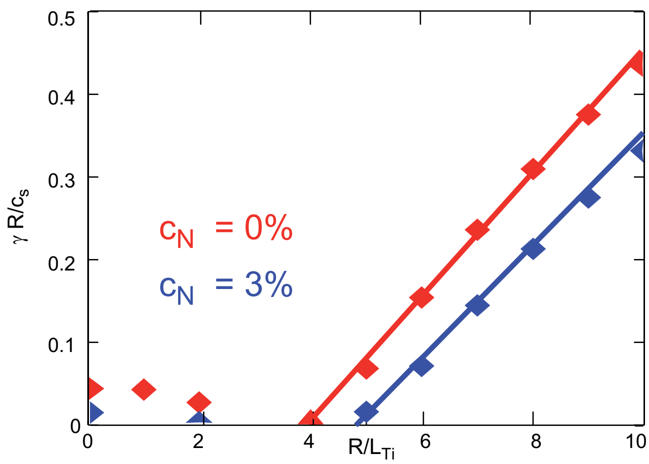

Figure 13: ITG stability analysis at half radius with the code GS2 with 3 % N_2 (blue) and without (red).

A stability analysis of similar discharges with and without N_2 seeding with the GS2 code highlights the role of deuterium dilution for the reduction of the core ion heat transport due to the ITG mode, dominant under the experimental condition (see figure 13). The reduced core heat transport, however, explains only partly the overall confinement improvement.

7.2 Central Impurity Transport

Previous studies have shown that central ECRH in NBI heated H-modes enhances the central impurity diffusivity and suppresses the neoclassical pinch (in one case giving rise to positive convection). Gyrokinetic GS2 simulations predict a positive turbulent convection in plasma regions where $R/L_{Te}>2\ R/L_{Ti}$, $q<1$ and low shear. To further test these conclusions in different plasma scenarios and to access the parameter space required by the GS2 calculations, the transport of argon has been studied in low density, pure ECR heated L-modes. Figure 14 shows the total Ar density profile evolution for on-axis (# 24709, right) and off-axis ECRH (# 24916, left), simulated with the experimentally determined sawtooth-independent transport coefficients. The Ar puffs were performed at 2.1 s. Approximately 1.1 MW ECRH power was deposited at ρ_p~0.22 and at ρ_p~0.63 respectively (magenta gaussians in bottom plots), with sawtooth inversion radii at ρ_p~0.4 and 0.3. Clear faster central diffusion is observed for on-axis ECRH (right), as well as less peaked central density. A closer look at the peaking parameter $v/D=1/n\cdot\partial n/\partial r$ (normalized density gradient), shows how on-axis ECRH leads to a global positive convection around its deposition region which translates into a hollow central equilibrium Ar density profile. For off-axis heating, v/D is instead negative for the full range. GS2 and neoclassical calculations are being performed to better understand these phenomena.

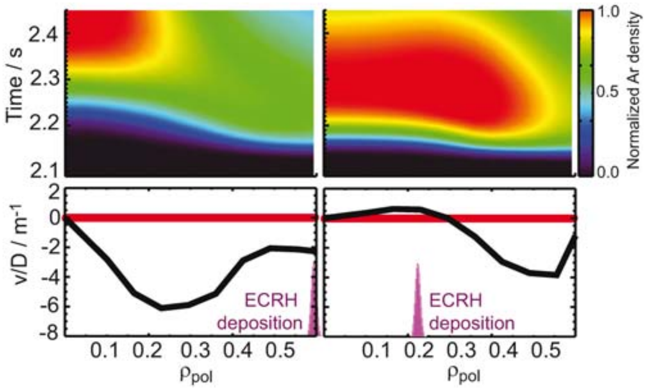

Figure 14: Ar density profile evolution (top) simulated with experimentally deduced transport coefficients (bottom); left off-axis, right on-axis ECRH.

7.3 GAMs, I-mode and the L→H Transition

Using two swept frequency Doppler reflectometers – in toroidal sectors 5 (fixed) & 13 (stepped) – the Geodesic Acoustic Mode $E\times B$ flow oscillation (driven by non-linear turbulence interactions) is found in L-mode to be highly correlated across its finite radial (zonal) extent (i.e. long range toroidal/poloidal correlation) confirming the $m=n=0$ mode structure. A controlled transition into the H-mode can be engineered by ramping the additional heating power. At low collisionality (low density and strong ECR electron heating) the L-mode improves with the edge negative E_r well (i.e. mean $E\times B$ flow velocity) deepening by a factor of 2 and enhanced, fast pulsing of the turbulence amplitude. The GAM is still strong in this I-mode but its radial extent and correlation are reduced – as shown in figure 15 – e.g. the GAM k_r increases, commensurate with the narrower/deeper E_r well. With increasing power the energy confinement (H_{98}) rises, scaling with the E_r well depth. Just before the H-mode transition the GAM becomes stronger, more correlated and radially narrower; but then disappears with the drop in turbulence as the H-mode develops. The relative causality between the GAM and turbulence remains to be clarified, however, the enhanced turbulence eddy shearing due to the GAM prior to the L-H transition may provide the much sought after trigger initiating the well-known $E\times B$ velocity shear feedback loop and subsequent bifurcation into the H-mode.

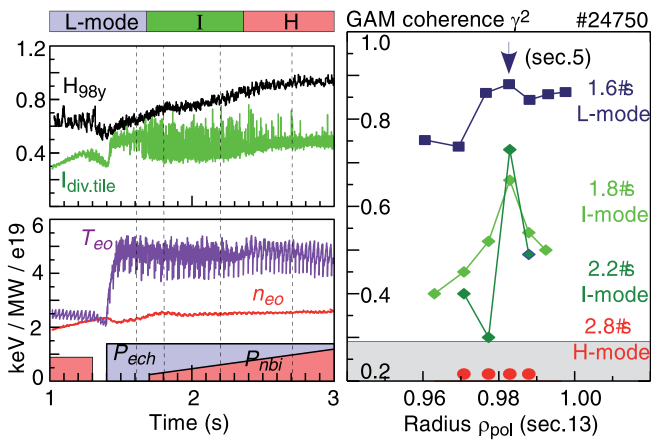

Figure 15: (a) Parameter time traces showing transition to I-mode & H-mode during power ramping at low density (b) Radial profile of GAM toroidal correlation at indicated time points.

7.4 Safety Factor during Stochastic Phase of the Sawtooth Crash

Investigation of sawtooth crashes shows that in many cases the magnetic reconnection is not complete. In this case, the mode (m=1, n=1) survives the crash and position of the resonant surface can be determined also after the crash event. Analyses of such sawteeth show that position of the q=1 surface remains the same during the crash. This experimental result is consistent with the stochastic picture of the sawtooth crash where q=1 remains at the original position after the crash. The stochastic phase during the crash can be also modelled by means of mapping technique as shown in figure 16.

One can define a safety factor value for each magnetic field line and investigate the safety factor behaviour during stochastic phase of the crash. It is clearly seen in the figure that all lines inside the island have the same helicity, as expected from the topology of m=1 and n=1 structure (q=1). The stochastic area consists of several different values of safety factor which are overlap in the same region. It is interesting that even in highly stochastic phase, the main feature of safety factor profile remains the same (smaller is in the core and higher close to the q=1 surface). This points to small changes in safety factor (and current profile) during the crash which was also reported by others experiments.

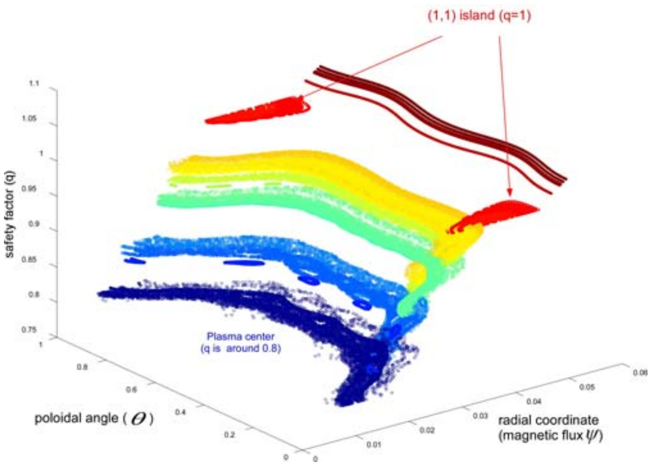

Figure 16: Modelled safety factor during the stochastic phase of a sawooth crash.

7.5 Localisation of MHD Activity in Fast ECE Measurements

The 60-channel electron cyclotron emission (ECE) radiometer measures the radial electron temperature (T_e) profile with 1 MHz sampling rate and radial resolution of approximately 1 cm across most of the plasma minor radius. Correlation of the radiometer measurements with other diagnostics provides a powerful tool to study the correspondence between radially localized T_e fluctuations and other signatures of activity, e.g. oscillations in external magnetic measurements caused by magnetic islands or fast ion losses associated with Alfvén eigenmodes. The former example is incorporated into a real-time system for locating and suppressing neoclassical tearing modes (NTMs): as the T_e profile crosses the center of the NTM, the phase of T_e oscillation undergoes a phase shift of 180° with respect to magnetic measurements at the mode frequency. This determines the NTM radial location, and allows ECRH power to be deposited at the correct location to stabilize the mode. In the latter example, correlation of T_e and fast ion loss detector (FILD) measurements in the respective frequency bands of toroidal Alfvén eigenmodes (TAEs) and Alfvén cascades (ACs) allows the radial structure, possible overlap, and consequences for ejection of fast ions to be revealed (see figure 17).

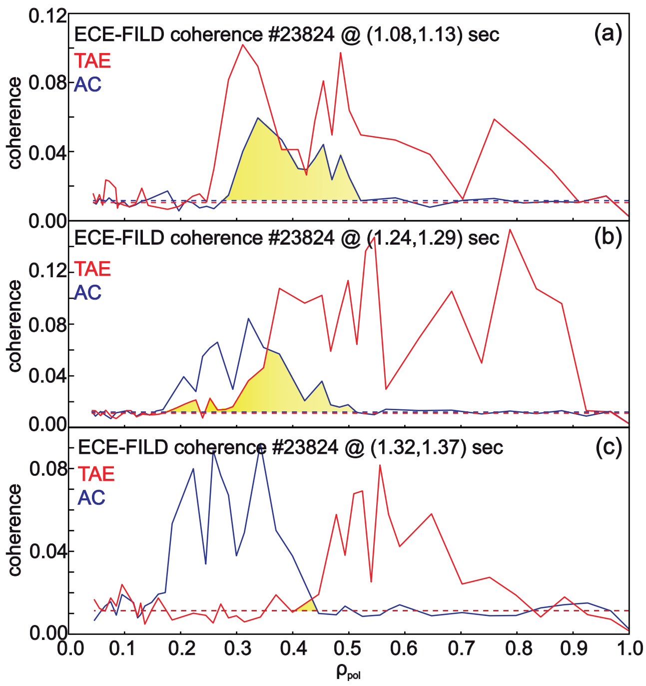

Figure 17: AC and TAE radial structures obtained by ECE-FILD coherence calculation, showing evolution in time from highly overlapped to negligibly overlapped mode structure.

7.6 Massive Gas Injection

Massive Gas Injection (MGI) experiments with the in-vessel valve have continued in 2009. The fast valve, close to the plasma, is advantageous for MGI shut-down since it reduces the time delay between trigger and start of the plasma current quench and has a larger fuelling efficiency with respect to valves located further away. Neon has advantages with respect to other noble gases in mitigating the disruptions in AUG and allows to reach the highest ratio between the effective electron density and the required critical density in runaway electron (RE) suppression experiments. The vertical forces and divertor localized heat loads start being significantly reduced by a tolerable amount of injected neon, which rises the line averaged electron density of $\Delta n_e \sim 10^{20}$ m^{-3}. The forces are further reduced by raising the density up to $5{\cdot}10^{20}$ m^{-3}; above this value, the current quench time and the radiated power reach asymptotic values and the increase of injected impurities does not decrease further the mechanical loads. The radiated energy measured by the AXUV diagnostic is highly toroidally asymmetric and larger close to the valve before the thermal quench; however the degree of toroidally asymmetry of the radiated energy integrated during the whole disruption has been observed to be small (factor of 2 between energy radiated in one sector and average).The plasma density required to assure the collisional suppression of runaway electrons in ITER is two orders of magnitude larger than the one needed for forces and heat load mitigation. Progress has been made in attaining an effective electron density closer to the critical one, namely $n_{e,eff}/n_c$~24 % , by injecting 3.3 bar · l of neon. At this large amount of injected impurities the fuelling efficiency remains at the level of 20 % for plasmas with a modest thermal energy (<0.4 MJ). Nevertheless, a significant decrease of this efficiency with increasing plasma thermal energy has been observed at large amounts of injected helium and neon atoms. Independent of the thermal energy, the density distribution is very poloidally and toroidaly asymmetric implying that multiple valves are needed to raise the density further. The fast current decay and the slow impurity redistribution in the plasma at large amounts of injected gas is the physics limit, which could prevent the applicability of this method to runaway suppression in ITER.

7.7 Z_{eff} Profile Analysis

The concept of Integrated Data Analysis (IDA) within the framework of Bayesian probability theory was applied to the combined analysis of CXRS and bremsstrahlung diagnostics to reconstruct Z_{eff} profiles. Redundancies provided by the joined analysis of the heterogeneous diagnostics allows one to resolve data inconsistencies due to wall reflections, gas fueling and passive line distortion of the bremsstrahlung background. The Z_{eff} profiles are validated using freshly boronized H-mode discharges with low impurity content and Helium discharges with known Helium concentration. Consistent results from simulations of the loop voltage and the neutron rate based on the reconstructed Z_{eff} profiles compared with the corresponding measurements could be obtained. Nitrogen seeding in the divertor results in an increased energy confinement. Although a detrimental effect of the Nitrogen impurity in the plasma was expected, the observed increase in the H-factor is correlated with an increase of Z_{eff} (see figure 18).

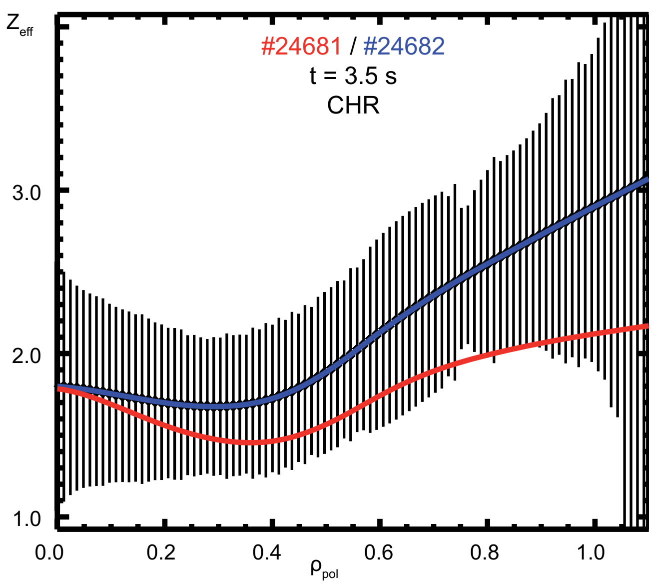

Figure 18: Z_{eff} profiles with (blue) and without (red) Nitrogen seeding in the divertor.

7.8 2D ECE-imaging

Early 2009 the new 2D Electron Cyclotron Emission Imaging diagnostic (ECEI) became operational. This diagnostic provides a high resolution 2D measurement of T_e and its dynamics. The ECEI diagnostic shares a vacuum window and part of its optics with the existing 60 channel 1D ECE system. It measures the temperature in an array of 8 (horizontal) by 16 (vertical) positions (so 128 channels total) in the poloidal plane, covering an area of about 13 by 40 cm. The data is sampled at up to 1 MHz. This powerful tool for the study of MHD instabilities in the plasma has taken a vast amount of data already of a variety of instabilities. Among them are sawtooth crashes, (neoclassical) tearing modes, edge localized modes (ELMs) and Alfvén modes.

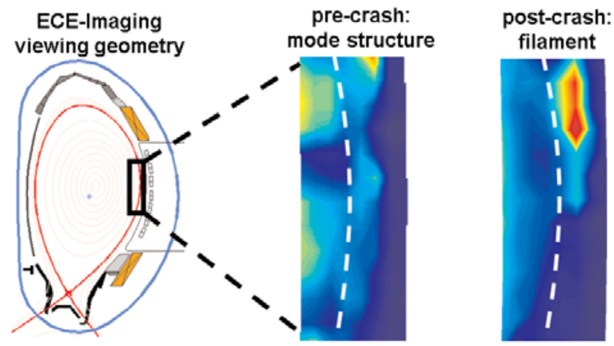

Figure 19: ECE-Imaging edge T_e measurements from two phases of an ELM crash.

An example of 2D data taken during an ELM crash is shown in figure 19. This data, taken at the plasma edge, shows two 'movie frames' taken at two phases of an ELM crash. Just before the actual crash the 2D structure of a precursor mode is visible. After the crash several hot filamentary structures (only one shown) are observed passing through the ECEI observation volume. Another example of ECEI data (the structure of an Alfvén mode) is shown in section 4.

8 Edge and Divertor Physics

8.1 EMC3 Modelling of Limiter Discharges

Owing to toroidal axisymmetry tokamak plasmas are usually simulated by 2D models. However, certain phenomena, e.g. the plasma-limiter interaction, the localized injection of impurities into the SOL or the application of perturbation coils are intrinsically 3D phenomena. For this reason the Edge Monte Carlo 3D (EMC3) – Eirene code package was implemented. EMC3 solves the Braginskii equations on a three dimensional grid by means of a Monte Carlo approach, while Eirene simulates the neutral particles. As a first benchmark, the 2D situation of a plasma limited by the toroidally symmetric inner heat shield was simulated and compared to previous simulations by the SOLPS 5.0 code package.

Despite a discrepancy in the boundary conditions the two codes were in good agreement. In a second step the full 3D situation of a plasma limited at the low field side was modelled (see figure 20) and compared to the measurements by the Li-beam and the ECE diagnostics. Similar profiles, as well as similar absolute values of n_e and T_e were found. Additionally, EMC3-Eirene has been implemented to the divertor configuration and tested successfully for a divertor discharge. A benchmark with SOLPS is ongoing.

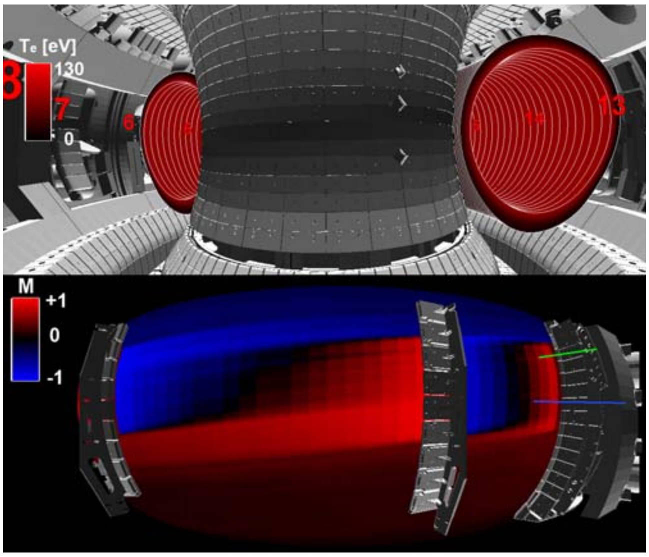

Figure 20: T_e (top) on the entire grid and Mach number $M_{||}=u_{||}/c_s$ (bottom) on the flux surface ρ=1.01 computed for a limiter phase by EMC3-Eirene.

8.2 Flushing and Erosion of W during ELMs

The outer limiters have been identified as the dominant W source area with regard to the plasma W content, while the absolute W fluxes are considerably higher in the divertor. At the limiters, about 70 % of W sputtering is due to ELMs. ELM sputtering as well as inter-ELM sputtering is dominated by the impact of low-Z impurities. Nevertheless, discharges with lower ELM frequency usually have higher tungsten concentration in the confined plasma. The sputtering and edge transport of tungsten during an ELM cycle has been modelled with the multi-impurity transport code STRAHL. The W influx is calculated from the impurity ion losses to the wall, the yields for physical sputtering and the fraction of not promptly re-deposited W ions. The impurity transport coefficients in the radial region of the edge transport barrier (ETB) are taken to be neo-classical for the light impurities and W. Thus, a large inward pinch is acting in-between ELMs and leads to a strong peaking of W across the ETB. The increased radial transport during the ELM causes a flushing of W from the confined region with each ELM. At the limiters, T_e and T_i increase during the ELM and impurity ions with higher charge hit the plasma facing components, leading to a sharp increase of the W influx. The evolution of T_e and T_i at the limiters is not measured with sufficient precision and is adjusted in the code to fit the measured W influx evolution. An example for the modelled W density evolution during an ELM cycle is shown in figure 21.

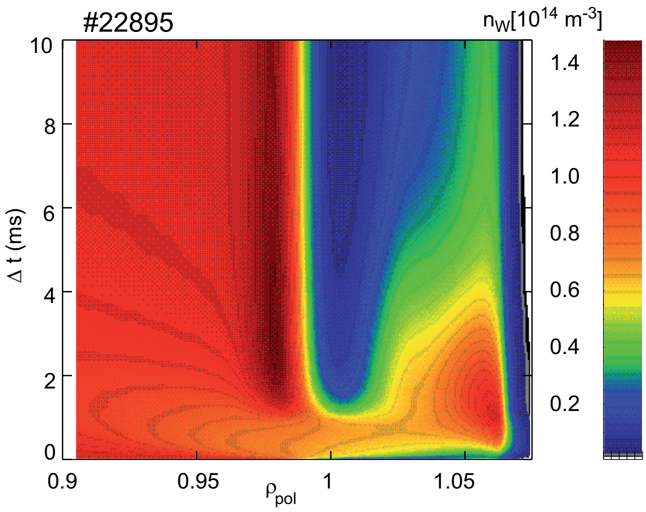

Figure 21: Modelled evolution of the total W density n_W during one ELM cycle.

For a set of H-mode plasmas with ELM frequencies between 50 and 200 Hz, the model described the measured decay of the temporally averaged W density in the confined region to within 10 %. This encouraging result needs further experimental investigations on the various assumptions used within the code. However, it seems that the dominant mechanisms of tungsten edge transport have been captured.

8.3 Divertor Detachment

For deuterium fuelled Ohmic and L-mode discharges a strong asymmetry of the peak ion flux density between the inner and the outer target is observed. At the outer target the peak ion flux density initially increases and finally decreases during partial detachment as a function of line averaged density. Along the vertical target plate at the inner target the ion flux density vanishes completely, defined as full detachment, an observation which cannot be recovered in numerical simulations by the code package SOLPS 5.0 using a standard set of boundary conditions and parameters (as e.g. currently used for predicting the divertor performance in ITER). In He fuelled discharges the outer target reaches partial detachment at the highest line averaged density. At the inner target the ion flux density at the strike point steadily decreases whilst remaining relatively constant in the far SOL as a function of line averaged density. This behaviour is also not seen in numerical simulations. However, the poloidal distribution of the total radiation is qualitatively reproduced in the simulations for He fuelled discharges. It has been assessed that the failure of modelling detachment at the inner target is not solely a problem of an inadequate description of volumetric atomic and/or molecular processes and their related power and momentum exhaust. Inclusion of additional processes in the SOL appears to be necessary for understanding the detachment along the inner target plate. Simply adding a parallel momentum source in the simulations, generating additional parallel flows in the SOL, does not lead to an enhanced degree of detachment along the inner target plate for He and for D fuelled discharges.

8.4 Target Power Load after Boronization

Comparable improved H-mode discharges were run with and w/o boronization. Whereas the plasma stored energy and the line averaged density was comparable for the discharges, the edge behaviour and the power flow into the divertor revealed significant differences. The divertor heat load profiles became steeper by a factor of two and the target averaged power was increased by a factor of 1.25 for the boronized discharge. In accordance with this result the edge T_e and pressure profile in the midplane separatrix region were found also to be steeper. The electron temperature is about 20 % higher and the electron density slightly lower in the pedestal region for the discharge without boronization. These experiments show that even without affecting the performance of the core plasma expressed as plasma stored energy the heat load into the divertor can be strongly influenced by the wall condition. This demonstrates that for machine safety, the use of global parameters like input power and radiated power to estimate and restrict the divertor load is not sufficient.

8.5 Radiation Distribution during Impurity Seeding

After boronization in the full W device the radiation level has decreased due to the reduced level of radiating intrinsic impurities. In order to avoid too high power fluxes to the divertor, radiative cooling was achieved by feedback controlled injection N_2. Whereas in un-seeded discharges a total radiated power of about 60 % of the input power was observed, the radiation level in the nitrogen seeded discharges increased as expected to a level of about 80 %. However the distribution of the radiation changed significantly: the increase of the total radiated power is mainly caused by increased radiation from the X-point and divertor region, where the ELM averaged local radiation emissivity increased by more than 50 % to values comparable to former campaigns with mixed carbon and tungsten PFCs. The radiation during type-I ELMs raised from 20 % of the ELM energy in un-seeded discharges to 40 % in nitrogen seeded discharges, mainly due to the decreased ELM energy. This value is comparable to that found previously with carbon PFCs. Consequently, the power load to the divertor targets during type-I ELMs dropped significantly with nitrogen seeding.

8.6 Optimisation of Divertor Power Load Feedback Control

To further optimize the feedback system for the divertor power load using nitrogen injection, an analytical model for the plasma response to the N_2 injection was developed. The model solves the nitrogen particle balance taking into account the valve flux, the pumped flux and the storage and release of nitrogen by the tungsten plasma facing components. Intermittent wall and divertor storage of nitrogen was found to have a strong impact on the N_2 gas consumption, leading to a by a factor of 3 increased nitrogen puff rate for unoccupied wall conditions. Results from laboratory experiments suggest the formation of a thin nitride layer in the region close to the W surface. Saturation of nitrogen storage occurs when about 1:1 N/W atomic ratio is reached over the first few nanometers, which corresponds to the nitrogen penetration depth for ion impact energies around 100 eV.

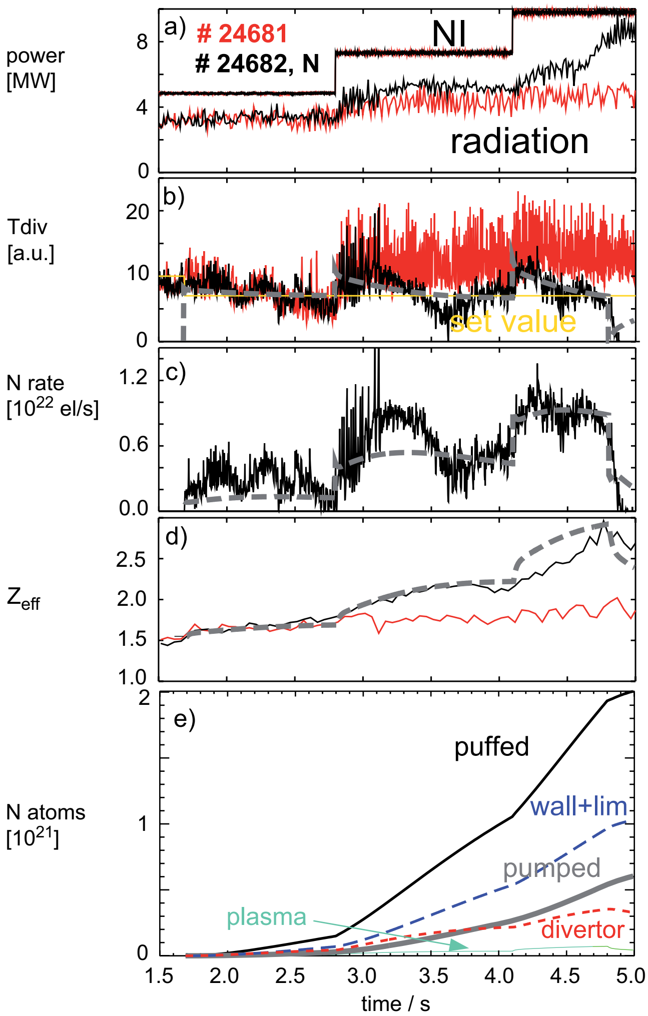

Figure 22: Heating power and radiated power of two discharges with (black) and without (red) divertor power load control. b) T_{div}, measure for divertor temperature/power load for the two discharges and model prediction for the seeded pulse. c) experimental N puff rate and prediction by the analytical model of the feedback system. d) measured and modelled development of average plasma Z_{eff}. e) Model prediction for the N particle balance.

The nitrogen is released from the tungsten surface by a sputtering-like process, leading to a latency of about 3 discharges without injection until the nitrogen level has dropped to a small level. Figure 22 compares two discharges with and without divertor load control for unboronized conditions. The prediction of the feedback model for the discharge with nitrogen seeding is also shown. At the end of the N_2 injection phase, most of the N atoms stick to wall, limiter and divertor surfaces, about one third has been pumped. As usually observed, the discharge with nitrogen injection exhibits improved energy confinement, which was found to correlate with the increase of Z_{eff}.

8.7 Pellet ELM Pacing

Investigations for advanced ELM pacing using pellet injection were continued. In order to reduce the deleterious impact on the confinement due to additional convective particle losses found in previous experiments, the blower gun pellet injector was modified. Originally laid out for fuelling size pellets (cylindrical shape, length=diameter=2 mm, nominal particle content $3.8{\cdot}10^{20}$ D) the pellet dimensions were now reduced (l=d=1 mm, $0.5{\cdot}10^{20}$ D). However, sustainable and reliable operation was found to be delicate in this operational domain. Further development and optimisation is required to achieve pellet pacing at high repetition rates with low fuelling impact. Hence, investigations were focused on the trigger physics in single events taking advantage of the intrinsic pellet size scatter to encompass the pellet size respectively penetration depth required to achieve ELM triggering. Confirming recent experimental findings from JET it turned out very shallow penetration is not sufficient to generate an ELM event. Reliable triggering can only be achieved for pellets reaching about the pedestal top of the plasma pressure profile.

8.8 ELM Characteristics in Helium Discharges

To achieve sufficient confidence on the predictions for ITER on behaviour of ELM and their mitigation techniques, it is important to compare ELMs in He and D plasmas in present day experiments. In AUG helium H-mode discharges, a similar ELM phenomenology as in deuterium is observed showing both type-I and type-III like behaviour. A somewhat larger heating power in He than in D seems to be needed to enter reliably the type-I regime. The fraction of ELM energy losses W_{loss}/W_{MHD} lies in the same range as in D discharges and scales similarly with confinement and ELM frequency (see figure 23). About 50 % of the energy loss reaches the targets. These first results indicate that type-I ELM regime in He is reached with $P_{tot}/P_{thr}(He)\geq 1.5$. Assuming for ITER about 70-80 MW available for heating and the predicted $P_{thr}(D)$=53 MW, type-I ELM may be reached only if $P_{thr}(He)\sim P_{thr}(D)$ as found earlier in AUG. If the LH power threshold is considerably higher, as seen in JET, type-I ELM may be still obtained in He discharges at reduced plasma current.

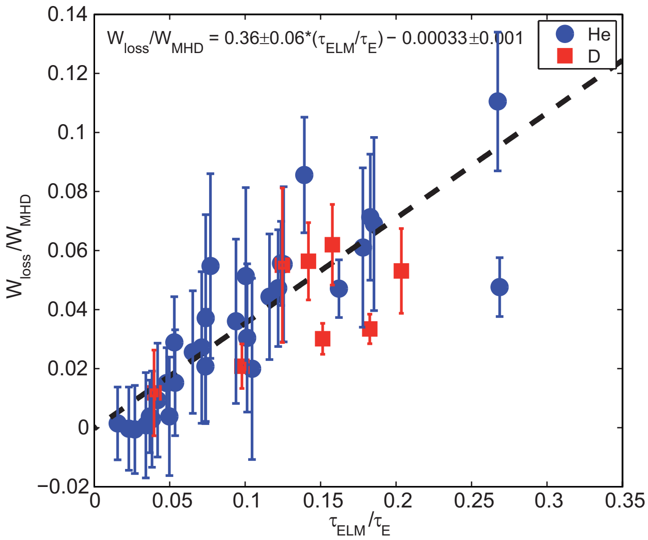

Figure 23: Energy loss fraction as a function of the ELM period normalized to τ_E for discharges with δ> 0.2.

8.9 Controlled W Melt Investigations

A key issue for the use of a full W divertor in the ITER experiment is the possibility of W melting by off-normal transient heat load excursions. Apart from structural damage to the plasma exposed surfaces, release of molten W into the divertor plasma may lead to an unacceptable rise of the W core concentration (c_W) and corresponding degradation of plasma performance. To study the behaviour of molten W in the divertor and its possible escape towards the main plasma, a W pin of 1×1 mm^2 cross-section and 3 mm length was exposed at the outer target plate using the divertor manipulator system. The pin was exposed in an H-mode discharge with 6 MW auxiliary heating. The temporal evolution of the melt event was observed by a fast camera system with 20000 fps while the W source in the divertor as well as c_W were measured spectroscopically. Inspection of the retrieved sample revealed that molten W droplets had flown down along the sample almost vertically. From this observation one can infer that gravity is the dominating force on the molten droplets, at least as long as the droplets are in contact with the target surface. The fast camera showed, however, that W-droplets are also ejected into the plasma, where they move along the divertor over toroidal distances of the order of 1 m. An important observation was that the droplets all move into the same direction of the plasma flux, i.e. away from the core plasma. Penetration of evaporated W from the melting rod or the droplets into the confined plasma was compared to that of a main chamber W source by subsequent W laser blow off (LBO) and measuring the respective response of c_W. After exposure, the entire part of the W-rod protruding above tile surface level was found to be melted away, resulting in a mass loss of about 15 mg. The number of $4{\cdot}10^{18}$ atoms was estimated to be evaporated from the impinging power flux and W vapour pressure data, corresponding to about 10 % of the droplet material. Although this is 10 times more than the number of atoms ablated by the LBO, the corresponding increase of c_W is only half as much as for the LBO source. This demonstrates that the divertor efficiently retains evaporated W material, comparable to the retention of sputtered tungsten.

8.10 Dust Investigations

The licensing procedure of ITER promotes the topic of dust in fusion devices. Dust was collected, quantified and characterized and detailed investigations were carried out by optical microscopy, SEM and EDX yielding a variety of different shapes and chemical elements. Their composition and morphology indicate that many particles were produced by in-vessel work and workers as well as by non-perfect components of in-vessel diagnostics. One has to distinguish between dust (plasma-produced or plasma contact) and debris (everything else). Special collectors were used to gather only particles produced or mobilized by the plasma. Whereas sub-micron particles are predominantly W spheres, bigger particles often consist of an agglomerate of boron, carbon and tungsten. The spheres are presumably droplets produced by arcs on the W coatings. The agglomerates show the same morphology as the deposited layers at the inner divertor baffle region. Complementary to these studies, dust events in the plasma are observed by a fast camera. Apart from the initial conditioning phase, dust is mostly observed after disruptions. Since the trajectories after disruptions are straight lines, it could be inferred, that the interaction of the particles with the plasma is only weak. The typical speed of the particles is 10-100 m/s. The huge amount of agglomerates collected and their delicate structure point to the fact that most of them did not experience strong plasma contact and therefore are not detected by the cameras.

8.11 Gas Balance Investigations

During the last years hydrogen retention has been studied by surface analysis and gas balance methods. To complete these investigations, different kinds of relevant discharges are repeated with longer plasma flat top after the re-commissioning of generator EZ4. The amount of gas puffed, which is the most relevant parameter for wall saturation, was enhanced by 50 %. Previous results could be confirmed with a higher accuracy. During the 2008 campaign the amount of gas, which as to be temporally retained to reach wall saturation, was $2{\cdot}10^{22}$ at for the unboronized and $1.5{\cdot}10^{22}$ at for the boronized wall. In 2009 only 1.2 to $1.5{\cdot}10^{22}$ at are needed, even if the wall was not boronized. As proposed by ALCATOR C-mod, experiments were performed where only with the in-vessel cryo pump was operated to enable high accuracy gas balance measurement using the in vessel pressure after cyro pump warm up, i.e. 10 minutes after the discharge. This procedure excludes the use of the NBI sources in AUG, i.e. allows operation only with low gas puffing levels. High (medium term) retention of 25 to 50 % of the amount of gas puffed was observed. The absolute amount of retained deuterium (0.6 to $3{\cdot}10^{20}$ at) in these shots agrees well within the error bars with the retained amount obtained in the high density discharges. Therefore, the apparent discrepancy of the C-mod and AUG results seems to be due to the different amount of gas puffed during the discharges.

9 Stuttgart University

IPF at Stuttgart University contributes directly to the experimental program in the fields ECRH technology, ECRH of ITER-relevant discharges using the O2- and X3-mode, turbulent transport studies in the plasma edge and reflectometry. The activities related to ECRH and turbulent transport are summarized in the respective sections of this report. For interpretation of Doppler reflectometry measurements, IPF carries out simulations with the IPF-FD3D full-wave code. Doppler reflectometry is an important diagnostic for density fluctuations and poloidal flows on fusion experiments. For the interpretation of fluctuation data, the dependence of scattered power on the fluctuation strength needs to be calculated with numerical methods. The IPF-FD3D code is used to simulate wave propagation and scattering in magnetized plasmas. In 2009, extensive simulations of Doppler reflectometry in turbulent plasmas were carried out for O- and X-mode polarisations. It was found that a priori knowledge of the radial fluctuation spectrum is necessary if one wants to reconstruct the turbulent poloidal spectrum of the fluctuations. It was then possible to recover this spectrum from the Doppler signal. It is planned to extend these investigations to AUG geometries in 2010. Furthermore, IPF actively contributes to the development of a European Reflectometry Code.

10 International & European Cooperations

10.1 International Cooperations

The role of the Implementing Agreements (IA) as a vehicle to enable joint experiments (J.E.) proposed by ITPA was also of high importance in 2009. AUG contributed with dedicated experiments to 19 ITPA J.E. Among others, studies of plasma breakdown using ECRH assist, simulations of the plasma current ramp-up and ramp-down (ITPA IOS 2.2), were conducted. The 2008 results of ECRH assisted breakdown were extended to a toroidally inclined launch (ITPA IOS 2.1). Breakdown in X2 mode could be demonstrated for toriodal injection angles up to 20°. Plasma current ramp-ups with an electric field as low as 0.2 V/m (ITER design value: 0.33 V/m) were achieved. These ITER relevant studies were done together with a visiting scientist from EFDA-JET. A broad collaboration between AUG, DIII-D and the University of Irvine (California) has been started on energetic particle physics.

The AUG team is giving advice for the design of a Fast-Ion Loss Detector (FILD) for the DIII-D tokamak. The University of Irvine is supporting IPP in the development of a Fast-Ion D-Alpha (FIDA) diagnostic through its expertise with the interpretation code of the measured spectra. In the framework of ITPA J.E. Alfvén Eigenmodes have been driven unstable in AUG by NBI fast-ions. NBI pre-heating during the current ramp-up phase in low-density plasmas has allowed the identification of Toroidal Alfvén Eigenmodes (TAEs) and Reversed Shear Alfvén Eigenmodes (RSAEs) through global and local fluctuation measurements. The radial structures of TAEs and RSAEs were reconstructed using the fast Soft-X Ray diagnostic, the Electron Cyclotron Emission radiometer and the multiband reflectometer. More details on these results can be found in section 4.2.

Together with the University of San Paulo, Brazil, ICRH beat wave experiments were prolonged with the aim to excite TAE, EAE, Kinetic Alfvén continuum eigenmodes that may allow to determine the q-factor profile and the effective ion mass number. In discharge # 25509, after a minor disruption at t=3.18 s, a that series of TAE (or kinetic TAE) were excited by the ICR beat wave at f≈140 kHz producing a strong loss of accelerated ions which were observed by FILD. This emission of TAE spectrum was also seen by SXR and MHD diagnostics. The effect will be analyzed to understand the detailed conditions (mode number spectrum and it's radial position) for the mode excitation.

In another study the effect of plasma rotation on spectral characteristics of *sierpes* (or geodesic acoustic Alfvén) modes was investigated. In ICRH beat wave experiments these modes were excited and the effect of NB blips (# 25510) were compared with ECRH blips (# 25508) of equal length. It is found that the frequency of *sierpes* modes is slightly modified by ECRH due to the increasing electron temperature. In case of NB injection the frequency is strongly increased due to higher plasma rotation. The Doppler effect may partly be responsible for that frequency change.

10.2 EURATOM Associations

More than 40 scientists from 14 EURATOM Associations and from EFDA-JET participated in the 2009 AUG experimental campaign. The AUG Programme Committee responsible for the AUG programme met twice in 2009. The following EU Associates are represented in this body: CCFE, CEA, CRPP, DCU, ENEA, FZ-J, HAS, ÖAW, RISØ and TEKES.

CCFE (former UKAEA)

ICRF coupling experiments were performed on AUG in the framework of the EFDA task WP09/HCD-02/04 by a joint IPP/CCFE team. The goal of the experiment was to assess if local D_2 gas injection can be used to improve antenna coupling and to characterize the impurity and SOL electron density behaviour in these conditions. Various gas valves in the tokamak equatorial plane were used and the antennas were powered sequentially to characterize the effect of each valve on the coupling of each antenna. Preliminary analysis suggests that improved antenna coupling was obtained with local gas injection.

CCFE was involved in experiments at AUG to determine if the observed reduction in accumulation of W and Si during ECRH core injection is related to the theoretical effect of non-adiabatic passing electrons. This objective requires a study of the Z dependence of impurity transport in plasmas with varying level of core ECRH power. To achieve this, W, Ar and Si were injected into plasmas with ECRH power levels up to 1.5 MW with 5 MW of NBI and, in addition, the stationary profiles of B and He were measured. Analysis of the data obtained is ongoing.

Experiments have been performed on AUG and MAST to study why type II ELMs exist and why their energy loss is so small (ITPA PEP21). It has been shown that the parameter space for which these small ELMs exist is very similar on both devices. The ion saturation current has been measured on both devices as a function of distance from the separatrix and the radial decay length and spatial structure determined. A detailed comparison with similar results obtained during type I ELMs is ongoing.

Controlling the sawtooth instability will be an important technique for improving neoclassical tearing mode (NTM) limits in ITER. However, fusion-born particles are likely to stabilize the sawteeth, making them more likely to trigger deleterious NTMs. Experiments at AUG (contribution to ITPA MDC-5), have utilised the high-power steerable gyrotron to scan the deposition of electron cyclotron current drive in order to control the sawteeth. The change in the magnetic shear around the mode's rational surface resulted in significant changes in the sawtooth behaviour, even in the presence of very energetic particles born due to concurrent ion cyclotron resonance heating.

An experiment to study the effect of aspect ratio on Neoclassical Tearing Mode stability has been performed on AUG in collaboration with the MAST team (ITPA MHD-4). AUG and MAST are well matched in plasma shape, size and plasma current, but have very different major radii. Detailed analysis of the data will allow a direct evaluation of how aspect ratio affects the seeding mechanism for the NTM, the island evolution and the physics of NTM stabilisation at small island size.

The AUG Task Force '*SOL & Divertor physics and first wall materials*' was managed by a CCFE scientist for the period 2008/09.

CEA

Experiments were performed to study the relationship between impurity transport behaviour and the electron temperature profile. Impurity transport behaviour has been investigated by means of SXR signals of Si laser ablations. Modifications of the electron temperature profile were obtained by a scan of the electron heat flux at mid-radius produced by heating the plasma with ECRH at two different radial locations, central and off-axis, and changing the power fractions at the two locations,

while keeping the total heating power fixed. Impurity transport analysis will be performed with the ITC code at CEA. AUG plasma and diagnostics geometry have been implemented in the code, analysis of discharges is ongoing. Connected electron heat transport analysis has also started.
The method of pyro-reflectometry for measuring spot temperatures (pyrometer like) was tested at AUG. The active measurement to deduce the emisivity works well in the lab (also with AUG test probes). During in-situ measurements in AUG, however, the measurements suffered from too low signal to noise ratio. A more powerful laser would be required to overcome this restriction.

CIEMAT

The continuing study of plasma turbulence behaviour was assisted by a new collaboration with the CIEMAT Reflectometry Group. Re-commissioning the W-band Doppler reflectometer system with the low-field-side remote steerable antenna preceded dedicated scans of the turbulence wavenumber k-spectra to validate and extend previous measurements from the plasma edge region to mid-core during NBI heated L and H-mode conditions. The $k_\perp$-spectra show the expected flat behaviour at low k and a power law $k^{-\alpha}$ dependence at high $k_\perp$ with a knee-point around $k_\perp$~6-7 cm^{-1}. In 2D turbulence theory the knee corresponds to the energy injection scale, implying a preferentially excited 1 cm structure size. The spectral index α is around 4 in the L-mode edge, increasing slightly towards the core; while in H-mode α~7 in the edge and rises more strongly in the core. The knee-point also tends to move to higher values for decreasing radius (L-mode: $k_\perp\rho_s$~0.7 – 1.0 & H-mode: $k_\perp\rho_s$~1.6) – due to the enhanced Larmor radius. The turbulence falls towards the core – in both L and H-mode this reduction is predominantly at low $k_\perp$ < 8 cm^{-1} while the high $k_\perp$ is mostly unaffected. Previous H-mode gradient data also showed the same low $k_\perp$ drop but with a corresponding increase at high $k_\perp$ – consistent with the theory of turbulent eddy break-up by enhanced mean sheared flows. Finally, an important confirmation was the independence of the measured flow velocity $u_\perp$ from the probing $k_\perp$.

DCU – University College Cork

Progress made during 2009 in the context of the ongoing collaboration between IPP and University College Cork is summarized as follows: (1) Thorough testing and debugging of the fortran 90 version of the CLISTE code was carried out with extensive help from IPP personnel. The work to make the code machine-independent by removing embedded AUG-specific data is now underway. (2) A simplified algorithm for equilibrium database generation of Function Parameterization models that use both magnetic and MSE data for the purpose of realtime control of NTM's was developed and successfully tested offline. (3) Work has progressed on a PhD topic to study the influence of fast particles distributions on the β-limit using gyrokinetic simulations and the CLISTE code. Using CLISTE equilibrium solutions constrained by T_e, n_e and T_i data the kinetic ballooning mode dispersion relation was solved numerically to identify β- and toroidicity-induced Alfvén eigenmodes.

ENEA

Experiments on disruption avoidance have been carried out at AUG in collaboration with ENEA-Frascati and IFP-Milan. The localized injection of ECRH (1.5 MW) on a resonant surface has led to the delay and/or complete avoidance of disruptions at high β_N discharges (I_p=1 MA, B_t=2.2 T, H-mode with 8 MW NBI). In these low q_{95} and low density discharges NTMs get excited at the resistive β-limit and when they lock a disruption occurs. As soon as the disruption precursor signal (the loop voltage and/or locked mode detector) reaches a preset threshold, ECRH power is launched by the RT control (ECRH pulse duration 1 s). A poloidal scan in deposition location (ρ_{dep}) has been carried out by varying the angle of launching mirrors from one discharge to the other. Complete avoidance has only been achieved when the ECRH power is deposited close to the q=3/2 surface. In this case multiple unlocking of MHD modes occurs after ECRH application. When ECRH is injected at more external locations, the discharges, although not disrupting immediately as in the reference case without ECRH, show no mode unlocking and eventually disrupt. A threshold effect has also been observed: if the ECRH power injected on the q=3/2 surface is less than 0.8 MW no avoidance occurs.
Contributions to the study of electromagnetic turbulence in the SOL and edge region of AUG with a special probe head were made by ENEA-Padova (see section 2).

ERM/KMS

The Ion Cyclotron Wall Conditioning (ICWC) technique for ITER was further developed together with a large team of scientists from CEA, FZ-J, ITER IO and IST on a dedicated AUG shotday in the frame of an EFDA task. ICWC plasmas were reliably produced in widely-variable conditions: B_T=2.0-2.4 T; B_V=10-30 mT; $p_{tot}\approx(1\text{-}10)\cdot10^{-5}$ mbar; $P_{ICWC}\approx$30-200 kW; $f_{1,2}$=36.5 MHz + $f_{3,4}$=30.0 MHz; π- and π/2-phasing of the antenna straps. Antenna-plasma coupling (f=30 MHz) increased (up to 50-60 %) in the following cases: (i) at higher applied RF power, (ii) on shifting the fundamental resonance $\omega=\omega_{cH+}$ from the vessel axis (B_T=2.0 T) towards antenna side (B_T=2.4 T), (iii) at antenna operations with π/2-phasing compared with π-phasing. The ECE radiation temperature profile near the $\omega=\omega_{cH+}$ resonance revealed a tendency towards flattening (T_{rad}~1 eV) at high gas pressure (~10^{-4} mbar) and high hydrogen concentration (n_H/n_{tot}~0.3-0.4) and peaking (T_{rad}~5 eV) at low pressure (~10^{-5} mbar) and low hydrogen concentration (n_H/n_{tot}<0.1). The observed degradation of ICRF antenna coupling by applying a low vertical magnetic field (B_V=10-30 mT) or a short pulse (~0.5 s) of the ECRF power ≈110 kW at f=140 GHz needs further studies.

The preliminary assessment of surface isotopic exchange (D/H) using ($He+H_2$) ICWC plasmas shows the benefit from operation at higher coupled RF power and lower gas pressure. Desorption of deuterium from the wall during both the ICWC discharge and the post-discharge, occurs in the form of HD and D_2. However, a large fraction of the injected gas was found to be retained by the AUG wall. In particular, He retention was observed during He containing ICWC discharges, in agreement with the observed He storage in W materials during He glow discharges.

FOM

Experiments on highly radiating type-III ELMy H-mode with nitrogen (N) seeding at high electron densities were conducted at AUG. The radiative type-III ELMy H-mode is a possible solution for an integrated ITER scenario. Most notably the transient heat loads due to type-III ELMs are acceptable with even the most stringent boundary conditions. The radiative power fraction in those type-III ELMy H-modes at 1.2 MA/2.5 T (q_{95}=3.9) and 1.2 MA/2.0 T (q_{95}=3.1) was more than 70 %. The electron density is 80 % of the Greenwald density in those low triangularity pulses, although the absolute density is very high ($n_e=1.2\cdot 10^{20}$ m^{-3}) resulting in low plasma core pollution. For both edge safety factors (q_{95}) a power scan was carried out. It was possible to reach a maximum pressure β_N of 2.4. Increasing the power in those N seeded type-III ELMy H-mode discharges leads to an increase of confinement similar as in type-I ELMy H-modes resulting in a $H_{98(y,2)}$ close to 1 at the highest plasma pressure. The type-III ELM frequency varied between 150 and 500 Hz and the power flux density during the ELMs was reduced to less than 2 MW/m^2. For the development of predictive scalings the collisionality ν^* was varied between 0.4 and 0.9. IR thermography measurements are used to determine the temporal evolution and the power decay length of the type-III ELMs. These results will be used together with those from JET to make a better prediction of the type-III ELM power load in ITER.

Dedicated discharges with N seeding were performed to characterize the tungsten erosion, in steady state as well as during the ELM-phase for both type-I and type-III ELMs. The N flux to the wall and the influx of neutral tungsten were deduced from spectroscopic line intensities and compared for different divertor temperatures. At high radiative power fractions by high N puff rates, the electron temperature in the divertor was decreased below the sputtering threshold of tungsten.

First results of the ECE 2D imaging diagnostic are presented in section 7.8.

FZ-Jülich

Experiments with local injection of methane in the outer divertor leg of AUG have been performed. The aim was to explore (i) the impact of a W surface, and therefore the hydrocarbon recycling, on the effective photon efficiencies of different (hydro)carbon transitions (CH A-X band, C_2 Swan and CII lines), (ii) to determine in-situ the layer thickness of deposited a-C:H on W, and to investigate the capability of strike-point sweeping for in-situ layer removal.

Slow strike-point sweeping in L-mode was utilised to determine the spatial extension of the intrinsic hydrocarbon emission zone. Deposition of CH layers was induced by local CH_4 injection in the subsequent identical plasma discharges (L-mode~1.0 MW ECRH). A second slow strike-point sweep without local injection has been applied to determine the spatial extension of the extrinsic deposited carbon. To disintegrate the a-C:H layer, H-mode plasmas have been applied with 7.5 MW additional power in order to utilise ELMs and the strike-point position for layer removal. A final strike-point sweep in L-mode has been used to determine the final extension and source strength of the remaining freshly build layer. Though a reduction of the carbon source has been detected, a complete removal of the topmost soft layer has not been observed. The final analysis of the injected amount and the equivalent thickness of the deposit and its removal is ongoing.

HAS – KFKI RMKI, Budapest

The development of the blower-gun pellet injector (see section 8.7) to produce 1 mm diameter cylindrical pellets has reached the testing phase. HAS has developed and installed an expansion tank together with a second diagnostic section for pellet velocity and mass measurement. The injector characterisation showed pellet delivery efficiency up to 60 %. Using the blower-gun, low-field-side pellet injection experiments were conducted. Video cameras observed that these slow pellets (100-150 m/s) have very shallow penetration into H-mode plasma. The ELM-triggering potential of these pellets is around the critical level – many pellets do not trigger ELMs, whereas other pellets in the same discharge can clearly be associated with emerging ELMs.

A HFS pellet cloud database has been established, containing short exposure time (1-5 µs) images of the radiating pellet cloud photographed at 2-15 different time instances. Corresponding pellet parameters (e.g. velocity, mass, location etc.) as well as local and global plasma parameters (e.g. electron temperature and density at the cloud location, plasma scenario, auxiliary heating etc.) have been added to the database. Pellet clouds were classified according to their shape. The database will be used to study the dynamics of the pellet cloud (formation and movement) as well as the size of the cloud as the function of plasma parameters.

The development of a new high-current lithium ion source was still ongoing in 2009. After nearly a full year of development work a new source was tested in November. Reliable operation was achieved at 3 mA extracted ion current.

IPP CZ, Prague
Contributions to joint studies of fluctuations and turbulent transport in the SOL of AUG were made. A summary can be found in section 2.

IST – Centro de Fusão Nuclear
Activities to demonstrate the RT Plasma Position technique proposed for ITER have been continued in the frame of an EFDA task. The dedicated data acquisition hardware design was completed and all components were assembled in the RT data processing host. Most of the system software, as well as the prototype version of the RT processing code, were implemented. In 2010 the system will be integrated in the AUG RT plasma control system.
Operation of the FM-CW profile reflectometry was again hampered due to component damage on some channels – in part due to stray ECRH radiation and degradation of key microwave components after 15 years of continuous operation. Nevertheless, the diagnostic gave independent profile data with high quality at low density using the burst-mode analysis technique. In addition, the FM-CW system operating in fixed frequency, together with the fast-frequency hopping reflectometers, provided radially localized measurements of Alfvén wave cascades revealing HFS/LFS asymmetries. A PhD thesis on MHD and fast particle mode studies at IST University with joint supervision by IPFN/IPP was completed. A proposal to refurbish the FM-CW diagnostic was elaborated to make the HFS antenna front-ends compatible with ECRH stray radiation and to upgrade the electronics of the channels probing higher density. The proposal is based upon successful testing of novel front end techniques and modern electronics developed by IPFN for the JET FM-CW diagnostic. Synthetic reflectometry diagnosis of gyro-fluid turbulence were performed using the GEM code to simulate turbulent edge plasmas with typical AUG L-mode parameters and the REFMUL full-wave code to simulate the microwave reflectometer diagnostic. Contributions were also made to the development of the ICRF-assisted wall conditioning technique for ITER (see above ERM/KMS).

RISØ
Due to technical problems with the 105 GHz operation of the dual frequency gyrotron, no CTS data was available in 2009. However, significant progress was made on the analysis of the CTS data. Fast ion distribution results from AUG NBI heated H-mode discharges has been successfully attained from a Bayesian method of inference using a forward model. Fast ion distribution measurements from CTS of discharges with beam sources of similar beam line geometries but different injection energies show differences in distribution shapes as expected (see also section 4.1). Comparison of these results to the Monte-Carlo NBI code NUBEAM coupled with the transport code TRANSP show encouraging agreement.

ÖAW
In collaboration with the IAP, TU Wien, new high voltage switches for fast modulation of the lithium beam were designed and commissioned. With this improvements higher reliability of the beam as well as increased time resolution was achieved.
Contributions to joint studies of fluctuations and turbulent transport in the SOL of AUG were made by the Institute for Ion Physics and Applied Physics of the Leopold-Franzens University of Innsbruck. A summary can be found in section 2.

TEKES
Local ^{13}C methane injection experiments were modelled with the SOLPS and ERO codes. A new ^{13}C experiment in reversed field and current was carried out at the end of the campaign, to study drift effects on the deposition of carbon, and additional characterisation discharges were performed to verify the plasma conditions in earlier experiments.
A graphite probe with thin C, Al, Ni, and W markers was exposed to plasma during 5 discharges. The thicknesses of the markers were measured before and after the experiment, and their erosion was determined. Preliminary efforts were also taken to model the results with the ERO code. The marker tiles from the 2007 ^{13}C phase were analyzed using SIMS.
Bolometry and IRTV data was verified, and the re-assessment of the ohmic power calculated for a series of ohmic discharges was perform. These data is used for detailed validation of edge fluid codes, such as SOLPS and UEDGE. The latter was further validated by systematically varying boundary conditions, such as chemical sputtering yield and recycling coefficients, and documenting their effect for divertor detachment asymmetries. The use of SOLPS to simulate the width of the heat flux profile at the target was started.
Attempts to achieve QHM operation with co-injection in AUG were continued right after two boronizations. The main thrust was in maximizing the edge temperature and rotation. MHD phenomena with EHO characteristics were observed in some discharges, but only classical ELM-free phases were obtained. Since the densities could not be brought down to the levels achieved in DIII-D, it is believed that different wall pumping due to tungsten is responsible for the conditions unfavourable for co-injection QHM.
The code ASCOT was upgraded to include non-neoclassical effects in fast ion simulations: a theory-based anomalous diffusion model and a magnetic perturbation to model the effects due to NTMs were implemented Also a new, ab-initio NBI model for ASCOT was developed which has been benchmarked with both FAFNER and the NUBEAM module of TRANSP. ASCOT simulations of divertor load asymmetries due to hot pedestal ions in the presence of ELMs were performed. The asymmetry was found to depend on a delicate interplay between the particle pitch distribution, kinetic energy, and the magnitude of the radial electric field.

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JET Cooperation

Head: Dr. Josef Schweinzer

With the end of the 2009 campaigns and the beginning of the shutdown for the installation of the ITER-Like Wall (ILW), JET has begun a new era. For 26 years JET has been a predominantly carbon-walled machine. Now it is on its way to become a new device with the same wall materials as ITER. With this change to a carbon-free environment JET takes a step, which AUG has already taken, that will link the programs of these two machines even more strongly.

Introduction

JET continued its experimental phase with campaign C26 from January to April 2009. From April to the middle of June 2009 the JET operation was interrupted to install an improved system for vertical stabilisation, which was designed in conjunction with the IPP. The following campaign, C27, lasted from the middle of June until the 23rd of October. In total, 20 IPP scientists (~6 ppy) participated in the 2009 campaigns. Two of them continued their work as deputy task force leaders for TFs S1 and E. After C27 a 65-week shutdown commenced for the installation of the ITER-Like Wall (beryllium in the main chamber, tungsten in the divertor) and for the upgrade of the neutral beam heating from 25 to 34 MW. Experiments with the ILW are envisaged to begin in March 2011. The emphasis of these experiments will lie – similar to AUG in the year 2007 – on the characterisation of a carbon-free machine. The number of JET task forces for 2011 was reduced to only two. For the leadership of the TF E1, which will be responsible for the development of ILW compatible plasma scenarios, an IPP scientist was appointed.

In 2009 the IPP was also involved in 7 JET enhancement projects. In the framework of a feasibility study technical solutions for the high voltage supply of gyrotrons for a JET ECRH system were examined. Five new long term secondments of IPP staff to the JET Close Support Unit as well as to the JET Operator were started in 2009. Instead of attempting a comprehensive overview of IPP's contributions to JET in 2009, only selected examples of contributions to the campaigns as well as to JET enhancement activities are given in the following.

ELM Pacing with Pellets

Commissioning and optimisation of the new HFPI (High Frequency Pellet Injector) was led by IPP scientists. The HFPI was designed to demonstrate a tenfold increase of the intrinsic ELM frequency by pellet pacing in an ITER relevant baseline scenario while keeping the impact on the discharge performance small. However, in 2009 the HFPI could not attain its designed performance parameters. Therefore, ELM pacing experiments were forced to work with reduced operational settings. Instead of the planned 60 Hz pacing pellets the larger pellets of the 'fuelling system' delivered at 10 Hz had to be used. The 'pacing system' of the HFPI operating at its designed parameters would have a particle flux about 7 times smaller than that of the 'fuelling system' despite its higher launching rate. The conducted experiments had to live with the undesired additional fuelling caused by the oversized pellets (see figure 1). During the initial pellet sequence this residual fuelling increases the 7 Hz intrinsic ELM frequency to 18 Hz. The resulting ELM train consists of a mixture of triggered and spontaneous ELMs. Recovery of the initial plasma energy is achieved by a slightly enhanced heating power (at 20 s) raising the ELM rate further to 27 Hz. Presumably, a properly working 'pacing system' would be able to achieve the requested tenfold increase of the initial ELM frequency. Thus, the technique of triggering ELMs using pellet injection was confirmed on JET as well. Experiments that used the 'pacing system' focused on the trigger physics of single events due to the poor pellet delivery efficiency of the system. It was found that too small pellets (particle inventory ~$0.5 \cdot 10^{20}$ D) fail to trigger ELMs in hot edge plasmas. However, if the edge plasma temperature is reduced, thus increasing the pellet penetration depth, then small pellets can be used to successfully trigger ELMs. It seems that the threshold condition for ELM triggering can be reached only when the pellet penetrates at least a significant fraction of the edge transport barrier width.

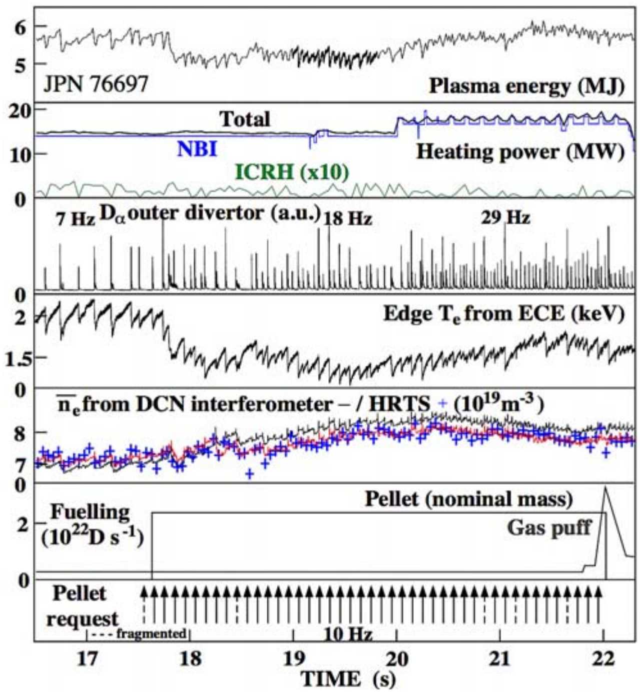

Figure 1: ELM pacing with the new HFPI in 'fuelling mode' in an ITER relevant standard H-mode scenario. Unavoidable strong fuelling causes a rise of the ELM frequency and results in a train of mixed spontaneous and triggered ELMs. Based on this result the demonstration of a tenfold ELM frequency increase in such a H-mode scenario seems feasible once the HFPI is operational in its 'pacing mode' which will deliver 60 Hz pellets with 85 % less total particle flux.

ELM Divertor Heat Loads

The infrared camera built (KL9) by IPP, which views the JET divertor, was used to study the temporal evolution of the divertor power loads in ELMy H-Modes. The high spatial resolution of the camera (1.7 mm on outer target) combined with a time resolution of 85 µs allowed ELM resolved measurements to be made. In a scan of the toroidal magnetic field ripple, the average ELM size, normalized to the pedestal energy ΔW_{ELM}, was found to decrease with increasing TF-ripple from 350 kJ to 100 kJ and the average ELM peak-power P^{outer} decrease from 80 MW to 40 MW. However, the peak heat fluxes to the outer divertor do not show a comparable trend, but remain almost constant around 55 MW/m^2 (+/-8 MW/m^2). This is caused by a decrease of the ELM wetted area A_{wet} with decreasing ELM size. A similar behaviour has been found for ELMs which are reduced in size by external magnetic field perturbation. Thus, in such cases a reduction of ELM size does not necessarily relax the situation for plasma facing components (PFC).
A systematic comparison of several aspects of spontaneous and pellet induced ELMs has been carried out focussing on lost, deposited and radiated ELM energies. The drop of plasma stored energy is higher by about 60 % for pellet induced ELMs compared to spontaneous ELMs. The radiated energy is enhanced by a similar ratio. Thus, the same absolute energy has to be deposited on PFCs. The evolution of power deposition on the outer divertor target has shown a ~30 % longer rise phase for pellet induced ELMs as well as a slightly longer fall off time after the peak heat flux. Spontaneous and pellet induced ELMs show comparable values for the wetted area, the maximum power and the peak heat fluxes.

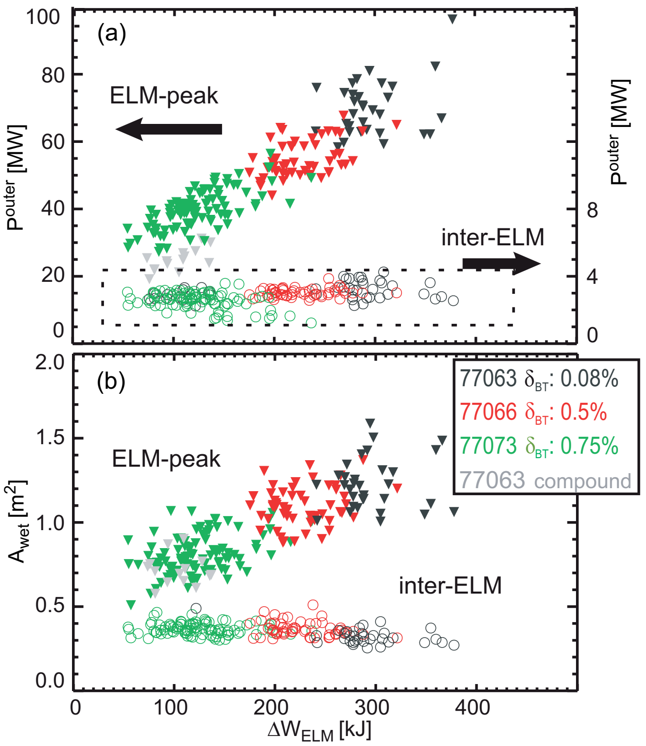

Figure 2: (a) Inter-ELM and ELM peak power and (b) wetted area for the outer divertor target versus ELM size ΔW_{ELM} in a scan of the TF ripple (δ_{BT}). Triangles: ELMs, circles: inter-ELM 1 ms before ELM.

Contributions to the ITER-like Wall Project

IPP continued its long-term programme to supply tungsten (W) coatings of plasma-facing material for the ILW project. In 2009 the focus was on quality assurance (QA) of the series production of W coated CFC tiles. High heat flux tests in GLADIS had identified problems concerning the application of W vacuum plasma spraying (VPS) on full-size JET divertor tiles. Therefore, VPS coating of divertor tiles had to be abandoned. Instead, it was decided to coat the approximately 700 divertor tiles with an alternative process: Combined Magnetron Sputtering and Ion Implantation (CMSII), performed by NILPRP Bucharest, Romania. Approximately 10 % of the manufactured tiles were supposed to be tested in GLADIS to ensure the quality of the employed coating process. As a consequence the number of tiles to be tested in GLADIS nearly doubled. Such tests of the divertor tiles were performed employing a hydrogen beam with a power density of 10 MW/m^2. An infrared camera, one- and two-colour pyrometers, and thermocouples were used as diagnostics. At the end of 2009 around 70 % of the QA tests were accomplished. All examined coatings performed well in the tests.
Special Mo/W marker layers (ML) for the investigation of W erosion and redepostion in the JET divertor were developed, and successfully tested in GLADIS. 15 divertor tiles were coated with this ML at NILPRP. The thicknesses of the MLs were measured at IPP using ion beam analysis with high energetic incident protons. The characterized tiles were delivered to JET for mounting in the divertor in the 2010 shutdown. 8 additional divertor tiles and 6 bulk tungsten lamellas from tile 5 are currently being manufactured.
Special deposition monitors for measuring material deposition in remote areas of the divertor as well as sachet samples for measuring Be and W erosion at the inner main chamber wall have been manufactured. The latter are currently being coated with W and Be marker layers.

Scientific Staff

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Enhancements: M. Balden, B. Böswirth, H. Braune, H. Greuner, S. Lindig, H. Maier, M. Mayer, R. Neu, J-M. Noterdaeme, S. Schmuck, A. Stäbler, W. Treutterer, W. Zeidner.

Stellarator Research

Wendelstein 7-X

Heads: Dr. Remmelt Haange, Prof. Dr. Thomas Klinger

1 Introduction

In 2009 the organisation of the project Wendelstein 7-X remained mostly unchanged. In spring of 2009 the two departments dealing with the superconducting coils were combined in a single department finalizing the work. In November 2009 the subdivision head "Magnets and Cryostat" retired and this position was taken over by an experienced engineer from this subdivision. Design and manufacturing of the different components of the basic device have considerably progressed, as described in chapters 2 to 4. The accompanying efforts of the engineering subdivision (chapter 5) and the design and configuration control (chapter 6) are still indispensable. The assembly of the stellarator device and the development of the related technologies have made significant progress, as described in chapter 7. Diagnostics developments (chapter 8) and the set-up of heating systems (chapter 9) as well as the development of control systems have continued. The Wendelstein 7-X device consists of five identical modules (M1 to M5), each of them consisting of two flip-symmetric half-modules each (M10, M11, M20…). Assembly started with module 5; the assembly sequence is M5-M1-M4-M2-M3.

In 2009, considerable progress was achieved in the construction of Wendelstein 7-X. Cryo-testing of all superconducting coils was finished in August and fabrication of all remaining components also progressed very well. Assembly of the device continued roughly to plan and by the end of 2009 the first magnet module was installed in the cryostat module and all five modules of Wendelstein 7-X had entered into the assembly process.

1.1 Quality Management

The Quality Management (QM) department reports directly to the project directors via the associate director coordination. The department organizes the QM system within the project W7-X and supports the supervision of all external contractors. It has taken over responsibilities for quality assurance during the assembly phase of Wendelstein 7-X. At the end of 2009 the QM system has been certified by the TÜV NORD CERT according to the DIN EN ISO 9001 for the "construction and commissioning of Wendelstein 7-X". In this process, the QM system has been updated and adjusted according to the ISO 9001:2008 standard.

1.2 Project Coordination

This subdivision comprises three departments dealing with coordination activities for the project Wendelstein 7-X: (I) the project control department (PC-PS) is responsible for the financial planning of the project, for the control of the expenditures and for the time planning and coordination of all activities within the project as well as of the external contracts. The department supports the component responsible officers in the handling of industry contracts; it deals with organisational

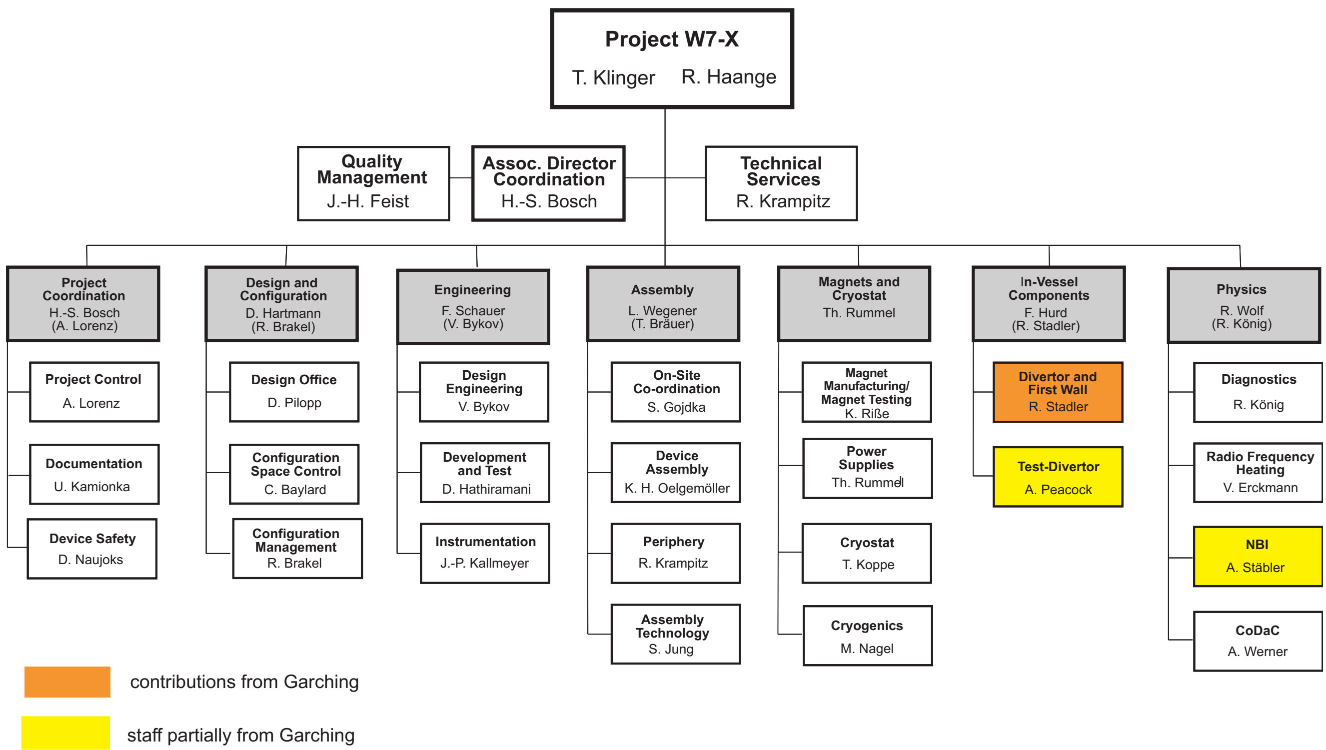

Figure 1: Organigramme of the Wendelstein 7-X project as of 31 December, 2009.

aspects of the project and is responsible for the reporting to all external supervising bodies, especially the supervising body of the financing institutions (Project Council). The development of a new Integrated Planning Tool (IPT), based on MS Project 2007, was continued in 2009. It is designed to integrate time and financial planning into one software solution with a dedicated interface to the already established SAP system. Not only does this allow to obtain automatic financial reporting to both the management and the supervising bodies, but it also improves the planning for the responsible officers and the feedback from administration with respect to the external contracts (delivery dates and cash flow). After a detailed testing phase was completed in February 2009, the financial report for the Project Council was created for the first time from the so-called Management Information System (MIS, the reporting part of the IPT). With the reporting part finished, the emphasis was put on the planning part, especially the release process which did not yet fulfil the requirements. A new two-stage release process involving the department and subdivision heads has now been implemented via an additional tool, the so-called control centre. The control centre allows the department and subdivision heads to get a quick overview over all their respective projects and allows a release requiring less interfacing with WS Project. This tool has been released in autumn 2009 and has proven very valuable for the organisation of the release process within the project W7-X. In parallel, the concept how to establish links between all sub-projects in a stable and reliable way, has been further refined and established within the W7-X project. (II) The documentation department (PC-DO) is responsible for an independent check of all technical drawings and CAD-models and for archiving all documents relevant to the project. Also, this department maintains the full CAD model of Wendelstein 7-X with all subcomponents, the so-called assembly of Wendelstein 7-X and is – in collaboration with the design office (DC-DO) responsible for the structure of the assembly. An electronic documentation system (agile-PLM) is used for archiving documents and CAD models (up to now mostly in CADDS5-format). Because of the increased use of CATIA V5 for design and collision investigations, an extension of the system has been implemented. In parallel with an update of the agile-PLM system from version 5.1 to version 6.1 (which is required for the CATIA-interface), an interface between PLM and CATIA V5 has been customized and implemented. This upgrade was released in November 2009. With the archiving of CATIA V5 models now being possible, the reference model could be transformed from CADDS5 to CATIA V5. This process is being planned in collaboration with the subdivision Design and Configuration (DC), as described in chapter 6.3. (III) The device safety department (PC-DS) plans, implements and leads the processes that are required to ensure safe operation of the Wendelstein 7-X device with its interacting components and supply systems. With respect to the device safety of W7-X, different topics have been considered together with the responsible departments. Among them have been the safety analyses of the W7-X components (33 analyses are completed in the first revision), a system analysis of the W7-X device, failure and load case analyses, fire protection, explosion hazards, emergency stop systems, emergency power supply, EMC and earthing concept, control interfaces between the W7-X components and the Central Safety Control, safety functions and interlocks. The department provided safety relevant information to the responsible officers in accordance to the European and national directives and standards. The department is checking regularly all assessments the Nonconformity Reports and Change Notes. Based on the analyses, several proposals for design improvement have been issued (e.g. specification of the safety valve system of the plasma and outer vessel, draining system of the cooling circuits, positioning of contact sensors in the cryostat). Information exchange and collaboration have been established with the Lithuanian Institute of Energy (under the EFDA agreement – Association Work Programme) on the topic of Loss of Coolant Accidents, with the LHC at Cern, DESY/XFEL, and JET on interlock systems and protection measures, with the IRSN (Institut de Radioprotection et Surete Nuclaire) on Loss of Vacuum Accidents. Regular meetings are held with the Employer's Liability Insurance Association ('Berufsgenossenschaft', BGIA in St. Augustin) and LAGUS, as well as with the Bavarian Insurance Chamber with respect to fire protection. A concept of fire protection in the torus hall during W7-X operation has been developed by GSSO ('Gesellschaft fuer Sicherheitstechnik/Schiffssicherheit Ostsee mbH').

1.3 Schedule

Also in 2009, the time schedule of the co-called "scenario 3" (developed in the autumn of 2007) was followed. Three out of the five milestones scheduled in 2009, have been achieved in 2009, one of them in time, the other two with some delay. Two milestones had to be shifted into 2010. These delays were caused by a combination of technical problems in the assembly of the busbar joints, delayed delivery of the cry-piping and delays in design, fabrication and assembly of the thermal insulation for the cryostat vessel. Therefore, the assembly sequence was re-arranged and work packages were shifted to modify the overall schedule in order to ensure the end of assembly and start of commissioning to be delayed as little as possible. While further acceleration measures are still under consideration, they are now scheduled for August 2014. By the end of 2009, the first magnet module was installed in the cryostat vessel, with the lower and upper shell not yet connected. On the second and the third module busbars and cryo-piping are being installed and the half-modules of the fourth module have been connected. Assembly the coils and the thermal insulation of the plasma vessel for the half-modules of the third module are in progress.

2 Magnets and Cryostat

2.1 Magnet

2.1.1 Superconducting Coil

The superconducting coil system of the W7-X consists of 50 non-planar coils and 20 planar coils. The manufacture of the coils has been finished in 2008 and most of the coils had been tested under cryogenic conditions in 2008 also. The remaining 13 coils passed the acceptance tests at CEA Saclay in 2009. IPP implemented additional test trials into the test program of the last coils. One coil was cooled down and operated successfully without casing cooling circuit by increased He flow through the CICC (Cable in Conduit Conductor). This test confirmed the good thermal stability of the coils. A second test demonstrated the high margin of the coils against mechanical disturbances. It was tried to initiate a quench in the coil mechanically by impacting the coil casing by a stem with the result that no quench occurred. The collaboration between IPP and CEA for the cold testing of the superconducting coils for W7-X was a great success and ended with the arrival of the last coil at IPP in September 2009. The procurement of the superconducting magnet system for W7-X was successfully finished.

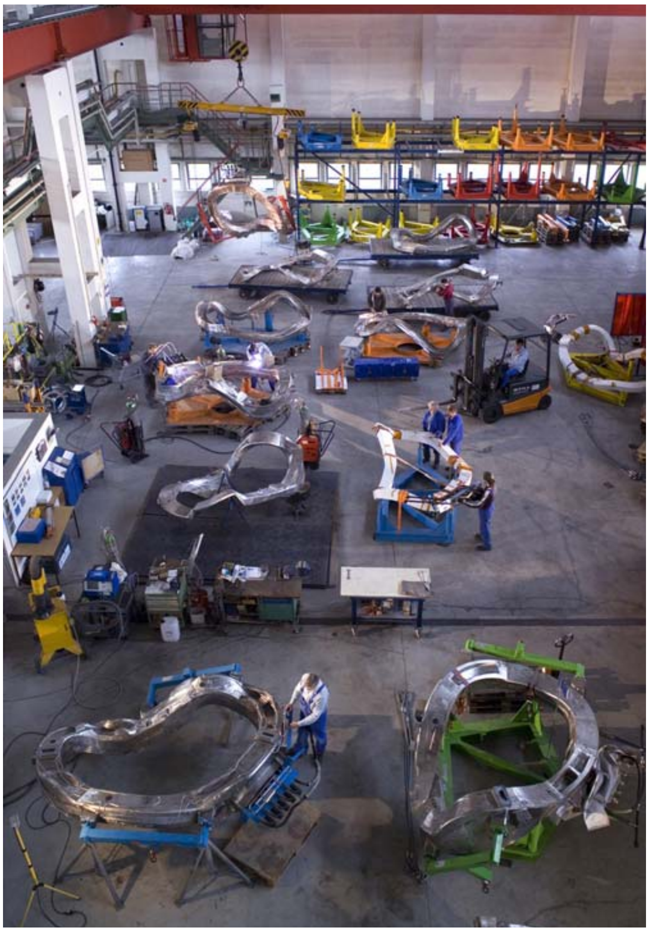

Figure 2: Non-planar coil assembly at BNG site in Zeitz.

2.1.2 Coil Support Structure and Cryo Legs

The support of magnet system is composed of 2 main components, the coil support structure and the cryo legs. The coil support structure had been manufactured by the Spanish contractor Equipos Nucleares, S.A. (ENSA). It consists of ten identical sectors (half-modules) with a total weight of 72 t made of steel plates and cast extensions. The final precise machining had been performed by the ENSA subcontractor CLP C.M., Italy. The 1st two half-modules were delivered to IPP in 2007. In 2008 and 2009 the other half-modules were delivered to IPP. Therefore, the contract was successfully finished in 2009. Eight half-modules have meanwhile been assembled with coils and completed to modules. The remaining two half-modules will be assembled with coils beginning of 2010. The coil support structure is vertically supported by 10 cryo legs (2 per module).Three contracts have been awarded for the R&D and the manufacturing of the cryo legs: to Zanon s.pa. (Italy) for the metallic structure and final assembly, to IMA (Germany) for the GFC bushes, and to SKF (England) for the sliding and spherical bearings. The delivery of the prototype and the first two cryo legs (M5) had been finished in 2008. The delivery of the remaining 8 Cryo legs (M1-M4) had been finished in spring 2009. The Swiss company Kompaflex provided the 10 bellows. Afterwards IPP installed the instrumentation for measurement of vertical forces. The cryo legs of three modules have meanwhile been installed in the W7-X machine.

2.1.3 Inter-coil Supports

Different types of support elements connect the coils with each other. The narrow support elements (NSE) between non-planar coils take up pressure loads while simultaneously allowing sliding and tilting. They consist of coated pads, pad frames and sliding parts. In order to accelerate the coating of pads in 2009 the manufacturing was switched from just in time into serial fabrication. All pads were coated and stored in 2009. Also the pad frames and sliding parts were manufactured completely. Therefore all the NSE between the modules M5, M1, M4 and M2 could be completed and assembled. The half-modules M30 and M31 will be assembled in beginning of 2010. The lateral support elements (LSE) join the non-planar coils in the outer side of the torus by welding. The semi finished products of all LSE's (with one exception at the module separation plane) have been manufactured. The final measurement, costume machining and assembly for M5, M1, M4 and M2 were successful completed. The half-modules M30 and M31 will be assembled in beginning of 2010. For the LSE at the module separation plane (D06) a new design (Monoblock), easier to assemble, has been created. The testing of a relevant mock-up is running. Afterwards the material and the fabrication can be ordered. The planar support elements (PSE) connect the planar coils to the non-planar coils. For module M5, M1, M4 and M2 all PSE are delivered and assembled.

For module 3 the prefabrication (E-beam welding) of PSE B1 at company Josch will be finished beginning 2010. Two kinds of contact element (CE) support the non-planar coils at the half-module separation plane and at the module separation plane. In module M5 the smaller CE's for the half-module separation plane were assembled in 2008. The smaller CE for module M1 and M4 were assembled in 2009, the remaining are prefabricated. For module M5 the CE's for the module separation plane were also prepared for the assembly, the assembly starts beginning 2010.

2.1.4 Connection Elements

All connection elements for Coil Support Structure and Inter-coil Supports (bolts, super-nuts, round-nuts, sleeves, spherical washers) have been delivered and given to assembly. Only connection elements of LSE-D06 have not yet been ordered as the design is still under discussion (see above).

2.1.5 Current Leads Mechanical Support

Mechanical support of Current Leads is needed to support the current leads at the section between warm and cold side with all the allowable movements during machine operation. The also support the bus system up to the central support ring. They consist of two main parts. Firstly the supports at the central support ring with the connected horizontal rods to join the coil support structure with the fixing box. Secondly the fixing box itself with the bearings for the current leads and the bellows. For module M5 the first part was completely assembled in 2009, for module M1 the manufacturing was finished and the assembly will start in 2010. The manufacturing for module M4 has been prepared and the parts for the remaining modules will follow after a collision check. Because of the reduced access during the assembly of the fixing box a new design has been suggested (by PPPL Princeton). To check the new design a mock-up will be manufactured and tested. Only then the decision about the final design will be taken.

2.2 Vessel, Cryostat and Ports

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. Its function is to create a cryostat keeping the magnet system at cryogenic temperature and constitute the boundary between the W7-X main device and the external environment. 254 ports give access to the plasma vessel for diagnostics, additional heating and supply lines. MAN Turbo AG (MT, formerly MAN DWE), Germany, is responsible for manufacturing the plasma vessel, the outer vessel and the thermal insulation of plasma vessel, the outer vessel and ports. Romabau Gerinox (Switzerland) is responsible for manufacturing of the ports.

2.2.1 Plasma Vessel

The plasma vessel, made of the austenitic steel 1.4429 (X2CrNiMoN17-13-3), is composed of ten half-modules which are divided into two sectors to allow stringing of the innermost coil during assembly. Manufacture of all ten half-modules has already been completed in 2005. In 2009 the installation of the thermal insulation has been nearly finished (except the sector separation area). All 15 vertical supports of the plasma vessel (three types / module) were delivered by MAN Turbo. The vertical supports for the modules M5, M1 and M4 were welded successfully to the lower shell of the outer vessel by IPP. For the horizontal support/centring system the design, the calculation of horizontal adjustment (University of Rostock; Germany) and the technical specifications were completed. The standard parts are being manufactured by IPP. The additional brackets to the 5 ports AEU by TRINOS has been welded successfully.

2.2.2 Outer Vessel

The outer vessel, made of austenitic steel 1.4429, the same material as the Plasma vessel, is also made of 5 modules. Unlike the plasma vessel, each outer vessel module is divided into an upper and a lower module shell. The outer vessel is designed to have 524 domes for ports, supply lines, access ports, instrumentation feed through and magnetic diagnostics. All modules passed the works acceptance check and the last half shells were delivered to IPP in 2009.

2.2.3 Ports

A total of 254 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 rectangular and are equipped with bellows to compensate deformations and displacements of the plasma vessel with respect to the outer vessel. All the ports and their fixing tool were delivered in 2007 and the contract with Romabau was successfully concluded. In 2009 measuring and assembly preparation of the ports has been started. Up to now all water pipes at port tubes in direction plasma vessel have been removed because of collisions. At some special ports additional copper stripes were installed for heat transfer. Furthermore additional circular channels have been installed at supply ports for module M5. The routing of water pipes in the bellow area was corrected. An enlargement of dome plates was necessary for some ports because of misalignments. The additional parts were designed, ordered and tested.

2.2.4 Cryo-pipes

At the beginning of 2009 the design work focused on the pipes of module M1 (lots 1-4). Therefater the design work continued with the rest of the module (lots 5-8). During the year the design of modules M4 and M2 was also completed.

The design work for module M3 has been started. First the manufacturing drawings for module M1 were delivered by the engineering company ibk, a subcontractor of Romabau. When ibk went insolvent in the second quarter of 2009, IPP took over temporarily this task. This was required because Romabau required several weeks before the company could find a new partner (Numrax Limited). In the meantime the process is under control again and the manufacturing drawings of the pipes for modules M1, M4 and M2 have been finished by a new subcontractor of Romabau. An acceleration of the pipe production has been achieved by two additional measures: Lot 1 and 2 of module M4 were fabricated in parallel by a second supplier (Dockweiler Company). The pipe routing of M1 was used as default routing for the other modules wherever possible. So it was tried to minimize changes in the pipe routing compared to module M1. This has allowed a kind of a small series production, which was very helpful especially for the pipe bending process. Pipes were bent in advance before the design was finalized for all the modules. The design of the supply pipes for the current leads of the planar coil system is delayed. The development of the assembly concept for the current leads turned out to be very difficult because of lack of space for the assembly process inside the cryostat. This directly affects the available design space for the pipe routing. The cryo-pipe header located inside the cryostat and the process pipes running from the helium refrigerator to the cryostat have to be connected inside the cryostat. A design concept for the connection of both pipe groups was developed. This concept requires an enlargement of a dome opening which is located at the module separation plane between module 2 and module 3. The impact of the design change on other components has to be investigated further (e.g. impact on the mechanical structure of the outer vessel).

2.2.5 Thermal Insulation

The thermal insulation of the plasma vessel was installed for module M2. The 40 shield panels were mounted on the plasma vessel of both half modules. The cooling pipes were attached on the panels, adjusted and fixed on the shields. Copper tresses were soldered to the cooling pipes to achieve a thermal contact between the GFC-panels and the stainless steel cooling pipes. The panels of the plasma vessel were measured and adjusted using a laser tracker. The plasma vessel brackets (AFF, AEA) were insulated as well. The first two outer vessel half shells were insulated in the workshop located in Lubmin. The insulation of the base body consists of 22 panels made of brass shields and a Multi-Layer Insulation (MLI), consisting of aluminized Kapton and a glass-silk spacer. The 8 cooling pipe loops were adjusted on the surface, fixed and welded together. They were soldered to the copper stripes that were welded on the panels to ensure a good thermal contact. Additionally, the domes on the outer vessel (current domes, valve domes, feed through domes, etc.) and additional built in components (e.g. supports, cryo-legs, water pipes) were insulated using the same basic concept (MLI + bronze shield). Based on a detailed analysis of the assembly sequence within the cryostat new demands were made by the W7-X project concerning larger assembly tolerances. This caused a new comprehensive check of all distances between the thermal insulation and its neighbours inside the cryostat. This led to the identification of new critical areas with a high risk of collisions. Therefore the shield design was adjusted to the new requirements. These adjustments vary from cutting holes on already installed shield components up to a redesign and remanufacture of shield components. After finalizing the outer vessel insulation a test assembly of both half shells was carried out. The upper shell was positioned on the lower shell and adjusted. In that configuration the positions of the thermal shields, the cooling pipes and the dome insulations were measured using two laser trackers. The measurements showed that the thermal shield is mounted within the allowed tolerance range. The design activities for the thermal insulation proceeded as well. The CAD models for construction phase 1 for module M1 and module M4 were sent to the manufacturer, MAN Turbo (MT). This data package consisted of panels, cooling pipes, dome shields etc. The manufacturing drawings or models of the shield components for module 1 were provided by MT, checked by IPP and finally released for production. The assembly of the thermal insulation of module M1 in Lubmin has been started. CAD- models for the port shields were designed by IPP and forwarded to MT. 27 out of 58 manufacturing models were generated by MT. These models were checked and released for production by IPP.

Figure 3: Thermal Insulation, mounted on a plasma vessel sector.

3 Supply Systems

3.1 Current Leads

The current leads (CL) are the electrical connection between the superconducting magnet system inside of the cryostat and the power supplies outside of the cryostat, operated at room temperature. The main challenge in W7-X is the so-called upside-down orientation of the CL, that means the cold end is on top and the warm end is on bottom. The development and production is being performed by the Karlsruhe Institut of Technology (KIT). In 2009 KIT procured all material for two prototypes and started the manufacturing of the CL prototypes. In parallel the development of the electrical insulation for the CL system was finished. The connection between the current leads and the W7-X mechanical support structure will be done with the radial and cryostat flanges. According to new, more precise calculations, the forces and moments acting on these flanges are higher than assumed before. Therefore, tests on the mechanical stability of the flanges have been started. The contract was awarded to IMA Dresden. Tests at the first mock-ups showed no problems on the flanges itself, but de-bonding between the stainless steel tube and the glass fibre reinforced plastic insulation during the cool down to 77 K, consequently the technology was changed and new mock-ups have been ordered. For the development of the test facility for testing the prototype leads CuLTKA, KIT decided to manufacture the valve box, control box and test box within KIT workshop. This would have resulted in the completion of the test facility by May 2010, which was not acceptable to IPP since the prototype leads will be ready by the end of January 2010. Therefore it was agreed between KIT and IPP to refurbish the TOSKA test facility and use it for the test of the first current leads. The work has been started in 2009 with high priority, and the completion is scheduled for January 2010. The test procedure for the upcoming tests of the prototype CL were discussed and finally agreed between KIT and IPP.

3.2 Helium Refrigerator

The commissioning of the refrigerator is in progress. The installation of test box-2 containing the main test heaters, together with the interconnecting transfer-line, electrical cabinets for transformers and current leads were completed. The test box-1 has been delivered to IPP. Commissioning of cooling water system, compressor system (except oil system), dryer and gas management system was completed. The cooling performance of the high pressure stage oil heat exchanger was not satisfactory because the maximum temperature was exceeded. Wrong bearing material for the pump shafts resulted in scratches on the pump shafts. The surface quality of the oil pumps shafts was also not satisfactory. Linde Kryotechnik (LKT) will replace both the heat exchanger and the pump shafts. The mounting of cold machineries i.e. cold compressors, cold pumps and turbines is in progress. LKT has proposed to change the control program from FUP to PCS7 for most control units, which was accepted by IPP. The change of control program is presently being implemented. LKT has announced a delay in completion of commissioning and documentation with the new finalisation date of December 2010. The contractual consequences are under discussion between IPP and LKT.

3.3 Magnet Power Supply

The superconducting magnet system is divided into seven electrical circuits, containing five circuits with ten non planar coils each and two circuits with 10 planar coils each. Seven independent power supplies provide 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 or severe faults is realized by fast circuit switches which short-circuit the coils and dump the magnetic energy to resistors. After the declaration of the acceptance in mid 2007, several test campaigns were performed in 2009 to train the staff and to identify possible weak points. Based on these tests some auxiliary components had to be replaced and some service procedures were updated. The procurement of spare parts turned out to be more complicated than expected, because some components are not longer available on the market. In addition the failure rate tends to increase. Therefore some effort has been spent to look for alternative solutions and components.

3.4 Quench Detection System

The quench detection system of W7-X will 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 provide a redundancy in the quench detection, it was decided to install a back-up Quench detection system. It runs in parallel to the original system, but allows as an additional feature to detect symmetric quenches in adjacent double layers of the coils. Due to a slightly different cabling concept the number of necessary units is less than in the original quench detection system. In total 560 Quench detection units are necessary. The production of the units was awarded to the company Prettl (Lübeck). By the end of 2009 all Quench detection units were produced, tested and delivered to IPP.

4 In-vessel Components

The in-vessel components consist of the divertor target plates, baffles, panels and heat shields, control coils, cryo-pumps, port protection and special port liners for the Neutral Beam Injection (NBI) and Diagnostic NBI (DNBI) and the complex system of cooling water supply lines. Plansee SE is manufacturing the High Heat Flux (HHF) target elements and MAN Turbo manufactures the wall protection panels. The horizontal and vertical target modules of the HHF divertor are designed to withstand power fluxes of 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 remaining first wall components are subject to neutral particles and plasma radiation of up to 0.3 MW/m^2. In 2007 it was decided to start operation of Wendelstein 7-X with a test divertor unit (TDU) without water cooling. The TDU is designed for short pulses of 6.25 seconds at a maximum heating power of 8 MW. The recovery time between pulses at maximum load shall be 20 minutes. Assembly of the target modules from target elements for both the TDU and HHF Divertors, the fabrication of the TDU frames and module structures, baffles, heat shields, the cryo-pumps and of the supply lines is performed by the Central Technical Services of IPP in Garching or the Technical Services in Greifswald. Specialized companies are used to perform the vacuum brazing, pipe bending, specialist welding processes and machining. All in-vessel components are tested in Garching (geometry, He-leak tests and hydraulic tests) before delivery to Greifswald. For the first operational period with the TDU it is foreseen to operate with a limited number of cooled components. These include the control coils and some special areas close to diagnostics and heating systems. However, in order to reduce the length of the subsequent shut down, all the other components and their cooling circuits necessary for steady state operation will be installed. Only the cryo pump, the HHF divertor and their respective water supply lines will be omitted for this first operation phase. The input parameters for the cooling requirements during the first operation period are presently assessed in detail and fixed by a working group.

4.1 Target Modules

The ten divertor units of the HHF target are designed to remove 10 MW convective stationary power load. The ten units consist of two main areas: the first with an area of 19 m^2 which can be loaded up to 10 MW/m^2 and the second with an area of 5.4 m^2 which can be loaded up to 1 MW/m^2. Each divertor unit is assembled from 12 separate target modules. The highly loaded target modules are assembled from sets of bar-like target elements which are supplied with cooling water in parallel and fixed on a common frame. The supports of these modules are adjustable within a range of a few millimetres to allow for compensation of manufacturing and assembly tolerances of the plasma vessel or uneven heat-loading during plasma operation. For the higher-loaded area 890 target elements are required. Their surface closely follows the 3-D shape of the plasma boundary and will be machined before assembly of a module. The TDU will have the same surface contour as the HHF divertor. Some of the mounting frames and the intermediate area modules will be the same components to save time and cost. The TDU will use un-cooled fine grain graphite elements and is designed to withstand up to 8 MW/m^2 for about 6 seconds. A total energy input limit of 50 MJ has been set for the design phase. The detailed design of the modules and the support frames of the TDU with adjustment mechanisms has been completed in 2009. A prototype module with graphite from several different manufacturers was tested in GLADIS early in 2009. Using the results of this test the blanks for the fine grain graphite was ordered and delivered to IPP. In addition a prototype frame and adjusters was tested in collaboration with the assembly division. The divertor modules of the lower loaded area use a design similar to the Baffles with cooling provided by stainless steel tubes brazed onto the backside of the heat sink and these will be included in the TDU phase. In 2009 the detailed design of the HHF divertor modules has restarted in order to meet the required delivery. In the HHF divertor 8 mm thick CFC tiles made of SEPCARB® NB31, produced by SNECMA Propulsion Solide, are joined to a water-cooled CuCrZr heat sink. Tests have shown the improvement in the technology by the introduction of a compliant copper layer between the AMC® interlayer and the CuCrZr heat sink. The GLADIS tests have also shown the proposed changes to the cooling structure to be successful. In 2009 elements with repaired tiles were further tested successfully. Based on these results the series production of the HHF elements started during 2009. The results of the GLADIS tests have been correlated with the predictions from infrared measurements carried out in the ARGUS facility of Plansee SE and in the SATIR facility of CEA-Cadarache. This correlation should form the basis of the acceptance criteria for the target elements of the serial fabrication along with further GLADIS tests. With the support of the BMBF a pre-series of long elements was started in 2009 to develop and qualify the ITER-relevant technology for the end tiles and long cooling structures.

4.2 Baffle Modules

The baffle modules prevent back-streaming of the neutralized gas from the target plates into the main plasma and protect the water manifolds of the target modules. The design uses graphite tiles which are clamped onto a cooling structure made of CuCrZr. Water cooling is achieved by stainless steel tubes which are vacuum-brazed to the backside of the heat sink. The fixing screws for the graphite tiles are made from a molybdenum alloy (TZM). The cooling structures for 90 out of the 170 Baffle modules have been manufactured by the IPP workshop in Garching, the ordering of the graphite tiles runs in parallel to this manufacture.

4.3 Wall Protection

About 70 m^2 of the plasma vessel surface is covered by double-wall stainless steel panels with integrated water-cooling. In total, more than 320 panels have been delivered, including panels for the protection of the Plasma vessel behind the pumping gap and an additional 50 panels required due to the Scenario 3 changes have been delivered by MAN Turbo. The majority have been tested and accepted. Additionally other areas of the inner wall of the plasma vessel are protected by heat shields. These heat shields use graphite tiles which are clamped to a cooling structure using a similar design as for the baffles.

The design integrates several plasma diagnostic components as well as a NBI beam dump and mirrors for ECR heating. By the end of 2009, a total of 133 out of the 162 heat shield cooling structures have been fabricated in the IPP workshops. The procurement of the graphite tiles runs in parallel to the cooling structure manufacture. During steady state and full power plasma operation, the inner surfaces of the ports need to be protected in the same way as the plasma vessel. For budgetary reasons, construction of the port protection panels has been postponed to a later date. Nevertheless, the design of these protection elements was continued to fix their interfaces and define the routing of the cooling water lines. The NBI ports as well as the port for the diagnostic injector need to be protected against energetic particles by CFC and graphite tiles from the start of perations. The design work is completed, the manufacturing drawings are in preparation and a number of components are in manufacture.

4.4 Cryo-pumps

Ten cryo-pumps are located behind the target plates to increase the pumping capacity for hydrogen and deuterium up to 75 m^2/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 cryo-pumps is well advanced; however, the cryo-pumps will be installed only after the first operation phase. In order to guarantee the later completion of the cryo-pumps one pump will be assembled in 2010 and tested in the MISTRAL test facility. The coating of the water baffle with a coating for high ECRH radiation absorption is being qualified.

4.5 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 dynamically sweep the power across the target plate. Each coil is made of eight turns of a hollow copper conductor and is water cooled. All control coils, fabricated by the company BNG, have been tested and accepted. They have been delivered to Greifswald. The control coils are supplied by power supplies which are able to provide direct currents of up to 2500 A and alternating currents up to 625 A with frequencies between one and 20 Hertz in parallel. After the declaration of the final acceptance test campaigns to run the system under different scenarios have been started.

4.6 Water Supply Lines inside the Plasma Vessel

Cooling for the in-vessel components is provided from the main water system through 80 supply ports. The interface between the supply lines and the cooling loops inside the plasma vessel is achieved by so called plug-ins which contain groups of pipes and cables that can be installed as a single assembly with the port flange. The water cooling loops inside the plasma vessel form a very complex network of pipes with a total length of about 4000 m. Routing of the water pipes has to take account of the 3D-shape of the plasma vessel, avoid the diagnostics and heating systems port openings, take into account the restricted space behind the wall protection panels and identify appropriate attachment points. In addition, the design of the cooling circuits has to consider many interfaces with the diagnostics and heating systems. The detail design and the manufacturing process of the pipe work has been qualified by means of a full size prototype installed in the W7-X wooden model. Significant progress has been made in the detail design of the cooling circuits which is almost complete. The manufacture, assembly and testing of the first sets of cooling circuits has been completed, the manufacturing and assembly of the remaining cooling circuits is progressing according to plan. A prototype plug-in is being manufactured to qualify the technology and the design of the other seven variants. This is progressing in tandem with the target module design.

4.7 Glow Discharge Electrodes

The conditioning of the W7-X plasma vessel will be performed by glow discharges. Ten glow discharge electrodes will be permanently placed inside the vessel. These electrodes are ready and available for installation in W7-X. One prototype was tested in ASDEX Upgrade and was operated successfully for 4 months. Some small design changes will be made to the fixation of the glow discharge cathode. A second test in 2009 was also successful. Each glow discharge electrode is supplied by a separate power supply delivering a voltage of up to 3 kV and a current of up to 3 A. The power supplies have to be combined in one system with one central control unit. The contract for the development, production and test of the power supply system was awarded to the company Puls Plasmatechnik Dortmund. The whole system was produced and deliverd to IPP in autumn 2009. The acceptance tests were successfully performed, the documentation was delivered and the system was finally accepted by IPP end of 2009.

5 Engineering

The subdivision Engineering (EN) provides engineering support to the Wendelstein 7-X project. EN is organized in three departments: Design Engineering (EN-DE), Development and Test (EN-DT), and Instrumentation (EN-IN).

5.1 Design Engineering

5.1.1 Structural Analysis and Design

DE continued to investigate the mechanical behaviour of the W7-X structure system and its components during various assembly stages and modes of operation. Two independent coarse global model (GM) sets, one for the magnet system and the second for the cryostat, and detailed local models were used.

The latter can be run independently with boundary conditions extracted from the GM. The global models include elastic material properties only, but they take into account nonlinearities like friction and gaps. Fracture mechanics investigations were continued in order to assess cracks in welds and weld influence zones which occur particularly during welding of the inter-coil structure. Analytical and semi-empirical methods were employed which were previously confirmed with the help of FE tools. Investigation of fracture mechanics problems using recently developed approaches and numerical methods has been started in order to confirm previous conclusions. In the course of stellarator system studies a new code MODUCO (MODUlar COils) for interactive magnetic field optimisation, parameter studies, and coil layout was developed. The code reproduces well the magnetic field of Wendelstein 7-X and can be easily used to model further stellarator experiments and reactors. Using the input of MODUCO, a variant of the structural GM was created and successfully applied within the frame of a first conceptual study concerning the mechanical structure of a 5-periodic HELIAS stellarator reactor (HSR5).

5.1.1.1 Magnet System Global Analysis

The magnet system GM encompasses the non-planar and planar coils (NPC and PLC, resp.), the central (CSS), and the inter-coil support structure. The latter comprises the “narrow support elements” (NSE) and “lateral support elements” (LSE) between the non-planar coils, the “contact elements” (CE) 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 as well as the CE basically consist of sliding aluminium bronze pads, held by steel pad frames, and corresponding steel counter-faces. The highly loaded interfaces between the CSS and the coils, the so-called central support elements (CSE), comprise the complex bolted and wedged flange connections which partially open during operation. Two GM variants of the magnet system are routinely in use: The 36°-GM encompasses one half-module and thus represents the elementary cell of W7-X symmetry. With this 36°-model, bolt loads, cool-down, and magnetic loads can be simulated quickly. The influence of the neighbouring half-modules is accounted for by cyclic boundary conditions. However, the 36°-model cannot be used for loads which are not in accordance with the stellarator symmetry like gravity and the reaction forces of the cryo-legs. Therefore, a 72°-GM (one module) is needed whose operation is more involved and time-consuming. For loads not complying with the five-fold torus symmetry, like asymmetries caused by module misalignments or trim coil fields, a complete 360° model is required. This third GM, a simplified variant which can be handled with reasonable effort, is under development. Due to the non-linearity of the structure, the GM and is very sensitive to variations of some initial parameters and boundary conditions. For sufficient confidence, at least two independent global FE-models are indispensable. For the W7-X magnet structure, three independent FE-GMs were created: The ANSYS GM is developed furthest, with fully operational 36° and 72° variants and a 360° one under development, the ABAQUS GM in the 36° and 72° variants, and the ADINA GM in the 36° variant. Even for the mature ANSYS GM development activities, i.e. continuous updating as well as improvements, are still ongoing. Systematic documentation was continued and basically completed. The ANSYS global models are the workhorses which are heavily used for all kind of magnet system analyses. The ABAQUS GM 36°- and 72°-variants, originally created by LTC (Italy), are now continuously operated and updated by IPP. They are used for benchmarking, comparative studies of special structural questions, and for special tasks for which ABAQUS is better suited (e.g. NSE energy release estimation, frictional study of cryo-legs, large deformations, limit analyses, serration effects, etc.). The ADINA code was for many years the only tool for magnet structure design. The new 36° GM, recreated from scratch with partial support from IBK company (Germany), is totally independent from the ANSYS and ABAQUS versions. It is now completed and used for benchmarking of the other models. The ADINA model contains critical structural elements like CSE and NSE as well as the PLCs in more detail, and the components were modelled in one piece with contact interfaces only at places where such ones exist also in reality. In addition, one FE GM version with quadratic elements was created in order to confirm that this more accurate model provides solutions similar to the original FE GMs with linear elements. The results confirm that the linear element approach of all GMs is accurate enough. Comparison of these GMs created in different codes provided very helpful insight into complex modelling issues and led to corrections in all three FEM versions. Eventually, the results of all models agreed well, and the ADINA activities can be finished. The ANSYS and ABAQUS models will be used for further studies, but they still need continuously to be updated corresponding to the as-built geometry and real materials. The principal GM applications are calculation of stresses, deformations, and forces/moments in the main structural elements which occur during different assembly stages and modes of operation. Also the influences of the winding pack embedding pre-stresses, different friction factors at the gliding elements, tolerance deviations, etc., are simulated. Studies concerning operational limits due to the structure have been restarted, using realistic NSE gap tolerances as known from the already assembled modules. Since these real tolerances are about twice as large as previously assumed, significantly higher loads on the structure, particularly on the CSE, are expected which might use up the original safety margins.

In the worst case some extreme field configurations with 3 T at the plasma axis might not be completely accessible. Moreover, the highly nonlinear behaviour causes that some loads and moments are not scaled proportionally to the square of the current. Therefore, even reduced field configurations have to be analysed for final conclusions. Investigations were also performed concerning partial magnet load cycles which are typical during changing the stellarator field configurations. The effects of such partial cycles on the wear of the gliding NSE-, CSE- and PSE-surfaces were compared with full 3-T-load cycles (cf. 2.1). In order to accelerate the assembly procedure in the bottom region of current leads, an option with early removal of temporary supports at the interfaces of three assembled modules is being investigated. For this, a 216° FE model including the temporary support system was created. Preliminary results show no structural problems but some additional residual asymmetry in module deflections which is being evaluated.

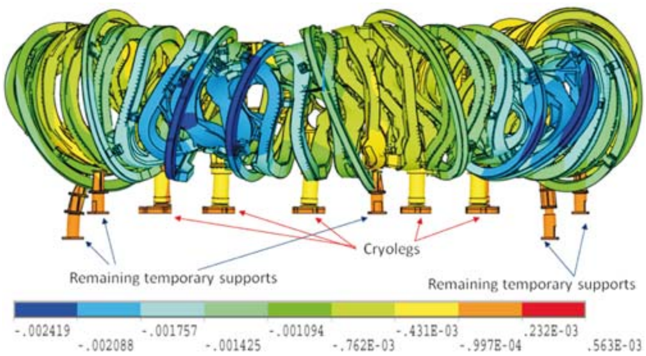

Figure 4: 216º ANSYS FE model of three magnet system modules with remaining supports during assembly (one cryoleg and two remaining temporary supports are not shown for clarity). Vertical displacements [m] after application of deadweight and removal of four temporary supports.

The structure concept of a HSR5 reactor with ≈12 T maximum induction was investigated using a simplified 72° FE-model. A double shell inter-coil structure was found to be feasible, and no massive central support ring, as installed in W7-X, is required. One weight support per module is attached at the magnet system inboard side. The stress plots in figure 5 show that most of the stress intensity is far below the allowable limits of the envisaged forged steel 1.4429, and only some local stress peaks exist which partly can be accepted and partly are due to rough modeling of component interfaces. Only a few stress peaks remain to be eliminated in the course of a detailed design. It was shown that this structure – and also the complete HSR5 magnet system – can be built with technologies developed for ITER, and no significant development leaps are required. However, much design and optimisation work remains to be done.

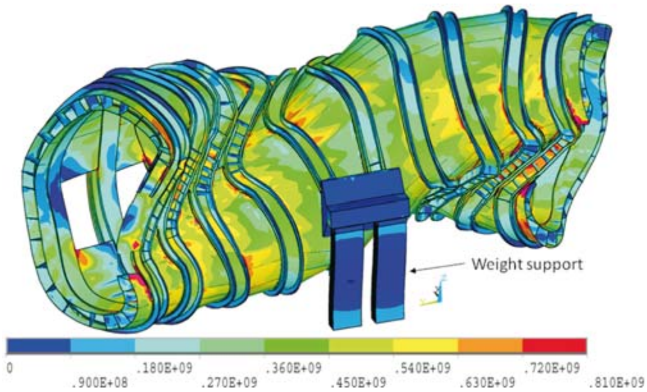

Figure 5: ANSYS FE model of a HELIAS reactor module with cyclic boundary condition for structural study. Tresca stresses [Pa] after application of deadweight, cool-down and electro-magnetic forces.

5.1.1.2 Detailed Analysis of Magnet System Components

The local structure models are continuously updated corresponding to final component design and production, and adapted to the machine modules which are generally not completely symmetrical. Development, refinement and updating work was done mainly at IPP. Cooperations exist with Forschungszentrum Jülich (bus system), Warsaw Technical University (CSE, LSE-D06 and limit analysis of coil extension welds), and with LTC (NSE limit analysis). Work has been continued on updating and refining the coil models according to as-built geometries. Accompanying calculations for W7-X assembly have to be performed continuously, in particular due to geometry non-conformities as well as in the course of collision analyses. Dynamic FE studies, in particular concerning safety issues, were continued in preparation of the "MQ-test" in Saclay, France (cf. 5.2.3) where a cold NPC under current load was hit with different pendulum energies in order to determine the stability of the superconductor with respect to mechanical disturbances. FE-calculations were performed in support of decisions concerning corrections of geometrical non-conformities of the CSS and concerning acceptance of tolerance deviations of shear pins for the step-flanges between half-modules. Investigations were continued on the problem of sliding of the module connection flanges (cf. 5.2.2). The detailed parametric FE-models for all 14 CSE-connections were updated with regard to last design changes in close cooperation with WUT. These models were mainly used for analysing the consequences of tolerance deviations and to decide about assembly corrections. The design of the highly loaded and complex LSE D06 was changed to a "mono-block" variant without wedges. This simplifies the assembly and allows the use of steel instead of the previously foreseen inconel which is expensive and difficult to machine with required precision. For the new design corresponding FE-analyses had to be performed, including nonlinearities like plastification, serration effects, and friction.

A functional specification was issued. WUT was entrusted to create a detailed parametric FE model.
The layout of the bus system, provided by FZJ, was checked and in some cases corrected and/or updated together with FZJ. In particular the interfaces to the current leads and coil headers are a continuing issue to be dealt with. Bus deformations were extracted from analysis data and prepared for collision control. Other FE-calculations were performed in support of the evaluation of aluminium welds and its heat influence zone at the cable jacket (cf. 5.2.4). In order to confirm the coil FE-models, the deformation of a non-planer coil under a mechanical spreading force (cf. 5.2.5) was evaluated. Experiment and calculation agreed well within the limit of accuracy. Another example of FE-analyses was the support for clarification of the out-of-tolerance projection of a NSE pad frame from the coil.

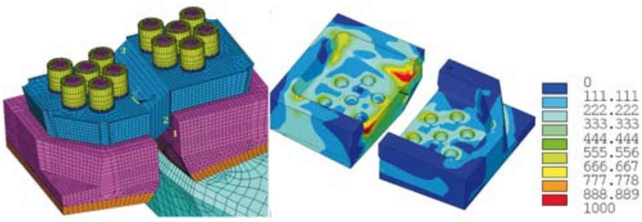

Figure 6: Preliminary ANSYS FE model for the LSE 5-5 monoblock variant (left). Von Mises stresses [MPa] in the respective coil blocks after cool-down and application of 120 % of electro-magnetic forces in the Low Iota configuration (right).

5.1.1.3 Fracture Mechanics

Fracture mechanical evaluations were continued due to repeatedly occurring surface cracks during welding of the LSE. The analyses were performed with analytical, semi-empirical methods with high safety margins. None of the concerned welds had to be re-welded. In order to be prepared for cracks which could not be treated analytically, work started on numerical crack analyses as well as re-estimation of already accepted cracks with recently developed approaches.

5.1.1.4 Cryo-piping

FE-modelling (in ANSYS) of the cryo-pipe system was completed for the second module to be assembled (module M1). The analyses were performed iteratively hand in hand with the proceeding piping and pipe support design. The effect of internal pressure was implemented in the complete model. Modelling of the third module (M4) has been started.

5.1.1.5 Cryostat

Main application of the ANSYS cryostat GM was again the study of assembly load cases of the outer vessel half-shells, and the extraction of inputs for detailed component. Adequate assembly support structures and handling procedures were defined. This work is ongoing and has to be performed for all shells due to the asymmetry of the modules. The ANSYS cryostat GM is under continuous development to reflect design changes such as port removal, port and dome extensions, and load changes due to in-vessel components modifications. Activities concerning the analysis of welds between the plasma vessel and ports were considerably extended.

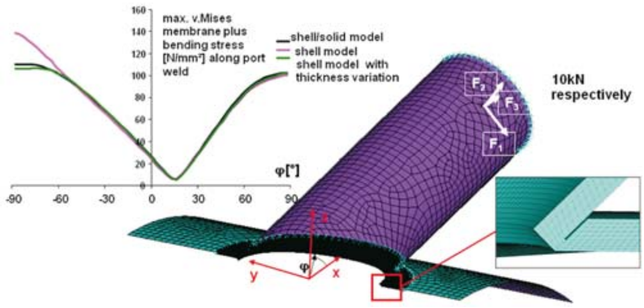

Figure 7: Stresses along the port weld length (given in the angular measure φ) resulting from of the semi-analytical port weld analysis and a local ANSYS FE model (insert at the right) for verification of the procedure.

Previous analyses suggested a re-consideration of these welds, and a new weld design was created by AS in cooperation with EN. An analytical analysis method was created using the cryostat GM (contains 3-D shell elements only) results as input. With this method the majority of the ports could be treated and released for welding with the qualified standard weld seam. For special ports, and in cases of doubt, a laborious 3-D FE analysis has to be performed. These works are ongoing, but for some cases the necessity to increase the weld strength has been already realized. Corresponding weld qualification work was initiated in the assembly subdivision.

5.1.1.6 In-vessel Components (KIP)

Main activities were thermo-mechanical analyses supporting the design of KIP components and diagnostics. Examples are investigations concerning shields on top of the diamagnetic loop and of the XMCTS, and studies on heat loads and corresponding deformations of retro-reflectors, Langmuir probes, test and high heat flux divertor targets. Activities have started on re-evaluation and systematisation of all thermal loads within the plasma vessel.

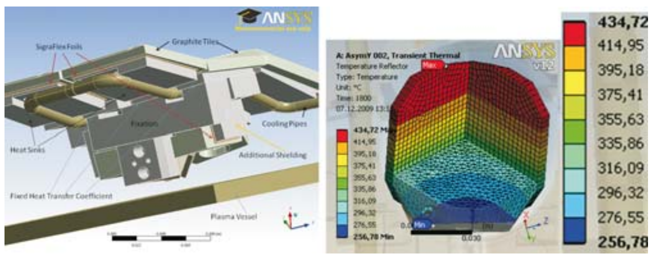

Figure 8: ANSYS model for thermal stress analysis of the interferopolarimeter QMP under heat loads (left).Temperature distribution (ºC) within the reflector after 1800 sec (right).

5.1.2 Magnetic Field Analyses

In order to compensate the influence of accumulated construction errors on the magnetic field configuration, the module positions have to be corrected accordingly. The corresponding software was prepared and tested. All known technical limitations at the module separation plane were included in the software package. A target function, based on weighted field error components, was defined to be minimized for an optimal field configuration. The first module was placed on such pre-calculated optimized coordinates which were evaluated taking into account all 5 modules. These coordinates will be corrected step-by-step according to further measurement results.

5.1.3 Thermal Analyses

Collision checks based on the as-built W7-X components and realistic tolerances revealed many constriction areas between ports and coils with high collision probabilities. In order to relax the situation it was decided to remove the cooling/heating pipes from all inner port tubes (i.e. the part of the port at the plasma vessel side) wherever possible and replace them by copper stripes for conduction cooling/heating. In support of this re-design, several ports including bellows where thermally analyzed and corresponding layouts were proposed. Thermal and fluid mechanical analyses were performed for the design of special port cooling/heating channels. Cooling/heating of the port bellows via radiation exchange with the surrounding copper foil shields was analysed, and corresponding foil attachments at the bellows flanges were specified.

5.2 Development and Test

5.2.1 Coil Support Elements

The test program concerning component development is practically completed, and the emphasis of the EN-DT dept. activities has shifted to assembly issues. EN-DT is helping to prepare and update work instructions for support elements and the CSS, and is heavily involved in evaluating achieved tolerances and non-conformities. Furthermore, MoS_2 layer applications and coil spreading for LSE assembly are supervised. Another ongoing routine work is to check and release drawings of the connection elements. The NSE test program was finally reviewed and documented in an executive summary. Main parameters responsible for the lifetime of the sliding bearings were identified from own experimental results as well as from literature. The study was used as a basis for the assessment of friction and wear during partial magnet load cycles. The friction test device at BAM in Berlin for scaled down NSE-samples was upgraded from a bath-cryostat to a vacuum test environment, cooled by a LHe loop, in order to simulate more closely the W7-X conditions. An extended 4000 cycle friction test on scaled NSE, at loads corresponding to W7-X maximum design values, showed neither any degradation of the friction coefficient nor stick-slip of the bearings. The achieved temperature was about 20 K which is close enough to the W7-X operation temperature for ensuring realistic physical conditions. Systematic sliding pad MoS_2 layer ageing experiments were continued at different temperature and humidity levels in order to estimate possible impact of the long-term exposure to air during the W7-X assembly phase.

5.2.2 Module Connections

Concept, design, and functional specification of the LSE D06 were developed in close collaboration with EN-DE and the subdivisions MC, DC, and AS. At the bolted connections of the CSS flanges and the LSE-D06 high shear forces have to be transmitted, but sliding has to be limited to a minimum. The coefficient of friction for steel is not sufficient and has to be significantly increased. Therefore, a qualification program has been started for commercially available friction foils. Tests in LHe showed their principal functionality, a friction coefficient of about 0.5 was achieved. Dependent on the flange surface material, roughness and pressure, the optimal friction foil has to be selected; a corresponding experimental setup was developed.

5.2.3 Coil Quench Experiment

The mechanical quench (MQ) test was successfully executed on the non-planar coil AAB49 at the end of the coil acceptance test program at Saclay. The objective of this test was to simulate the impact of possible stick-slip events within structural components during W7-X-operation. It was explored whether the associated dynamic loads are able to trigger large enough elastic energy releases of the superconductor strands to cause quenches by frictional heat.

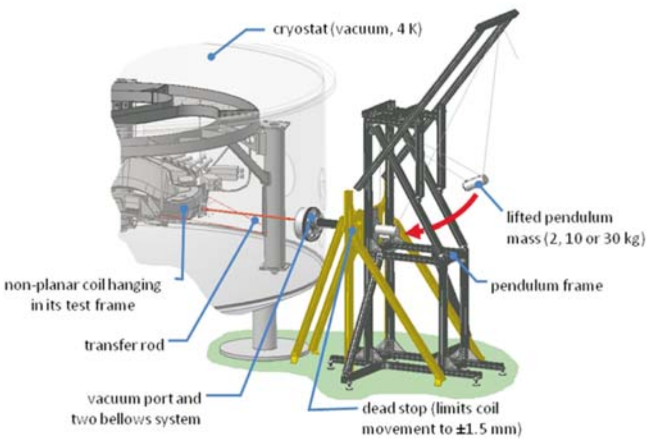

Figure 9: MQ-test setup. The coil is hit by different pendulum weights via a transfer rod which is fed through the cryostat wall and the LN_2-shield. The transfer rod is sealed against the cryostat wall with a double bellows system with intermediate vacuum. The pendulum is released from different heights. The dead stop frame limits the movement of the transfer rod and the coil attached to it.

The dynamic test loads were applied by a pendulum via a transfer rod to the casing of the cold and energized coil within the cryostat. No quench was triggered even with the maximal impact of 167 J, corresponding to the worst estimated disturbance within W7-X, at coil operation conditions with the lowest nominal superconductor stability margin. One can thus be quite confident that no quench will be initiated by mechanical disturbances like stick-slip effects during the operation of W7-X.

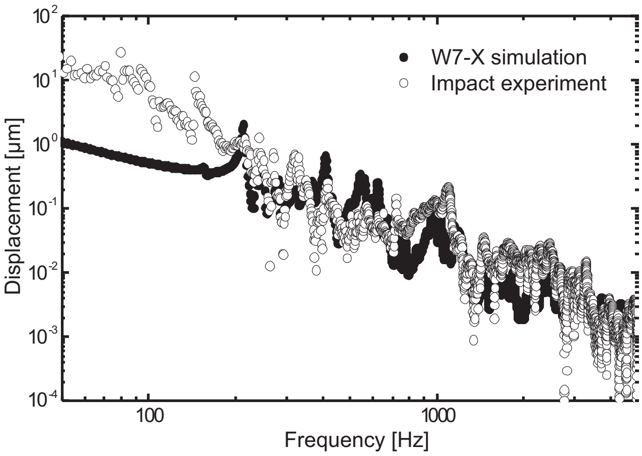

Figure 10: Spectra derived from the maximum impact energy test, and from simulations of the expected worst case stick-slip event in the W7-X magnet structure. The vibrational movements within the coil cross section due to the impact test are above or comparable to those from disturbances within W7-X. Displacements below the µm-range are unlikely to initiate slippage of superconductor strands.

5.2.4 Bus-bar Joints

A test program for better understanding the quality of the cable jacket Al welds and weld influence zones was finished. Tensile tests on full size weld seam samples were performed at 4.2 K. In contrary to tensile test results at room temperature, the fracture location at cold temperatures is not within the heat affected zone but within the weld seam (see figure 11).

Figure 11: T&C weld specimens after tensile tests – breakage within the weld influence zone at RT (left), and within the weld at 4K (right).

A room temperature tensile test was developed in order to provide quick statements on the weld quality. With this equipment the weld proper could be loaded without stressing the heat influence zone. The scatter of the mechanical fracture force for the Al weld was determined on 25 representative specimens, and the influence of typical welding errors on the fracture limit was evaluated. Due to the advanced state of assembly this quality assurance measure was not implemented any more as a standard test at the beginning of the welding campaigns.

5.2.5 Benchmark Tests

A NPC type 2 was spread along its short axis by loads of up to 80 kN. The observed displacements with respect to the spreading force validated the assumptions taken in the FE-calculations. Some of the CSE bolts are loaded during W7-X operation up to the plastification limit of inconel. The most critical bolts are instrumented with strain gauges. Their signals may be used to find operation limits of W7-X and, therefore, must be reliable. The principal functionality of this instrumentation was already shown during the CSE bolt test campaign, but was restricted to operation temperatures of 77 K. For complete qualification the entire strain gauge measurement chain was now tested down to 4.2 K on a ∅30 mm inconel bolt under defined loads. This instrumented bolt is now used as a calibration standard.

5.2.6 Materials

EN-DT accompanies the 4.2 K material tests at KIT. An ongoing activity is maintenance and supplementation of the material data base (MDB) which is a collection of thermal and mechanical property data of all kind of cryogenic materials within W7-X, including all test results from the materials qualification programmes. The huge amount of data was evaluated with respect to average values and standard deviation. This collection, therefore, might be interesting also for other projects encompassing cold components (like ITER). However, for high load applications, particularly in which plastic deformation is expected, the testing of individual construction materials is indispensable.

5.3 Instrumentation

Development and design of the magnet structure instrumentation, the coil displacement sensors (figure 12), and collision sensors were completed in 2009. The coil displacement sensors were tested twice on planar coils during the coil acceptance tests in Saclay under cryogenic and magnet field conditions. Such sensors were also successfully used during the MQ tests.

A collision sensor was developed to monitor potential collisions during cool down and energising of the coils. The active part of this sensor is a fraction of a millimetre thick and can easily be placed on practically any location within the cryostat.

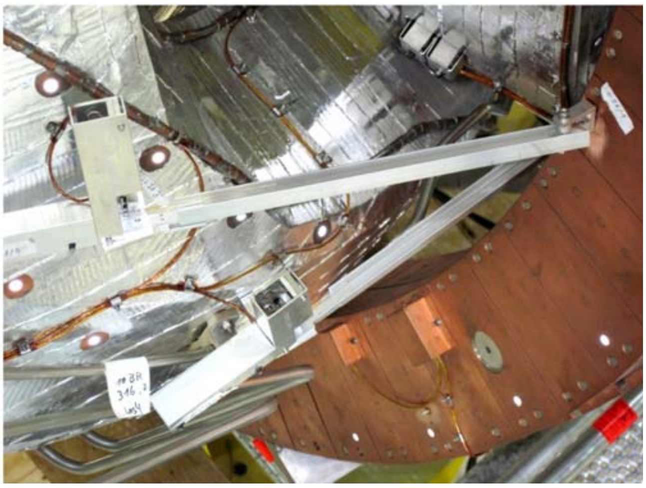

Figure 12: Coil displacement sensors between a planar and a non-planar coil.

The sensor application within the cryostat of Modul 5 was completed and instrumentation of the other modules is on-going as planned. Technical specifications for the remaining cryogenic instrumentations were written and released in 2009. Experimental and theoretical investigations on strain gauge electronics in preparation of the technical specification has been started. Important aspects of this work are the study of crosstalk between signal channels and electromagnetic influences on the signal transfer along long transmission lines. Instrumentation for the MQ-test, including the electronics, was supported. This concerns the strain gauges on the impact transfer rod for detecting the direct and reflected pressure waves, as well as the cantilever system to measure coil oscillations. The Extended Instrumentation Team (EI-Team) continued its work in 2009. Its activities were to work out an overview of all the required and applied sensors in the magnet structure, a review of the I-Port design and its assembly, and the grounding concepts for instrumentation cabling, electronics, and cubicle line power connections.

Figure 13: Collision sensor placed between a bus conductor and a support clamp.

6 Design and Configuration

The subdivision "Design & Configuration" is responsible for configuration management of W7-X, thus for establishing data structures and data change processes that at any time provide a complete and up-to-date data set of all components of W7-X, for configuration control of the components in the cryostat, the plasma vessel and the components in the experimental area and for providing design capacities and design standards for most of the components of W7-X. These tasks are taken care of in the three departments "Configuration Management" (DC-CM), "Configuration Control" (DC-CC) and "Design Office" (DC-DO).

6.1 Configuration Management

The tasks of the department Configuration Management (DC-CM) are to provide the complete and up-to-date system identification of all components of W7-X and to ensure proper change and deviation management. This then allows the determination of the present design or implementation status of all components of W7-X and provides detailed information on the history of any design changes. The system identification of all components and documents related to design, installation and operation of W7-X is stored in individual documents, the so called "Ringbuch" documents, that either provide the information or refer to the presently most up-to-date information. Of those, interface documents describe in detail the nature and agreed upon specifics of all interfaces between pairs of components and change notes describe changes in the design that were adopted after the initial design had been released. The product lifecycle management (PLM) system is simultaneously used as a documentation data base, as a navigation platform to the specification of W7-X and its components and for notification on new releases of CM-relevant documents. Permanent control of the various CM processes is supported by specific process data bases, e.g. status and open issues of change requests, quality deviation reports and interface descriptions, are monitored. Well-established procedures are being followed to counteract any delays of in the change note processes or to assist particularly critical issues. By now the configuration management for system identification, change and deviation management, interface coordination are routinely applied. Currently, 663 design change requests are registered in the change data base. 78 % of the requests have been accepted, 14 % are in the decision process and 8 % have either been rejected, withdrawn or became obsolete by revision. 43 % of the accepted change requests have been closed, i.e. the relevant design and assembly documents, CAD-models and drawings have been revised according to the change. Major attention is now given to improve configuration status accounting in order to ensure that the configuration is kept consistent including all design changes. The W7-X interface matrix is currently built up of about 60 components.

184 pairs of them have identified interfaces which are followed up by the interface coordination process. 42 % have been released, 53 % are being processed. For the residual 5 % the design process of at least one of the components and thus the interface definition is pending.

6.2 Configuration Control

The tasks of the department Configuration Control (DC-CC) are to ensure collision-free operation of W7-X for all modes of operation and to coordinate the space requests of peripheral components in the torus hall and adjacent buildings. In 2007, tools and procedures were established, to improve the speed, reliability and accuracy of the investigations. In 2008, procedures and interfaces with others department were defined or improved and the global strategy for configuration control was defined with the W-7X board. Due to missing or late information on the deformation of those components and a lack of engineers able to perform the sophisticated investigations needed to deal with the complexity of the components, it was necessary to take some risk management decisions: no configuration control for cryopipes was being done, the tolerance chains were simplified. In 2009, the number of engineers in the department was temporarily doubled from 17 to 34 to cope with the workload and deadline of the thermal insulation configuration control. This required a change in the organisation: the group leaders were replaced by a team of projects leaders, and tasks were organized in projects, allowing high reactivity and flexibility for the realisation of the tasks to be done by the department. Two internal training sessions ensured that all engineers were properly educated in the quality standards and methods adopted. The department continues to improve existing tools and to establish new ones. An easy-to-handle tool was developed that allows 3D visualisation of all CAD parts and assemblies in CADDS5-PLM that is available without additional licenses required to all people within the W7-X Project. The templates and databases for issuing configuration control reports were further refined to better fit the demands, provide complete information on all relevant issues and information sources used and to better track the changes in the CAD models. The CAD database tool Smarteam has been implemented for the system layout in the torus hall. The configuration control investigations of coils, central ring, bus system and cables trays, e.g. for instrumentation and quench detection, were being continued. The most demanding, due to their deadlines, of these were the assessments of the conflicts of the thermal insulation. In 2009 about 1450 collision reports were issued. The main mission of the group System Layout is to provide and document the space reservation of all the components outside of the cryostat in the torus hall and adjacent buildings. 10 space reservations for components were revised or established. For the cooling water lines, the space reservation implied the draft of a preliminary design. In addition, about 30 change notes were processed that were triggered either by the requests for additional space in the torus hall for new components or to eliminate a collision between components that was detected in the system layout process.

6.3 Design Office

The tasks of the department Design Office (DC-DO) are developing design solutions and providing fabrication drawings for components, supports, and tools for W7-X in close cooperation with the responsible officers from other departments. Additional tasks are defining and implementing design guidelines for working with CAD programmes and maintaining a proper structure of the CAD models in the data base. The numbers of designers had to be increased in order to cope with additional tasks, i.e. when originally externally designed components were decided to be designed in-house or when the challenges in finding design solutions turned out to be more time-consuming than originally estimated. Care was taken that for particularly time-critical design activities a sufficient number of properly trained designers was available. The design office is organized in four groups that specialize on different design tasks: The Cryostat group, the Structural Elements group, the Components-In-Plasma-Vessel group and the Diagnostics group. In this way it is possible to coordinate related work packages, to maintain the same standards and design characteristics, to ensure simultaneous engineering, to adopt the design resources quickly to the extent of the design tasks, to effectively train new personnel and to inform the project of the design capacities needed to timely complete all design activities. Most of the components of W7-X were originally designed using the CAD tool CADDS5. The increased need for additional designers, in particular to complete the design activities in the cryostat, made it necessary to also use the more common CAD tool CATIA V5 in addition, since it was difficult to hire external designers that were sufficiently well trained in CADDS 5, but comparatively easy to hire external designers with at least two years of hands-on experience with CATIA V5. In close collaboration with the departments DC-CC and PC-DO, work flow procedures were developed and implemented that facilitated simultaneous engineering using the two different CAD tools even in areas where the components are intricately interwoven as in the cryostat. At the heart of these procedures is the overall assembly of all components that are part of the W7-X basic machine. This assembly with all its sub-assemblies is maintained up-to-date in the product lifecycle management (PLM) system of W7-X using CADDS5 CAD data. All CATIA V5 models are converted into CADDS5 models and included in the overall assembly by the Documentation department, PC-DO. The CATIA mirror image of this CADDS5 overall assembly, that is kept up-to-date daily, is provided by the department DC_CC. Thus, both CADDS5 and CATIA designers are being provided with the same information as to the status of all other components.

During 2009 some of the components whose original design solutions were begun in CADDDS5 where either re-designed in CATIA V5, e.g. the thermal insulation of the ports and the domes of the cryostat, or their design was continued in CATIA V5 in other modules, e.g. the cable trays for instrumentation cables and quench detection cables in the cryostat. Detailed design solutions that were provided by external companies, e.g. thermal insulation of the cryostat by MAN Turbo were included in the overall assembly as CATIA V5 models. The Structural Elements group mainly provided design solutions for various structural components in the cryostat: In accordance with the overall assembly progress detailed design drawings were provided for the support elements to accurately fit the intended space envelope. Various design options were developed for the lateral support elements that connect the two type 5 non-planar coils across the module separation. The supports of coil current connectors in the coil header region were designed for the first two modules based on the as-built data and fortified when the design loads were reassessed and found excessive. Various design solutions were developed for the attachments of the current leads to the central support ring. However, due to the complexity of the assembly process no final design solution has been decided yet. Further design solutions and in part fabrication drawings were made available for modifications and extensions of domes and ports .The group Cryostat completed the design of the thermal insulation, of the cryogenic helium supply pipes and of various supports for permanent or temporary use within the cryostat. The design of the cable trays for the instrumentation and quench detection was finished in module 1 and 4. Caused by the tightness of the available space and the displacement of all components relative to each other of typically several centimetres during the various load cases the design iterates with repeated assessments by configuration control and the respective responsible officer. Due to an increase in the feasible assembly tolerance design of the thermal insulation the models had to be redone. Procedures were implemented to organize and monitor the design iterations to keep the delay of the overall project as short as possible. The sections of the cryogenic helium supply pipes were designed to allow multiple repetitions in the other models wherever possible. The original CADDS5 design of the cable trays in module 5 was parametrically re-designed using CATIA V5 to accelerate the adaptation in other modules. The Components-In-Plasma-Vessel group nearly completed the design of the heat shield, of the covers of the diamagnetic loops, of the water cooling pipes and of the wall panels in the plasma vessel based on the design requirements of the initial phase of operation. The Diagnostics group kept its focus on the design of those diagnostics that need to be installed first or that require the longest time of development and fabrication. Towards the end of 2009 with a number of designers that had been working on issues in the cryostat began working on other diagnostics. The design tasks of all diagnostics were internally reviewed to facilitate better planning of the available resources. Most diagnostics are being designed in CATIA V5.

7 Assembly

In 2009 the preparation of the assembly sites, the assembly equipment, and extensive assembly trials have been continued. An additional assembly area (assembly of the thermal insulation onto ports in hall 22) was put in operation. The third and fourth magnet module passed successfully the mechanical pre-assembly. The first magnet module was already put into the outer vessel module on its final position in the experimental hall. The alignment accuracy achieved is much better than originally expected. The last module is in the stage of the half-module pre-assembly. Further complex assembly devices for the final assembly (assembly ramps, vessel rigs) have been delivered and commissioned. The manufacturing of the bus-bar system (cooperation with FZ Jülich) was continued as planned. The components for the bus-bar system of the last module are presently being produced. The bus-bar system, the helium piping and the instrumentation of magnet modules runs smoothly and without essential problems. The preparation of plasma-vessel sectors and coils and support structures has nearly finished. Both the mechanical preparation of the outer vessel shells (including the complex plasma vessel supports) and the installation work of their thermal insulation run routinely. Comprehensive assembly trials with ports and with in-vessel components (KiP) have been performed to ensure the mountability. Welding procedures for ports were developed to minimize the welding-shrinkage during the port assembly. The assembly sequence and technology for current leads were optimized further with the assistance of the PPPL in Princeton. Several new engineers and craftsmen were recruited. The challenging assembly process-planning, process documentation and work safety system run reliably.

7.1 BUS System

The manufacturing of bus-bars and the associated complex mechanical supports runs routinely. Works on the components for the last module have started. Bus-bars and supports for the first three modules were already installed. The technical problems with the insulation for bus-bar joints were overcome successfully. A manually made insulation was qualified for all different design variants of joints. This system bases on the experiences of the coil manufacturer BNM. Skilled technicians for these works were hired and trained. Meanwhile all belonging works run smoothly and the schedule is kept. Special challenges had to be solved in conjunction with the QD-wiring. Frequent damages to these wires occurred during the insulation works due to the badly accessible installation space. This applies particularly to those spots where the wires protrude out of the insulation. The cured resin forms sharp edges which damage the insulation of the wires. A mechanical protection system for the QD-wires has been qualified. The compliance of the compatibility of that system with both the conductive painting of the bus-bar system and the integrity of the electrical insulation was very effortful. The associated development program took a few months. Development works for the electrical connection of bus-bars and current leads have been started. This connection is quite similar to the joints mentioned above; however the current leads require a modified technology because of the limited accessibility conditions. These development works must be carried out in conjunction with the technology development for the mechanical assembly of the current leads. It is planned to incorporate the assistance of the PPPL, Princeton and ORNL, Oak Ridge in these developments.

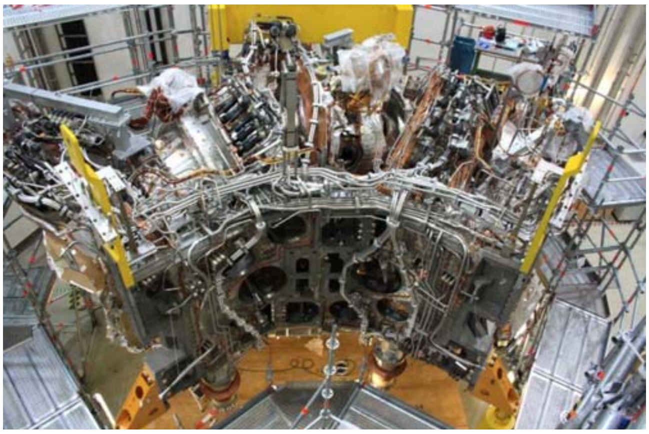

Figure 14: 1st magnet module complete with bus-bar connections and helium pipe system.

To keep within schedule the working time had to be extended to more than 80 hours per week. The number of technicians and engineers allotted to these works had to be increased accordingly. The cooperation with IFJ in Krakow was further extended and contractually agreed. IFJ provides a major part of the technicians and the responsible line management for the daily works.

7.2 Vacuum Technology

The work packages of the vacuum technology group in 2009 were continued as in the years before. Main tasks were: leak detection on single components and on the cryo piping of thermal insulation; Paschen tests on coils and on the bus-bar system during the coil preparation and the 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 procedures was further continued (see figure 15).

Design works on the vacuum systems were continued; first components have been ordered. Special attention was paid to the qualification of fast piezo valves for the gas-inlet. The use of already existing valves after their refurbishment is an alternative which is being investigated at the moment.

7.3 W7-X Assembly

7.3.1 Component Preparation

The work at the preparation of coils, plasma vessel sectors and support structures has nearly accomplished. Works at outer vessel shells and ports are continued as planned. The scope of these works is growing fast according to the progress in the final assembly. In addition the scope of these works increases because of both the still necessary design changes and several quality deviations at the delivered components. The preparation work on outer vessel shells is continued as planned. Two shells per module are put together temporarily and geometrically checked after the preparation. The shell contour is stabilized by an additional frame work (yellow parts in figure 16). Several turnbuckles enable the local correction of the outer contour to match the CAD design. The comparison between achieved contour accuracy and the demanded values is made by means of Laser Tracker measurements. The values achieved are within +/-5 mm. Only with this stabilisation the individual shells can be handled, transported and assembled. The frame work is removed once both shells have been welded together, later in the final assembly. The installation of the thermal insulation at the inside of the shells requires special effort. The insulation is split into several panels. Every panel's shape is customized individually to the available installation space. This leads to very high complexity in design, collision check and manufacturing and hence, to large time needs. Additional assembly equipment was procured and the work flow had to be optimized several times to minimize the impact onto the project schedule. Meanwhile the preparation works on the shells of the third module have started.

Figure 15: Test chambers at bus-bar joints.

7.3.2 Pre-assembly

Four magnet modules (out of five) have been completed mechanically in the pre-assembly. These works are continued routinely at the last module (fifth pair of half-modules). Meanwhile, there are hardly technological changes left in these pre-assembly works. The cooperation between all participants, including the parts of the external supplier MAN Turbo works fluid and within the planned times. The first three modules were moved into the experimental hall. On the second, third and forth magnet modules the bus-bar system, the helium pipe system and the instrumentation are being completed. These works are running routinely. This applies particularly to the manually manufactured electrical insulation of the bus-bar joints. Special test procedures were developed for the electrical insulation of the bus-bar joints. Evacuate able test chambers were built which match individually the available space of the joint. Joints are leak-tested after the welding of the joint housing. After completion of the electrical insulation a Paschen test (5 kV) at different pressure stages is being performed. Two joint specimens were made during the assembly of the bus-bar system and tested by the Efremov Institute in Russia at 4 K. The purpose was to validate the resistance values achievable during the real assembly and to compare them with those values achieved during the qualification phase two years ago. The test confirmed values far below 1 nΩ which is far below the specified limit of 5 nΩ. The installation of the helium-pipe system has turned out to be as demanding as the bus-bar system. Batches of pre-bent pipes known as “Lots” are positioned above and below the bus-bar system. The pipes are fastened at the coils and structural elements. G10 spacers in the support bearings prevent inadmissible heat conduction flows between neighbouring pipes at different temperature levels (inlets, outlets). Flexible hoses complement the helium-piping. These are used to compensate for displacements of the magnet structure due to both the temperature shrinkage and the operational deformation. During the installation it became necessary to re-bend some pipes. Some pipes showed too big manufacturing deviations and, therefore, constrictions had to be widened between neighbouring components. For this purpose, special bending tools and alignment templates were procured. Special attention had to be directed on the alignment of the mechanical supports of all 3 systems: bus-bars, helium-pipes and instrumentation trays. Time consuming alignment procedures supported by Laser Tracker measurements ensure that the base accuracy of these supporting points is within +/-1.5 mm. The originally assumed idea that the above 3 systems will get the same accuracy as the supporting points could not be realized. On the one hand the span width between these points could not be made sufficiently small because of limited installation-space and on the other hand conductors and pipes are too instable to become bent three-dimensionally with sufficient accuracy. This caused local deviations of the pipes and conductors of 5 to 10 mm in comparison with the given CAD co-ordinates. Hereupon and considering the actual assembly tolerances the CAD models of all components of this module were analysed geometrically (configuration control). That required some additional weeks of work for the associated metrology, data processing and data comparison as well as on-site inspections. With that some critical areas were identified and the position of the affected components was corrected accordingly. Also the next module is being subjected to this final geometrical check. This minimizes the later risk of possible collisions albeit these measures are quite effortful. In addition to the originally planned instrumentation of the first module many contact sensor had to be installed. They support during the machine operation the monitoring of the above critical areas and small interspaces. The bus-bar and helium pipe works are much more time-consuming than originally planned. A special challenge is the work densitiy in the very limited work-space of the magnet module. Scaffoldings, which are extensive and customized, are used to make as many parallel work spots available as possible. Nevertheless, the planned degree of parallel work could not be achieved completely. On the other hand many technological time contingencies could be dissolved since there were only very few technological uncertainties. The planning was modified accordingly and the contingencies have been reduced. The assembly works on the above systems are organized in an expanded double shift system with nearly 90 work-hours per week. For the first two modules the completion milestones are kept as planned. For the forthcoming modules it is expected that the time needed is reduced due to the learning curve effects.

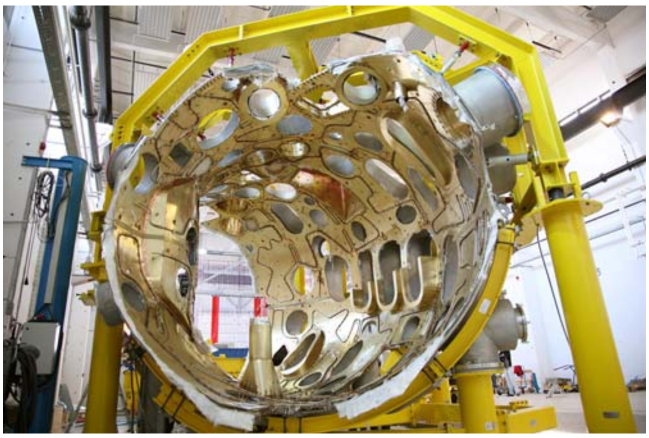

Figure 16: Preparation of outer vessel shells.

7.3.3 Final Assembly

In the final assembly the construction work at the first module of W7-X has started. The transportation and alignment of the bottom shell of the outer vessel went without any difficulties.

This applies also to the alignment of the two cryo feet (weight supports of the magnet system) and their complex integration into the bottom shell (welding of bellows, helium leak tests). The magnet module was positioned into the bottom shell and the upper shell of the outer vessel added. The alignment process of the magnet module in the W7-X coordinate system was easier, faster and more accurate than planned (+/-1.5 mm). The positioning of the upper shell worked similar smoothly. This applies also to the precise alignment of the plasma vessel whose dead weight was shifted from the temporary suspension system to the original plasma vessel supports. Only the plasma vessel's shape was deformed locally by about 4 mm after the temporary supports of the suspension system had been removed. This is to be compensated by repositioning of the plasma vessel before the port-assembly work is starting. To save time the above works were made on mounting stand IV. This is possible because for the first module sufficient space is available on both sides. For the following modules the original sequence has to be kept, i. e. the magnet module is lowered into the bottom shell on mounting stand IVa and afterwards moved as a combined component onto the machine base. This is a challenging operation which is used the first time with the second module. At present both outer vessel shells are being welded together. Large domes which are situated directly in this plane are also welded together with the vessel shells. Simultaneously, the thermal insulation is complemented at these spots. This work is done by MAN Turbo for the first time. The work proceeds smoothly and within time plan as for the other works described above. For the assembly of ports special equipment was delivered and put into operation. This comprises the heavy port-assembly bridge which spans three sides of the module, and the two port assembly ramps which can be operated independently. About 40 ports are being installed in conjunction with the individual module completion. Another 4 to 5 ports are situated at the so-called "module separation plane – MSP". These will be installed later when two neighbouring modules are being connected with each other. The port assembly comprises 4 main stages: the contour taking (definition of both the actual port position and the actual 3D-contour of the port opening in the plasma vessel), the port preparation (cutting to shape and length), the port installation (the thermal insulation and the port itself) and the welding (one weld seam at the inside of the plasma vessel and two weld seams at the outer vessel). It is estimated that these works will take per module about 6 months with double shift work. In general two ports will be worked on simultaneously with two teams. This requires the above two port assembly ramps as well as the doubling of the remaining special assembly equipment. Whilst the port position at the plasma vessel is clearly defined by the actual port hole itself the outer vessel opening allows a lateral adjustment of 10 mm. This is used to widen narrow locations between the port and the magnet system which are caused through deviations from the nominal CAD positions (manufacturing and assembly tolerances). Ports do consist of a steel tube and a bellows. Since the bellows diameter is larger than the port diameter bellows can also cause clashes with components of the magnet system in axial direction. The same applies particularly to the thermal insulation that surrounds the entire port contour. The definition of the length, the contour and the position of the port is carried out in a three-stage process. In the first stage the position of the magnet system, the PV holes and the OV holes is being measured (Laser Tracker and Photogrammetry) in the W7-X coordinate system. Out of it the required port-position, its length (at a defined spot along the port's circumference) and the axial bellows position is deduced in the second stage. In this process the optimum location with respect to distance to neighbouring components is considered as well as deformations of all components which are caused by the operational forces, thermal expansion, vacuum forces and compression forces. The result is the lateral offset of the port axis in the OV hole, the nominal port length and the length between port end and bellows flange plate. In a third stage these data are directly used by the technicians to cut the port and to align their port alignment tools. That procedure was tested a few times with dummy parts. The overall accuracy achieved was better than +/-1.5 mm. Special tools were developed and tested for the alignment of ports. The above bridge and ramps are the main tools to hold and to align the ports in all 6 degree of freedom. The bridge with towers and cross beam weighs about 11 tons; a ramp weighs about 2 tons. Ramps can be operated from the floor or on platforms, which can be moved upwards and downwards in the towers. The ramp can also be positioned on a carriage on the cross beam and moved forth and back. The carriage contains a turret that allows the 360° rotation of the ramp. Towers can be operated independently or connected with the cross beam to a bridge. The bridge can be easily and precisely moved circularly around the machine centre on rails and air cushions. During the first tests of this complete system with the largest port (1.5 tons) it was found that the port axis in its outermost position (2,5 m) deviated from the given vector by more than 5 mm. Though the system had got quite a massive structure it already reached its mechanical limits. Hereupon the ramps have been equipped with automatic levelling systems which compensate the weight deflection during the movement of the port. After this improvement the accuracy of the ramp/bridge system corresponded to the specified values. Another problem was the very high complexity of that system with its many actuators and the difference between the direction of the actuators and the desired direction of the port axis. It turned out that the idea to convert the direction of the port movement into a sequence of individual actuator movements is too time consuming during the practical use on site.

When the port is moved through the cryostat there is only a save clearance of about 5 mm at narrow locations. On the other hand during the way from the OV opening to the PV opening the sight is blocked by the already installed thermal insulation. Therefore a more simple laser-supported system was developed which allows the technician to precisely control the alignment process by monitoring a laser-target system. In every port opening a target template will be installed that is precisely machined according to its 3D contour. A second target structure is positioned in the OV opening. This target can be adjusted laterally with given offset values. Once the ramp laser meets both target centres the nominal vector for the port axis is found and the port can be installed. The installation of the thermal insulation is split in two stages. This work is carried out by the company MAN Turbo. In the first stage the first part of the pre-manufactured insulation (bottom insulation tube) is mounted directly on the port during its preparation. In parallel, the second part (upper insulation tube; so-called Domtopf) of this insulation is mounted onto the OV insulation. Thereafter the port is partially installed; both insulation tubes are connected together flexibly; the port is further inserted and the TI gets connected to the PV insulation. Simultaneously the backing gas equipment is fastened at the PV opening. This provides later the backing gas for welding and afterwards the helium for leak testing. After that the port is finally positioned and tack welded. The final welding procedure for the ports required expensive development work in 2009. This applies particularly to the weld at the PV side. Any deformation due to the weld shrinkage (less than 1 mm) and discolouration had to be minimized in the process development. For this a narrow gap plasma welding procedure was further developed with cold metal transfer (CMT) based on existing technologies. Another problem is the large gap tolerance (locally 1 to 5 mm) at installed ports due to large manufacturing deviations. To cope with that a combined buttering/peening procedure was comprehensively tested and qualified. This is used at the PV opening and ensures a constant welding gap of about 1 mm. Since pneumatic peening is quite noisy these works have to be made during the night shift. To minimize discoloration, laser-slit pipes provide a weak but sufficient stream of backing gas at the rear of the weld. After the installation of the ports a single module of the W7-X is completed with the exception of the plasma facing components. Once three modules have been completed the connection of neighbouring modules (module separation plane) can start at the earliest in the middle of 2011. The concept for the connection of neighbouring magnet modules (shim plates, bolts, fitting elements) has already been worked out. Refined technologies will be developed in the forthcoming years. Tools and work procedures have to be qualified and described in detail. These tasks are assessed to be not critical at the moment. Another main work package will be the installation of the 7 pairs of the current leads which takes place after all 5 modules are in place. The base technology for it is presently being developed in cooperation between the IPP and PPPL/ORNL. When all 5 modules have been connected the base machine of W7-X is complete except for the machine periphery and the in-vessel components.

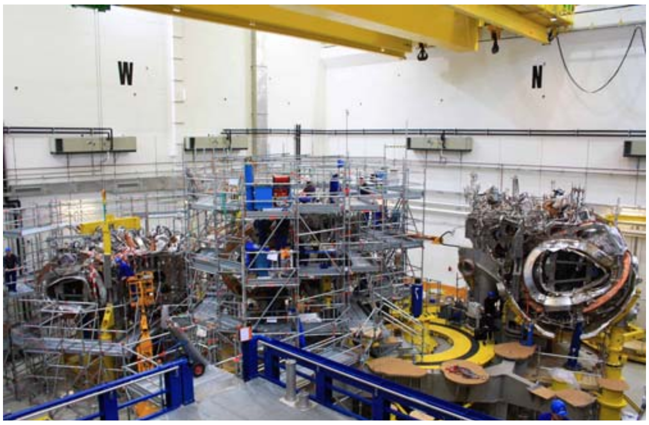

Figure 17: 3 out of 5 Modules in the Torus Hall.

The cooperation with the KiP division in Garching at the field of conceptual planning of the assembly of the KiP has been continued in 2009. Trial assemblies with wall panels, heat shields and sweep coils have been performed successfully. The system of platforms and cranes for the handling of components was developed further. A manipulator for the precise 3D-alignment of supports, bolts etc inside the PV was specified and ordered. The technology development in terms of logistics, tooling and procedures is continued as planned.

Figure 18: The port assembly bridge (inner and outer tower and upper cross-beam).

In the periphery, the work on cryo instrumentation in conjunction with the work at the bus-bar systems has been further continued. Installation works of the extension of the low voltage power supply system are continued. The conceptual planning for the realisation of the Electro-Magnetic Compatibility (EMC) during the construction of the periphery was started. The first construction stage of the cooling system is complete. These works are ongoing as planned. The assembly control and the planning proceed routinely as before. Additional resources had to be allotted to cope with the increased work load. The advanced weekly and 4-weekly plans are used as standardised tools. Further improvements are planned. The preparation of the assembly documentation (QAAP, work and test instructions) is ongoing without any severe problems. In 2009 a further refined resource planning was made. Quality deviations are reliably handled as in the years before. The assembly schedule was slightly updated. The planning for the final periphery (cables, cooling pipes, vacuum lines, and platforms) was further refined. The details here will become a highlight in the forthcoming planning period. The commissioning start date was kept constant in the middle of 2014 but the work density during the final assembly was increased further. Again the staffing for the assembly was increased (mechanics, insulation specialists) with personnel from industry. More responsible officers took up their employment. More external staff was included to cover the partial two-shift-system and extended working times in the assembly. Additional engineering staff started the work for the development and qualification of technologies for the final assembly. The cooperation with engineers and technicians of the Polish Academy of Sciences was continued.

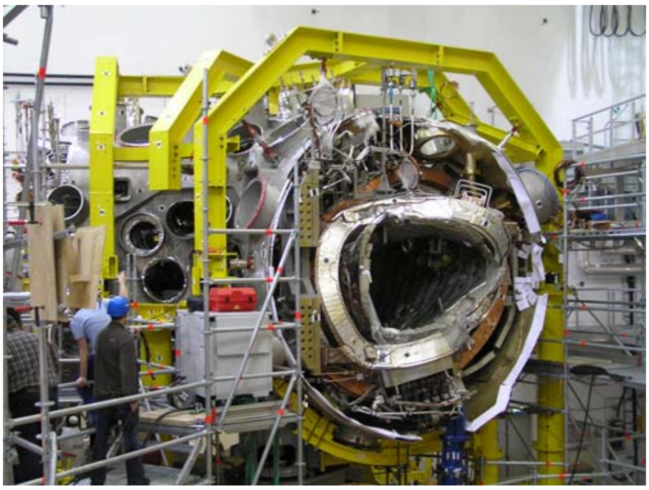

Figure 19: The first module in its outer vessel.

Altogether, assembly has reached the planned progress in 2009. Further new assembly technologies were qualified and successfully tested. The preparation of coils, plasma vessels and structural components is almost finished. The same applies to the mechanical pre-assembly of magnet modules. The assembly technologies for the bus-bar and helium pipe systems of magnet modules were finalized. The device assembly ran continuously and speedily as planned.

The port assembly technology was comprehensively developed and complemented. The assembly control with the planning and the documentation of assembly was further refined and works furthermore experienced and reliably. The cooperation with external partners who provide skilled and well-trained technicians and engineers for the realisation of the assembly work on W7-X has been very useful.

8 DIAGNOSTICS

8.1 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 for the initial operation phases of the experiment. The diagnostics department consists of three expert groups and a temporary working group which is developing and testing solutions for ECRH stray radiation shielding of in-vessel components. The following sections briefly summarize the main activities within the expert groups of the project.

8.1.1 Edge/Divertor and Magnetics Configuration Diagnostics

A mock-up of the flush mounted Langmuir probe array for the Test Divertor Unit (TDU) has been designed, manufactured and successfully tested in the GLADIS test bed for the standard case of 8.5 MW/m^2 for 6.25 s as well as for overloads up to 13 MW/m^2 and excess exposures up to 10s. The temperatures at the surface reached 1700 °C as forecasted by the FE calculations. Some re-design has been started to simplify the manufacturing and thereby reduce costs. The feasibility study for a piezoelectric drive for the High Heat Flux Divertor was completed, resulting in a proposal to develop a universal step-drive based on a piezo-rod for high temperatures (T_c≈600…800 °C). The prototype for the short manometer cannula was manufactured and assembeled, the manufacturing of the long prototype is ongoing. The newly developed digital electronics has been tested in AUG again and a number of weak points leading to large noise were identified. A redesign of the layout will be necessary. The detailed design of the video diagnostics – which is being developed by EURATOM HAS (Budapest, Hungary) – was finished in 2008. For the video observation the 10 equivalent tangential AEQ-ports of the W7-X vacuum vessel will be used, giving nearly full coverage of the entire plasma vessel. In the elaborated design, the Sensor Module (SM) of the Event Detection Intelligent Camera (EDICAM) is located at the plasma end of the ports and the Image Processing and Control Unit (IPCU) in the control-PC. The ports are under atmospheric pressure and the diagnostic front end is protected by a water-cooled plasma facing front plate with a pinhole. In 2009 the development of the special objective imaging the torus interior through the pinhole onto the CMOS sensor is finished and its manufacturing is started using conventional optical glasses.

The 10 Gbit link connecting the camera SM with the IPCU was manufactured and tested. The hardware integration of the 10 Gbit link into the camera SM end and into the IPCU was finished. Presently the firmware, for both units, is under development: the firmware of the first camera prototype will combined with the modules of the 10 Gbit link. Flow rates for pressurized air cooling at maximum port temperatures of 150 °C were determined to cool down the critical components to the temperature of 40 °C. The piping for the shutter movement and a possible Hydrogen flow to keep the front vacuum window clean were also designed. One piece of the video diagnostic system will be manufactured by HAS at the beginning of 2010 that will be used for a complete mechanical and thermal in-vacuum test in IPP-Greifswald. The mounting of the saddle coils and the out-of-vessel Rogowski and segmented Rogowski coils was completed. Design, construction, integration and documentation of the magnetic diagnostics were continued. The investigation of the thermal load onto the diamagnetic loops was continued and finished for the loops in the triangular plane. The tests on the sensitivity against ECRH stray radiation of the diamagnetic loops was continued, corresponding tests were started for in-vessel signal cables and for prototypes of the Mirnov coils and in-vessel Rogowski coils. To this end, a first prototype of the in-vessel Rogowski coils with ECRH stray radiation protection was designed and manufactured. The design of the routing of the in-vessel signal cables and investigations for the choice of these cables were continued. In addition, tests of the sensitivity against mechanical vibrations with a saddle coil and out-of-vessel Rogowski coils were performed together with the Assembly subdivision (such vibrations will be generated during the preparation of weld seams for port welding). On the WEGA stellarator a novel method to make magnetic field lines visible was tested. The method bases on the inelastic interaction of an electron beam with a background gas, e.g. argon, at a typical neutral pressure of $p=10^{-5}$-10^{-3} mbar, and results in a luminescent trace following the magnetic field line. A maximum range of about 100 m at 0.5 T was detected depending on the gas and the pressure. By observing the luminescent trace from four different camera view-points it was possible to determine the spatial position of the measured field lines with an accuracy of about 12 mm with respect to field line tracing calculations. A thermal helium beam gas nozzle head, manufactured by FZ-Jülich, will be installed in one upper and one lower divertor module. FE-based simulations have shown acceptable maximum temperatures of 787 °C at the nozzles tips in case of molybdenum nozzles and a “standard” temperature distribution of the neighbouring divertor tiles (1200 °C at the plasma facing side). Initially passive visible spectroscopic divertor observation will only be possible through the AEF and AEJ ports at one upper and one lower divertor and in both cases at the location of the helium beam nozzles.

A proof-of-principle set-up of an automatic mirror adjustment for all laser-based diagnostics was realized and successfully tested with two mirrors and two position-sensitive detectors using a PIC microcontroller.

8.1.2 Microwave and Laser Based Diagnostics

The group prepares the classical microwave and laser diagnostics measuring electron density and -temperature in the plasma core, namely interferometry, polarimetry, reflectometry, Thomson scattering and ECE. Highest priority has the development of all in-vessel components which have to be integrated into the tiles of the first wall heat shield. Within the framework of the European Fusion Training Scheme (EFTS), one Microwave Diagnostic Engineering and one Optical Diagnostics for ITER trainee are being hosted. For feedback density control of W7-X a single-channel two-colour CO_2-CO interferometer is developed, tested and qualified in the laboratory. The line of sight will be along the Thomson scattering laser beam to allow for cross calibration. The basic design of the port geometry common for both diagnostics has been finished, the design of interferometer transmission bench and the transmission line in the torus hall started. In the laboratory the test-interferometer has been optimized with respect to number of optical components and beam geometry. In the framework of the cooperation with CIEMAT, Madrid, a direct digital phase measurement has been developed and tested successfully. This detection system employs digital diplexing of the two signals corresponding to the two interferometer wavelengths so that the interferometer can be operated in a single-detector arrangement. With this set-up vibration compensation by a factor of 2000 could be demonstrated by introducing a vibrating mirror as a test-function. A first approach to the optical set up in the experiment hall was proposed together with the Univ. Carlos II, Madrid. Besides the design of the 11 high-heat-load retro-reflectors has been finished which will be integrated in the heat shield; FE calculations expect tolerable deformations under steady state conditions. As an option for W7-X and ITER a modular multichannel dispersion interferometer system is studied by a Post Doc at TEXTOR, Jülich, and its characteristics are compared quantitatively with the two-colour CO_2-CO interferometer at IPP Greifswald. In spring the first serial module was tested, however deformation and degradation of the Al- and SS-retro-reflectors in the TEXTOR vessel prevented plasma measurements. Commissioning of three further modules, delivered by the FZJ contract partners the Budker-Institute of Nuclear Physics (BINP), Nowosibirsk, is postponed to January 2010 due to necessary hardware modifications at the modules and technical installations mandatory for safe laser operation in the TEXTOR experiment hall. For redundancy of the density measurement a single intefero-polarimeter channel is planned in cooperation with the Akademia Morska, Szczecin, Poland.

The design of the required high-heat load retro-reflector integrated in the heat-shield of the first wall has been finished supported by finite element (FE) calculations. Despite the high temperature gradients expected under full-power steady-state conditions the deformation of the Molybdenum reflector and thus the degradation of the optical specifications are at a tolerable level. For the YAG Thomson scattering system several variants of the observation optics analysing the scattered light were compared as a part of the curriculum for an EFTS trainee. Design was finished and a call for tender for manufacturing the optical system was launched. Development of the polychromator also could be closed and a contract with the Institute of Nuclear Physics (INP) in Cracow for manufacturing 30 polychromators was signed. Components for a small pre-series of three polychromators were delivered in December. The ECE diagnostic in preparation for W7-X employs the radiometer system formerly used at W7-AS. Its adaptation to the conditions and the sightline at W7-X has been prepared together with an EFTS trainee. Besides, the high spatial resolution zoom radiometer was prepared. The design of the broadband Gaussian in-vessel viewing optics has been finished and the mechanical structures of both calibration- and in-vessel optics were manufactured. The design of a small high-field side microwave horn antenna dedicated to yield information of the electron distribution function was finished also. Although this horn antenna is integrated in the high-heat load tiles of the first wall, finite element calculations confirmed that heating of the microwave horn and the surrounding wall element will remain tolerable even under steady state conditions. The diagnostic group also operates the Microwave STray RAdiation Launch facility (MISTRAL), which allows for the testing of diagnostic and other in-vessel components in the environment of a strong 140 GHz microwave background radiation, as it will occur under certain ECRH heating scenarios. For the power flux density the measurements new graphite calorimeter balls were developed as ballistic detectors. Besides testing full diagnostic components, such as the bolometer head, the qualification of in-vessel components focused on cables and magnetic diagnostics that require isolators which absorb microwaves. It was shown that all kind of isolators have to be tightly shielded against microwaves and need to be sufficiently cooled to reach steady state capability.

8.1.3 Core Spectroscopy

The construction of the Russian Diagnostic Injector for W7-X (RuDI-X) which is needed for active CXRS and CX-NPA measurements is progressing. The major hardware components were built at the Budker-Institute of Nuclear Physics (BINP) in Novosibirsk, Russia. The largest component, the injector tank, could be finished and is presently installed on the test stand. The individual high voltage (HV) transformers are being tested and all cards for the installation into the HV tank were finalized. The manufacturing of the insulation parts for the ion optical system is completed. The closed-cycle cryogenic pumps for RuDi-X have been ordered and are expected to be delivered early 2010. A major obstacle for the design of these pumps had been their hardening against ECRH stray radiation. The design of the RuDi-X platform inside the W7-X torus hall is finished and the manufacturing of the vacuum interface between RuDI-X and W7-X almost completed. The positioning of the NPA diagnostics and their mechanical support on W7-X have been fixed. The impact of magnetic stray field on the performance of the NPA's was investigated at MAST. The count rates of low energetic particles were seen to be influenced by outer magnetic stray fields larger than 5 mT. Calculations for sufficient magnetic shielding have been started at IOFFE-Institute St. Petersburg. An ARMCO-shield, surrounding the CNPA-27 analyser, is foreseen for the prospective application at MAST and later at W7-X. The re-calibration set-up in IPP Greifswald was put into operation with a hydrogen-argon discharge as ion source. This discharge ensured stable operation parameters and a sufficient hydrogen flux. The high-efficiency XUV overview spectrometer system (HEXOS) is still running successfully on TEXTOR (FZ Jülich) for testing purposes. A PhD work being concerned with impurity transport investigations in plasmas with resonant magnetic perturbations using the extended spectral range and the good time resolution of the HEXOS system, was successfully finished. The completion of the HEXOS control system by the ZAT (FZJ) is progressing. At IPP Greifswald the design of the support structure at W7-X has started. Concerning the development of the C/O monitor diagnostic in the framework of a cooperation between IPP and University Opole (Poland), an ASDEX type counter was delivered to Opole for testing and modification to a multichannel detector. The detector was unfortunately damaged during shipping and is presently under repair in Opole. During 3 stays in 2009 of the cooperation partner at W7-X, the dispersive elements (MLMs for B V, C VI and N VII channels and KAP crystal for O VIII channel), the Rowland circle diameter as well as other geometrical parameters of the spectrometer were fixed. It was decided that the spectrometer will be constructed as two independent instruments – each one containing two spectral channels. The requirements for the vacuum system and the neutron shielding have been defined. For the bulk plasma bolometer system in the triangular plane, the design of the horizontal camera in port AEU30 has been completed. Manufacturing drawings of the shutter system were prepared for prototype tests. A concept, based on laser alignment technique, for monitoring the movement of the camera position due to machine pumping and loading as well as thermal expansion of the in-vessel (on which the camera is fixed) was developed.

Thus, relative deviations of the lines of sight from the unstressed and calibrated case can be corrected. The design of the vertical camera in port AEV21 is progressing. The impact of non-absorbed 140 GHz microwave stray radiation on the bolometer signal has been tested in the microwave laboratory and the MISTRAL stray radiation device using a gold-foil type detector. An absorption factor of around 10^{-3} was measured, being consistent with calculations. However, for the MISTRAL test much larger signals had been obtained than expected from single-path-absorption, pointing to multiple-path absorption inside the bolometer housing. Using a metal mesh with a microwave transmission factor of about 5 %, the microwave contribution could be reduced to about 1/10. Nevertheless, comparing with the expected plasma radiation induced signal, it is still not negligible. Present efforts are related to coating the inner surface of the camera enclosure with TiO_2/Al_2O_3 absorber layers aiming at reduced microwave multi-path-reflection. For the in vessel X ray tomography system (XMCTS), it was finally possible to manufacture a compact vacuum-tight electronic box (for accommodation of the preamplifier boards) including the custom-made multi-pin vacuum feed through. An upgraded design of the electronic box made from CuCrZr material is considered, which would improve the cooling of the preamplifiers and save slightly more space. However, the welding the stainless steel multi-pin vacuum feed through into a CuCrZr plate yielded still unsatisfactory results. The layout of the preamplifier platine was also optimized further and could be inserted into the electronic box for integral electrical and optical tests. A bandwidth of 400 kHz with low cross-talk between channels could be achieved. Problems with the robustness of the solder joints of the signal cables were identified and are being addressed by means of a strain-relief. The view geometry of the sight lines through slits in the heat protection could be verified and the design of the shutter was further optimized, improving its robustness and reliability. However, the long-time operation reliability still needs further improvement, since the full closure of the shutter is not always obtained as could be measured with a photoelectric relay. The pinhole in the X-ray pulse height analysis PHA system being built by IPPLM Warsaw was replaced by 2 orthogonal sets of variable piezo driven slits. The piezo driven slits and 2 types of detectors for the multi-filter foil MFS system (also IPPLM Warsaw) were already delivered. Both detectors were tested at IPPLM and found to be suitable for MFS application. A license of a CATIA CAD system was purchased by IPPLM and the first conceptual design for the PHA system based on 3 beamlines viewing the central plasma and being located at three separate ports performed. Radiation calculations of the expected signal strength using the RayX code have been improved. Further, a cooperation contract with IPPLM is in preparation, which comprises the constitution of neutron activation diagnostics and includes MCNP calculations for W7-X by INP Krakow. Presently, INP Krakow is integrating the CAD-geometry of the W7-X structure into the MCNP model. In the field of measurements of neutron fluence at W7-X a cooperation contract up to the end of 2013 was signed together with PTB Braunschweig. In 2009 a basic MCNP model was set up by PTB to define the geometry of necessary neutron monitoring system. First conceptual work was done for the calibration of the 6 neutron counters near the 5 W7-X modules and for the central counter with broader characteristics by IPP and PTB.

8.2 Technical Coordination

The assembly of diagnostics in the cryo vacuum was concluded in time with the main assembly schedule: The last 12 saddle coils were assembled on the small half sectors of the half modules 21, 30 and 31 and on the large half sectors of the half modules 20, 30 and 31. The last three outer magnetic probes were assembled on the small half sectors of the half modules 21 and 31 and on the large half sector of the half module 30. All these diagnostics were successfully tested. Temporary shields were mounted or dismounted where applicable. As part of the implementation of the grounding concept of W7-X, diagnostics were integrated in detail into the grounding system.

8.3 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. The Budker Institute in Novosibirsk, Russia, is developing and constructing the diagnostic neutral beam injection system, EURATOM HAS in Budapest, Hungary, is developing and constructing the video diagnostic systems for W7-X, IPPLM, Warsaw is developing a neutron activation system and performing MCP calculations for W7-X (collaborating with the Institute of Nuclear Physics, Kraków, Poland), the university of Opole, Poland is preparing a C/O monitor diagnostic and the Akademia Morska, Szczecin, Poland and the Szczecin University of Technology are investigating the sightline of the Interfero-Polarimeter and different microwave based polarimeter and interferometer methods, CIEMAT investigates potential and components for CO_2-Intefererometry, IST/CFN, Lisbon participates in developing fast tomographic inversion methods (P. Carvalho 1 months stay in Greifswald) and is developing ADC/DAQ stations being linked to XDV, PTB Braunschweig is working on the development of a Neutron-Counter System for W7-X and IOFFE Institute St. Petersburg, the Culham Centre for Fusion Energy (CCFE) and CIEMAT in Madrid are collaborating in the field of CX-Neutral Particle Analysis.

9 Heating

9.1 Project Microwave Heating for W7-X (PMW)

The Electron Cyclotron Resonance Heating (ECRH) system for W7-X is being developed and built by the research centre in Karlsruhe (KIT) 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. ECRH will support also operation of W7-X at reduced magnetic field, because the gyrotrons can be tuned to 103.6 GHz radiation emission with about half the output power. This is of particular importance during the commissioning phase of W7-X and for confinement studies. PMW is strongly involved in advanced and ITER related R&D activities for ECRH and CD-Systems with even higher power, efficiency, and flexibility. This activity is organized within the frame of the virtual institute "Advanced ECRH for ITER" (collaboration between IPP Garching and Greifswald, KIT Karlsruhe, IHE Karlsruhe, IPF Stuttgart, IAP Nizhny Novgorod, and IFP Milano), which is supported by the Helmholtz-Gemeinschaft deutscher Forschungszentren.

9.1.1 The W7-X Gyrotrons (KIT)

The first series gyrotron from TED has been tested successfully at KIT and IPP already in 2005 (920 kW/1800 s). All specifications were met and during the acceptance test no specific limitations were observed. The SN1 gyrotron was sealed to keep the warranty, whereas the prototype gyrotrons are routinely used for experiments and high power component-tests. The next series gyrotrons did not meet the specifications and showed a more or less different behavior with respect to parasitic oscillations excited in the beam tunnel region. These oscillations result in an excessive heating of the beam tunnel components and the gyrotrons, re-opened after initial operation, showed significant damages due to overheating at the ceramic rings and the brazing of the rings, which are believed to be responsible for the observed degraded gyrotron performance. In support of the manufacturer a dedicated R&D program was executed at KIT and IPF aiming at the development of a robust beam tunnel, which suppresses the parasitic oscillations efficiently. Tests with short pulse prototypes of a frequency step tunable gyrotron and a coaxial cavity gyrotron, respectively, were performed to validate the new beam tunnel design within the given experimental boundaries and time frame. In the first experimental setup a standard, azimuthally symmetric beam tunnel, as used in the W7-X gyrotron, was installed in the frequency step tunable gyrotron as a reference. Parasitic oscillations were clearly identified in high power operation. The appearance of such oscillations was related to a reduction in output power and efficiency, and an increase of stray radiation power as seen from figure 20. The cavity interaction of the desired operating mode was strongly degraded by the parasitic oscillation.

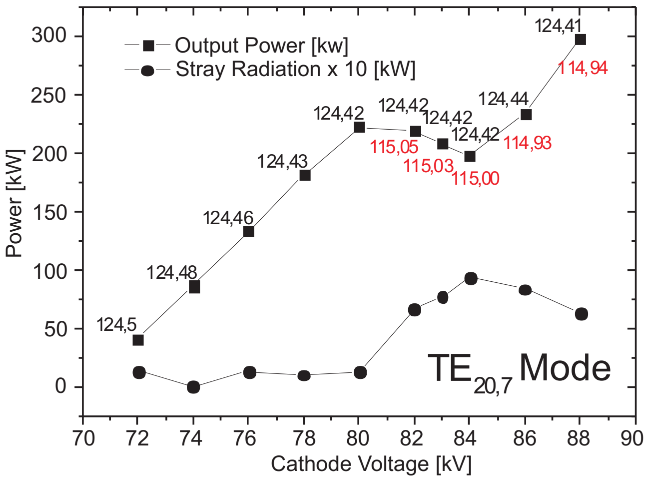

Figure 20: Output power (squares) and stray radiation (dots) vs. cathode voltage for the TE20,7 Mode at 124.4 GHz in the first experimental setup with the reference beam tunnel. The frequencies of the operating mode and the parasitic mode are indicated in black and red, respectively.

In a second experimental setup, this beam tunnel was replaced by a modified version with broken azimuthal symmetry to suppress azimuthally symmetric backward waves. The symmetry breaking was achieved by introducing irregular longitudinal corrugations in the copper rings, while keeping all other design features unchanged. The number, width, depth and periodicity of the corrugations is optimized and forms, together with the monotonously decreasing inner diameters of adjacent rings, a structure which also avoids longitudinal periodicity. Such a structure can also be considered as a grating with many different grating constants. This complicates the constitution of a resonant field structure and effectively damps $TE_{m,p}$ modes, in particular symmetric TE modes with m=0. High power experiments with this configuration did not show any beam tunnel parasitic oscillations as measured with the reference beam tunnel at similar operation parameters. Even at a beam current well above the design value (60 A) no beam tunnel RF oscillations in the high frequency range have been observed. The R&D programme at KIT was terminated on schedule in July 2009. The high power experiments with different beam tunnel versions showed the clear advantage of a beam tunnel with corrugated copper rings with respect to suppression of parasitic oscillations.

A formal recommendation to install a beam tunnel with corrugated copper rings in all W7-X series gyrotrons was submitted to TED soon after. TED provided a preliminary time schedule, indicating, that the first refurbished gyrotron with an improved beam tunnel will be delivered in April 2010.

9.1.2 Transmission System (IPF)

The transmission line consists of single-beam waveguide (SBWG) and multi-beam waveguide (MBWG) elements. The beam conditioning assembly for each gyrotron consists of five single-beam mirrors. Two of these mirrors match the gyrotron output to a Gaussian beam with the correct beam parameters, two others are used to set the appropriate polarisation needed for optimum absorption of the radiation in the plasma. A fifth mirror directs the beam to a plane mirror array, which combines the beams from five gyrotrons and is situated at the input plane of one (out of two) multi-beam waveguides (MBWG's) used for long distance power transmission to the stellarator hall. At the output planes of the MBWGs, a beam distribution optic (BDO) separates the beams again and distributes them via two other mirrors (M13 and M14) and CVD-diamond vacuum barrier windows to individually movable in-vessel antennas (launchers). The BDOs and the successive mirrors are mounted in so-called towers with "pinnacles" on top. In 2009, the manufacturing of all components of the basic 'out-of-vessel' transmission system was finished. This includes the mounting and screening boxes ('pinnacles') on top of the towers, the shielding structures around the vacuum barrier windows, the interfaces to the stellarator ports, and side absorbing screens. Figure 21 shows the assembly of three mirrors M13 installed in the towers.

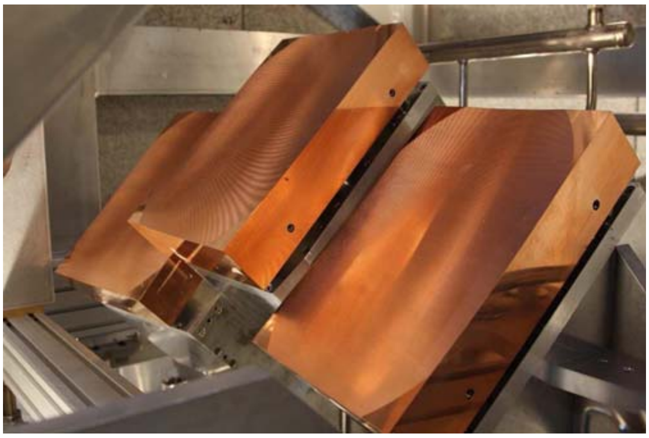

Figure 21: Assembly of 3 mirrors M13 installed in the towers.

Present work concentrates on a power detection and alignment control system in conjunction with focusing diffraction gratings, which were integrated into the surface of the mirrors M14, which is situated in front of the vacuum windows.

In addition, investigations on the temporal stability of the output beam of the gyrotrons have been continued, and recent measurements are under evaluation. Industrial high power cw dummy loads, which are based on thin absorbing layers on metallic cooling structures show a long-term destruction of the coating and a related degradation of the power handling capability. This long term experience has triggered new developments using uncoated metallic absorbers. One option is the "long load" which consists of a long (>20 m) waveguide made from stainless steel, where the power is coupled as a Gaussian beam. By appropriate successive reduction of the diameter, the absorption of the waveguide is matched to the local power loss along the guide. After first tests with a simple mock-up system using standard water tubes with welded connections had shown strong arcing, a second attempt with an un-cooled electropolished tube was successful. Therefore, the design of a water-cooled version with flanged connections is underway. Another approach was followed by the Russian company GYCOM, which is based on the absorption of a lossy 'Hohlraum' with compact dimensions and large absorbing surface area. Such a load was ordered from GYCOM and a microwave switch with imaging optics is under construction, which allows the integration of this load in the transmission line. For the development of high-power microwave components, reflection properties of surfaces were investigated and optimized according to their function. Al_2O_3/TiO_2-coatings were characterized to get a partial absorption of about 30 % needed for the refurbishment of the dummy load in the gyrotron test stand at KIT. In collaboration with the 'Institut für Fertigungstechnologie keramischer Bauteile' (University of Stuttgart), various coatings were characterized with the aim to maximize the microwave absorption of the chevrons, which prevent the cryo-pumps in W7-X from being heated by ECRH stray radiation. The minimisation of the absorption of low-Z coatings is required for in-vessel microwave reflectors and related investigations were executed (see chapter 9.1.5 'In vessel components'). The operation scenarios for W7-X also include high field side launch through the N-ports for physics investigations. "Remote steering" launchers are foreseen for the N-ports, as front steering launchers will not fit into these narrow ports. The remote steering effect is based on the propagation characteristics of the modes in a square waveguide leading to imaging effects: For a proper length of the waveguide, a microwave beam with entering the input of the waveguide at the atmospheric side under some angle will exit the waveguide (in vacuum, near the plasma) with the same direction. For W7-X, the vacuum window, a vacuum valve as well as a mitre bend must be implemented into the 5.1 m long waveguide. The position of these components must be optimized to reduce the antenna loss. Calculations on the transmission loss for various launching angles and a 22 mm gap in the waveguide as function of the axial position have been performed; good performance is obtained in an angular rage of ±12°. Optimisation calculations continue to further enlarge the steering range by modifying the dispersion relation of the waveguide; therefore, deformations of the cross section are introduced. The IPF-FD3D code has been adapted to the problem of finding the waveguide dispersion relation for arbitrarily deformed waveguide cross sections. Taking the wavenumber relation $k_0^2-k_x^2=k_\perp^2$, where k_0 is the free-space wavenumber and x is the coordinate along the waveguide, k_x can be calculated from $k_\perp$.The difference between the desired dispersion relation and the one for the rectangular waveguide is shown in figure 22 (left).

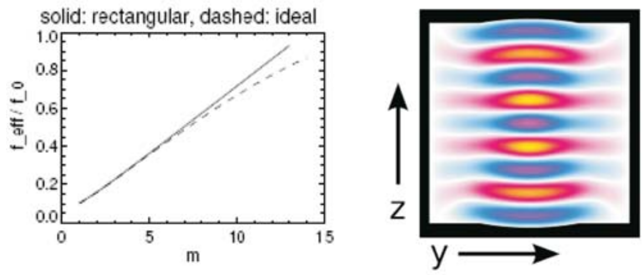

Figure 22: Effective frequency for various mode numbers m (left), and field pattern of the $HE_{1,9}$ mode in a deformed resonator (right). The metal boundary is shown in black.

Plotted there is the frequency that the effective perpendicular mode $k_{eff}^2=k_0^2-k_x^2$ would have in a 2D resonator. The code finds this frequency for a variety of modes and deformations. Figure 21 (right) shows the modified field pattern in a waveguide with outward bulges. Once the systematic investigation of deformations for an optimized cross section for remote steering applications are completed, it is planned to test these cross sections with IPF's specialized waveguide propagation code, followed by low-power experimental tests on a simple prototype waveguide.

9.1.3 HV-systems (IPF)

For the operation of gyrotrons with depressed collector, a precisely controlled beam acceleration voltage is necessary, which is supplied by the body-voltage modulator. The beam current of the gyrotrons is controlled by the cathode heater supply, which is on cathode potential (about -55 kV). In case of arcing inside the gyrotron, a thyratron crowbar protects the tubes from being damaged. All ten body-voltage modulators and the protection units are installed, tested and ready for operation. In 2009, some final optimisation issues concerning the system diagnostics in case of a gyrotron fault were implemented. The documentation of the HV modules was finalized and the HV modulator project is now completed.

9.1.4 Fast Control and DAQ System (IPP)

The operation of a gyrotron requires a precise and flexible timing of the high voltage pulses as well as a fast and reliable interlock system. For the documentation and evaluation of the experiments, a data acquisition is needed which provides operational data in different sampling rates (microseconds to hours/days), depending on the respective observable. An FPGA-based gyrotron control unit has been developed and manufactured in collaboration with the Electronics Division of the Technische Dienste (TD) and is shown in figure 23. It controls the voltage of the cathode power supply and the modulator as well as their fast shutdown inputs and takes care of the first-event detection. All parameters are loaded into the control unit from the gyrotron's master PLC via Ethernet. Security relevant functions such as shutdown conditions are realized in hardware and can be observed via the computer network. A successful test of the unit with high voltage dummy resistors has been performed. The interface between the fast control and the gyrotron's master PLC has been implemented and tested.
The interface between the central experiment control and the ECRH master PLC has been put into operation and the definition of the security interface has been completed. The PLC generated experiment data is fed into the W7-X data acquisition via this interface. A DAQ station for the measurement of the fast analog signals of one gyrotron has been installed and is now routinely used.

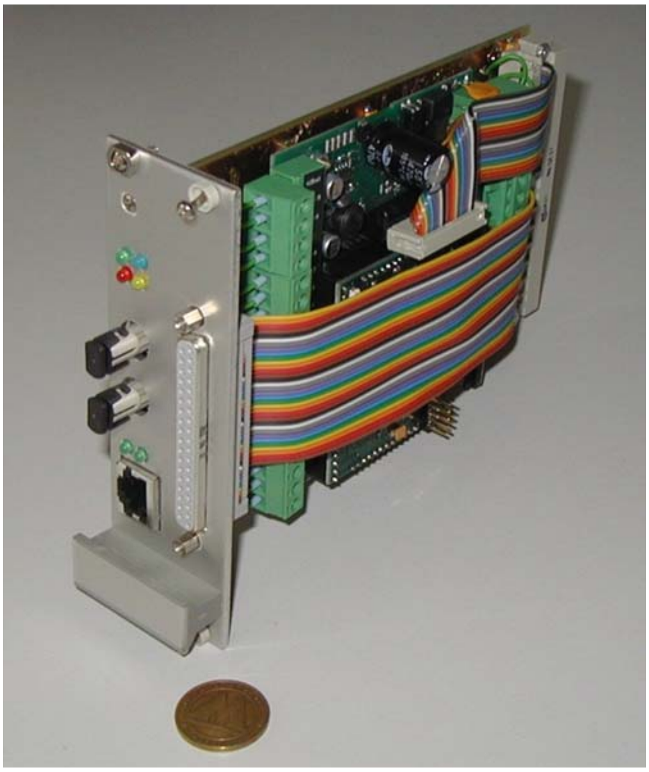

Figure 23: The gyrotron controller with Ethernet, optical fiber and Sub-D connectors.

9.1.5 In-vessel Components (IPP, IPF)

The ECRH System for W7-X must provide plasma start-up and operation at full performance in the first short pulse (5-10 s) period with the test divertor unit (TDU) as well as in long pulse operation up to 30 min with the high power steady state divertor. The plasma start-up will be initiated by ECRH at the resonant magnetic field strength for both operating frequencies at 103.6 GHz and 140 GHz. The control of the rotational transform profile during the density build-up requires a highly flexible launching and power control system.

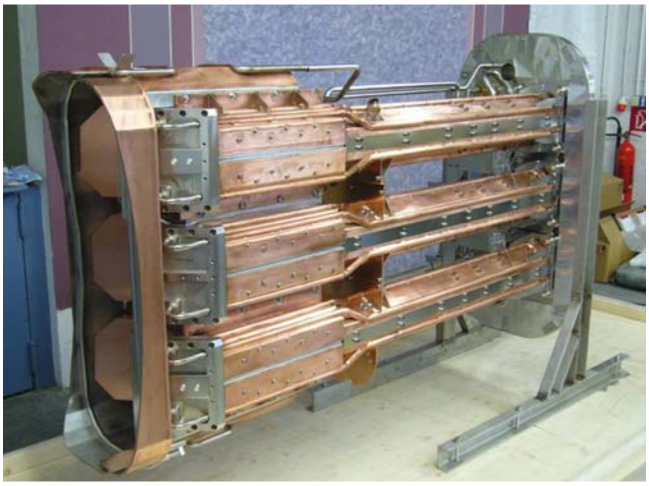

Figure 24: ECRH launcher unit for 3x1 MW, cw power handling. The 3 steering mirrors are seen at the front, the heat shield is shaped according to the plasma vessel contour.

As soon as the plasma density approaches the X2 cut-off density, a well-controlled transition from the strongly absorbed second harmonic extraordinary mode (X2) to a multi-pass second harmonic ordinary mode (O2) heating scenario must be performed. The single pass absorption is only between 60 and 80 % in that case. Therefore the beams must hit specially designed reflector tiles, which are integrated in the heat shield opposite to the ECRH antennas. These tiles will also be used for multi-pass heating at the third harmonic X-mode (X3) at a reduced magnetic field strength of 1.67 T. The single pass absorption here is similar to the O2 case, but the plasma start-up scenario still has to be developed. The key elements of the ECRH launching system are the four front steering ECRH-antennas in the outboard mid-plane A- and E-type ports. All parts of the antennas are expected to experience a high power loading by either direct microwave irradiation or by strong microwave stray radiation at the screening and mechanical support elements. Therefore all components require active cooling and/or screening. The assembly of three of four ECRH plug-in antenna modules for the A and E ports was completed and the launchers as seen from figure 24 were shipped to Greifswald for final acceptance tests.

The launchers were vacuum leak checked and mechanically tested in the MISTRAL vacuum chamber. The test arrangement is shown in figure 25, the plug-in launcher module is seen before insertion in the test chamber. The mechanical tests of the movable antenna mirrors displayed some non-appropriately assembled bearings. Laser tracking measurement of the antenna dimensions and the corresponding ports revealed a collision due to out of tolerance dimensions of both. The antenna size must be reduced while the port size has to be increased. A repair procedure for the driving mechanics and minor design changes were elaborated to bring the dimensions of both, port and antenna back into the specified tolerance field. The launchers were sent back to BTI-KIT for refurbishment. The ports, which are in IPP responsibility, will be expanded in Greifswald. The first port already passed the expanding procedure successfully.

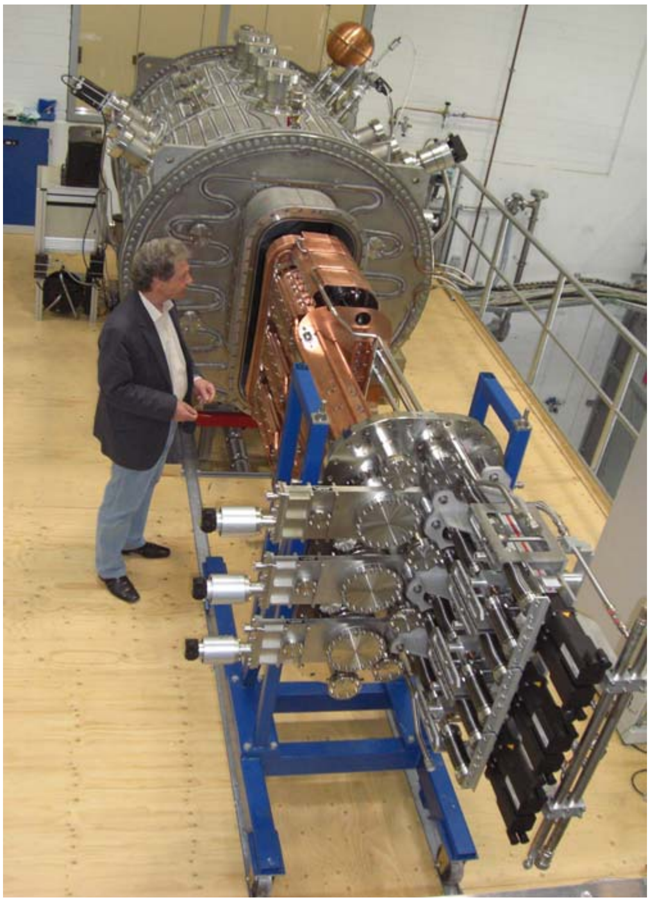

Figure 25: ECRH launcher before insertion in the MISTRAL chamber for vacuum leak check and mechanical cyclic fatigue tests under vacuum.

The reflector tiles at the inner torus wall will be made of the molybdenum alloy TZM. It is planned to coat these tiles by low Z microwave transparent material, in order to avoid plasma pollution by high Z impurities. Microwave absorption measurement at IPF showed that – at least for near perpendicular incidence – a diamond-like coated TZM plate has only slightly higher absorption compared with pure TZM, and therefore is a candidate for the reflector tiles in multi-pass ECRH schemes. The non-absorbed power as well as the beam position and its polarisation at the ECRH heat shield will be measured by an array of altogether 126 small pick-up antennas. This measurement will also serve as a protective diagnostic for save ECRH operation. The pick-up antennas are integrated in the shield and reflector tile structure and are connected with the vacuum interface at four B-type ports by four bundles of mono-mode circular waveguides. For assembly reasons the waveguide bundle has a disconnection point at the intersection of the B-port with the plasma vessel. The bundles will be inserted through the B-port and connected with the waveguide bundles inside the plasma vessel. The vacuum interface- structure is seen in figure 26 The assembly of the inner waveguide insertion will start at the beginning of 2010.

Figure 26: Vacuum interface flange for the B-port and the guiding tube for the ECRH transmission measurement waveguides.

All in-vessel elements in W7-X have to sustain a high microwave stray radiation, which is distributed inside the W7-X plasma vessel, ports and even behind the first wall panels. Near the ECRH-launch position a power flux density of up to 200 kW/m^2 is expected for heating scenarios with O2 or X3 mode. The modelling of the stray radiation distribution has been continued. In particular the stray radiation load at the divertor cryo pump has been estimated and measures for reduction have been proposed. For the first W7-X plasma operation ECRH concepts were elaborated in collaboration with the theory division, which include plasma start-up as well as density and power ramp-up with a simultaneous plasma current control by ECCD.

9.1.6 Advanced Components and ITER-related R&D (HGF Activity)

The possibility to combine two or more beams into one transmission line and/or switching them to different launchers is very attractive for future large-scale ECRH installations like those for W7-X and ITER. Diplexers have the requested features and their integration in the transmission systems would not only increase the efficiency and flexibility of ECRH, but also enable future power upgrades without the need for additional transmission lines or increased port space. The research on diplexer devices for the combination of high-power microwave beams and/or fast directional switching ("FADIS") with low loss and without mechanically moving parts, was thus continued under the umbrella of the 'Virtual Institute' of the 'Helmholtz-Gemeinschaft deutscher Forschungszentren'. A new test campaign was dedicated to the investigation of a compact long-pulse high-power diplexer making use of the W7-X ECRH system. The encouraging results achieved with a quasi-optical QUO-FADIS (MkI) as reported last year have triggered the development of a compact waveguide based device, 'MkII'. It is equipped with HE11 interfaces, and is compatible with the AUG-waveguide transmission system for later application in plasma experiments. As the pulse duration at AUG is 10 s, no active cooling is foreseen. Basic features were determined in low-power measurements at IPF Stuttgart, and are in good agreement with theory. In the non-resonant channel, the loss is mainly due to cross-talk (typically 2.2 %, i.e. near to theory), as well as absorption and mode conversion in the coupling elements to the input and the output (0.8 %). In the resonant channel, the absorption and scattering of two mirrors and two gratings with a power enhancement factor of 4.5 in the resonator results in an absorptive loss of 4.4 %. As the quasi-optical diplexer is a very efficient mode filter, any wrong modes entering the diplexer will not excite the resonator at the resonance frequency, but are mainly transmitted through the non-resonant channel, i.e. resulting in cross-talk (in the present case of 3.9 %). Thus, the total loss averaged over both channels is therefore 5.7 %. After characterisation in low power experiments, the MkII device was integrated into the quasi-optical transmission line of the ECRH system at IPP Greifswald for high power tests. The experimental arrangement is seen from figure 27.

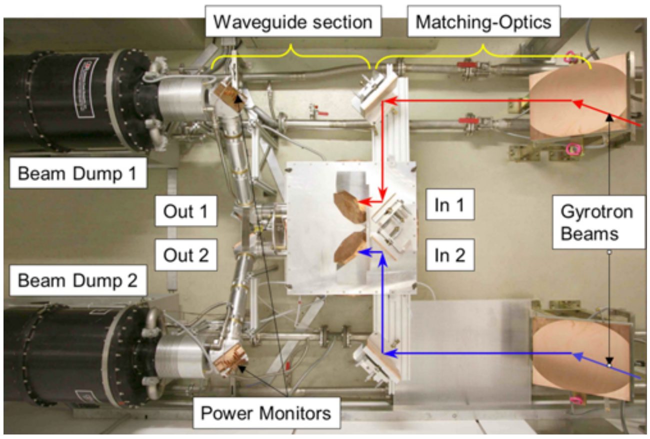

Figure 27: Photograph of the setup in the beam duct of the ECRH system for W7-X. The compact MKII diplexer is seen in the center. The arrows indicate the beam paths of both free-space beams (IN1 and IN2). The waveguide outputs (OUT1 and OUT2) with two mitre bends in each arm are seen on the left side feeding the two CW-dummy loads (beam dump 1/2).

Commissioning experiments were started with one gyrotron (TED-Maquette) to determine the power and energy capability with various fixed settings of the resonance frequency. So far, 75-s pulses with a power of 330 kW, and 550 kW with somewhat shorter pulses were obtained; extension to 100 s at this power level seems feasible. Note, that the device is operated without active cooling and under normal atmospheric pressure. The electric field strength at 550 kW is close to the theoretical limit for atmospheric breakdown and thus evacuated systems like in ITER are expected to have a much higher power capability. The MkII device is equipped with a tunable resonator mirror. The transmission functions were measured in high-power application by slowly varying the resonator length of the diplexer thus tuning it through resonance. An example is shown in figure 28.

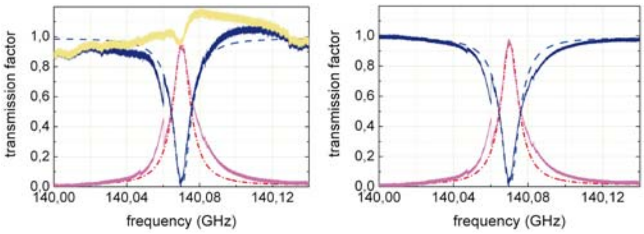

Figure 28: Transmission functions of the diplexer obtained by tuning the resonator frequency during one rf-pulse. Note that the abrupt steps (especially for frequency f = 140.06 GHz) are caused by frequency jumps of the gyrotron. Dashed and dash-dotted curves: calculated transmission functions for non-resonant and resonant output, respectively; solid lines: measured signals, with time-to-frequency conversion fitted to the calculated curves. Left: the sum of both output signals is displayed in yellow. Right: measured signals normalized to constant output power.

The fast switching characteristics were investigated by a square wave modulation of the gyrotron body voltage and thus the frequency; an example is shown in figure 29.

The drive of the tunable mounting of the resonator mirrors is being developed by a dutch group from TNO in Delft for frequency tracking of the gyrotron frequency. First tests with this feedback system could demonstrate fast tracking to the slope of the diplexer resonance, which is needed for optimum contrast of a fast switching system. Experiments to track the resonance for power combination from two gyrotrons are in preparation. Studies have been performed on the use of diplexers in ITER. An essential issue is the integration of diplexers in the existing ITER transmission line design. A study was made for a large model ECRH system employing two sets of 8 gyrotrons to be combined and distributed to two sets of 8 launchers each. Realistic dimensions of the diplexers for a 63.5 mm waveguide system with a basic distance of 0.3 m between adjacent waveguides have been assumed. It could be shown, that different types of diplexers such as the resonant diplexer, the waveguide Mach-Zehnder diplexer, as well as the two-loop diplexer can be designed such that quite compact and maintainable installations are possible, which comply with the boundary conditions of the ITER transmission line. It is proposed to replace the mechanical waveguide switches, which connect the ITER gyrotrons either to the Equatorial or to the Upper Launchers, by diplexers. Diplexers allow switching of the power from the EL to the UL without the need to turn off the gyrotrons during the switching process, as is the case for mechanical switches. Furthermore, power sharing with arbitrary fractions between the UL and EL is possible.

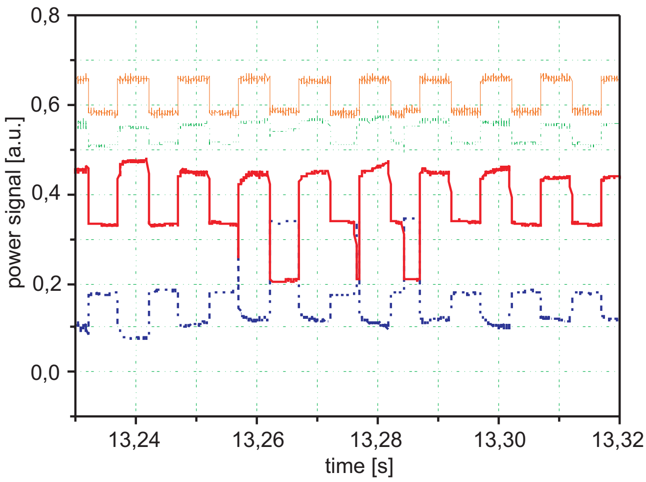

Figure 29: Input (orange, IN1) and output power signals (blue, dashed for OUT1, red, solid for OUT2) as well as the sum of both output powers (green, dotted). The body voltage of the gyrotron and thus the frequency is modulated with a square wave $\Delta U_{BI}=1$ kV, $f_{MOD}=100$ Hz, and the mean frequency is kept at the slope of the resonance of the diplexer.

Secondly, efficient AC-stabilisation of NTMs is possible as soon as a mode occurs: The gun anode or body voltage of the gyrotrons is modulated with the mode frequency, and the diplexers are tracked such that the corresponding frequency modulation results in a maximum power modulation at the outputs for the ULs, synchronous to the rotation of the island. There is no waste of installed power at the modulated operation, as the asynchronous power is still available at the EL to continue the task as before the onset of the NTMs. Thirdly, as the transmission lines are designed for a power of 2 MW and two gyrotrons could be fed into the inputs, the use of diplexers is desirable also from the point of view of a later power upgrade, which can be realized by either increasing the number of 1 MW gyrotrons or increasing the power per gyrotron, or both. In either case this would allow to double the power without the need to allocate additional port space and to increase the number of the transmission lines between diplexer and torus ports. As mentioned above, all transmission and launcher components have to comply with 2 MW power handling and have to be qualified at this power level, before being installed.

As there are no long-pulse 2 MW CW gyrotrons available at the time of development of these components, a proposal was made to combine the output beams of two ITER-gyrotrons with 1 MW each by means of a FADIS/BC. The combined beam from two gyrotrons can then be used to test transmission line components for ITER.

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9.2 Neutral Beam Injection

The NBI system under construction for Wendelstein 7-X consists of two injectors, both positioned on Module 2. Each injector box can be equipped with four beam sources arranged in a rectangle. However, only two sources on each box will be available for the initial phase of W7-X operation. Based on decision criteria like beam transmission through the NBI duct, beam power loading onto duct liners and onto inner wall areas due to shine through, as well as beam power coupling to the plasma, two horizontally adjacent sources on each injector, i.e. one more tangentially and one more radially injecting source, have been selected to start with. In this configuration a heating power of 7 MW for hydrogen and 10 MW for deuterium injection, respectively, can be achieved. The NBI project is supposed to be realized in close cooperation with partners from Polish institutes. However, the final agreement from the Polish government is still pending. Nevertheless, work at IPJ Swierk on preparing the procurement of cooling systems, ion deflection magnets, torus valves and injector support structures is well advanced. During the past year the procurement of the various components proceeded as planned. All parts to be mounted to ion source flange, i.e. source valves, beam steering units, neutralizers and ion dumps, are now in house. Figure 30 shows an ion dump as manufactured by industry. Completing the ion source flange assembly will be the first step of the pre-assembly of the injectors inside the NBI hall. All parts of the vacuum pumping system necessary to leak test those components mounted into the injectors are already available. In addition, the procurement of the calorimeter has started. Design work on the protection of NBI duct and inner wall is proceeding in the In-Vessel Components group.

Figure 30: Ion dump capable to absorb the unneutralized power from one beam of a neutral beam injector.

A prototype of a duct armour module has been tested successfully in the ASDEX Upgrade NBI duct during the recent operational campaign. The heat loads there are similar to those expected in the W7-X NBI duct. Also on the ASDEX Upgrade NBI system a RF transformer is being tested to prove its applicability for the W7-X NBI sources. Progress has been made in designing the various components of RF and high voltage circuits. The design of the HV cages including the components to be installed therein (core snubbers, decel and bias resistors) is completed. These HV cages are the first parts of the NBI systems to be installed inside the torus hall as soon as the corresponding space there is not required anymore for machine assembly.

9.3 Ion Cyclotron Resonance Heating

The design and development of the ion cyclotron resonance heating (ICRH) system has been further postponed since ICRH will not be a part of the start configuration of W7-X. However radio frequency (RF) supported helium plasmas at non-resonant conditions have shown to condition the plasma vessel walls by removing adsorbed gases to facilitate density control in later discharges. Since wall conditioning using direct current glow discharges cannot be applied with magnetic field but wall conditioning is also needed for reliable plasma built-up with ECRH such a means is particularly important for W7-X. Therefore, W7-X will be equipped with an ion cyclotron wall conditioning (ICWC). For that purpose two RF shortwave generators (3-26 MHz, 1 MW continuous wave) were purchased from General Atomics.

This system is planned to consist of one generator, of a transmission-line, a matching system and of one antenna optimized for plasma start-up, thus without a Faraday screen. This antenna will be operated via two dedicated ports in W7-X and not interfere with the later to be installed ICRF antennas. The conceptual design of the antenna and the matching system has been completed and the coarse mechanical design of the antenna has been started. The personnel list consists of one RF engineer full-time and one senior RF engineer participates part-time. Some part-time support by a mechanical engineer started at the end of 2009.

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Laboratory Plasma Devices WEGA and VINETA

On WEGA advanced experiments on electron cyclotron wave heating were performed. For 28 GHz ECRH operation an increasing number of contactless diagnostics are used. The prototype of the W7-X control system is operational now. In VINETA the major research objectives have been the investigations of electric field patterns in the plasma and their influence on the plasma dynamics.

WEGA

Head: Dr. Matthias Otte

Overdense Plasma Operation

The application of electron cyclotron resonant heating (ECRH) for high density and high beta operation in magnetically confined plasmas is limited due to reflections of the heating wave at associated cut-off limits that prohibit a propagation of the heating wave into the central plasma region. However, overdense operation in stellarators and high beta regime in spherical tokamaks can be achieved by an alternative heating concept based on the conversion of an incident electromagnetic wave into an electrostatic Bernstein wave (EBW). At WEGA experiments in overdense argon and helium plasmas fully sustained by electrostatic Bernstein waves were performed. For the generation of EBWs a 28 GHz ECRH system (10 kW, cw) and an associated transmission and mirror system were applied allowing a two-step OXB-mode conversion process at the plasma edge from second harmonic electromagnetic O- to X-waves and a subsequent conversion at the upper hybrid layer into EBWs which may propagate into the plasma without a density limit. The conversion efficiency strongly depends on the angle between the incident wave and the magnetic field vector and should have an optimum for an oblique angle of 55°. Therefore, a moveable mirror-system was installed that allows a variation of this angle. Additionally, the conversion process is only possible for a density threshold (O-mode cut-off) of $n_e=1\times10^{19}$ m^{-3}. To reach this density, additional heating using the transformer or non-resonant 2.45 GHz magnetron ECH (26 kW, cw) was necessary. In recent experiments with argon plasmas the density threshold could also be obtained by means of the 28 GHz ECRH system only. The density can be determined by a single-channel 80 GHz interferometer measuring the line averaged density and by a Langmuir-probe installed on a fast reciprocating manipulator. While the typical electron temperature and also the observed radiation temperature measured with a 12-channel microwave radiometer are in the order of 10 eV during second harmonic O- or X-mode wave, the radiation temperature increased up to more then 10 keV when reaching the OXB-regime. This result could be confirmed by soft X-ray measurements obtained with a pulse height analyzer. On a 12-channel bolometer a strong increase of the radiated power on the central channels was also visible during the OXB scenario. Furthermore, a sniffer probe, which measures the fraction of the non-absorbed 28 GHz stray radiation, showed a significant drop when reaching the threshold density indicating an improved absorption of the incident waves. It is assumed that the observed radiation temperature of 10 keV exist due to a small fraction of super thermal electrons in the central region heated by the EBWs, while the bulk electrons, also measured with Langmuir-probes, still have temperatures of a few 10 eV only.

Field Line Visualisation Experiments

The vacuum magnetic structure was studied using a novel method that is based on the inelastic interaction of an electron beam with a background gas (e.g. argon at a typical neutral pressure of p=10^{-5}-10^{-3} mbar). Depending on the gas and the pressure a visible beam with a length of about 100 m at B = 0.5 T could be detected. By applying close range photogrammetry on perspective pictures taken from four different camera view-points it was possible to determine the coordinates of the luminescent trace in the WEGA coordinate system. The accuracy of the whole system was estimated to ±5 mm, mainly influenced by the diameter of the luminescent trace. A qualitatively good agreement between the measured points of the first 4 beam transits at one toroidal position and numerically calculated trajectories by utilizing the W7-code could be obtained.

Development, W7-X Control System and Cooperations

For transport and fluctuation investigations inside magnetic islands on the low as well as on the high field side, a 2-dimensional 63-channel Langmuir-probe array was installed. A fast 16-channel AXUV photodiode array was used to study the heat transfer processes. An absolutely calibrated 12-channel radiometer (22-40 GHz) is applied for measuring the radiation temperature derived from electron cyclotron emission (ECE) and electron Bernstein wave emission (EBE). In preparation for long pulse operation a new highly sensitive integrator for flux and current measurements at Wendelstein 7-X was tested. The integrator, based on a chopped input stage and digital integration, shows a better common mode rejection and reduced drift behaviour compared with analogue integrators. An inner set of Rogowski, diamagnetic and compensation coils that allows the determination of plasma current and energy was installed. Furthermore, the 28 GHz ECRH system and further diagnostics were included in the Wendelstein 7-X prototype control system tested at WEGA. Beside the routinely plasma operation with X2-mode heating, advanced scenarios were realized including the automatic identification of an OXB regime and a related power adjustment of the ECRH component. In cooperation with the IPP Charkov, Ukraine, the HIBP diagnostic was improved, on NIFS, Japan, field line visualisation experiments were performed in LHD.

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VINETA

Head: Prof. Dr. Olaf Grulke

Control of Turbulent Plasma Fluctuations

Velocity shear layers are believed to de-correlate turbulent fluctuations, thereby reducing the fluctuation-induced transport. The time-averaged radial electric field in VINETA causes a nearly rigid body rotation of the plasma without any significant velocity shear. The generation of shear layers, however, is a difficult task. Standard biasing by current-less electrodes limits the electric field along the magnetic field to the sheath and pre-sheath region. In VINETA it was demonstrated that the evolution of the ion velocity distribution function in front of biased electrodes along the magnetic field as measured by laser-induced fluorescence is in accordance to the Bohm criterion, but remains essentially unchanged outside the pre-sheath region. For the shear-layer generation a different approach is pursed: In contrast to standard biasing the shear layer in VINETA is produced by an azimuthally symmetric emissive filament, which causes a radially localized m=0 perturbation of the time-averaged plasma potential. Compared to the unperturbed situation the amplitude statistics of the turbulent density fluctuations changes significantly across the shear layer. The probability distribution function gets flat and a decrease of the kurtosis across the shear layer is observed together with a decrease of the cross-field transport, whereas the tails of the distribution function are fairly uninfluenced. It indicates that predominantly small-scale fluctuations are influenced by the shear-layer. This interpretation is supported by the spatio-temporal investigation of correlation structures, which have been observed to form and propagate radially outwards even across the shear-layer. This finding stands in contrast to the paradigm of de-correlation of large-scale fluctuation structures by velocity shear-layers.

A much more pronounced influence on turbulent fluctuations is achieved if mode-selective parallel plasma current patterns are imposed. In VINETA this is achieved using azimuthal arrays of electrodes or magnetic field coils, respectively. With both arrangements synchronisation of drift wave modes as the result of nonlinear interaction between the imposed current patterns with the intrinsic parallel drift mode currents is found. In the case of coherent drift wave modes frequency pulling of the mode frequency by the imposed current pattern frequency is observed. The frequency range, in which frequency pulling occurs, increases nonlinearly with the amplitude of the driven current pattern, demonstrating the nonlinear character of the interaction. In drift wave turbulence full control of the fluctuations is achieved. The turbulent fluctuation energy is channelled into the imposed mode structure, which has all characteristics of coherent drift wave modes. In particular the fluctuation-induced transport is reduced to the level of the drift wave mode.

Double-layers

Helicon devices have attracted great attention in the context of plasma propulsion schemes since the formation of current-free double-layers in various helicon devices have been observed. The large axial electric field leads to the generation of ion beams, which produce the thrust for propulsion. The prerequisite of current-free double-layer formation is a diverging magnetic field into a large plasma volume, which are in most of the experimental configurations inseparably connected. The investigations in VINETA aim to study the role of the expending volume and the magnetic field gradient separately by changing the position of the magnetic field gradient with respect to the point of expansion of the volume. It is generally observed that the double-layer always forms close to the point of volume expansion and its position is rather independent of the position of the maximum axial magnetic field gradient. However, the strength of the double-layer depends sensitively on the magnitude of the magnetic field gradient. In figure 1 examples of double-layers with fixed position but different magnitude of the magnetic field gradient are compiled. The volume expands from r=5cm to r=20cm and mainly determines the axial position of the double-layer, which is strong with a typical drop of the plasma potential across the double-layer of $e\Delta\Phi/k_BT_e\approx10$. The width of the double-layer, however, decreases considerably with increasing magnetic field gradient, thereby increasing the axial electric field. The investigation of the ion kinetics in response to the electric field structures is the subject of further investigations.

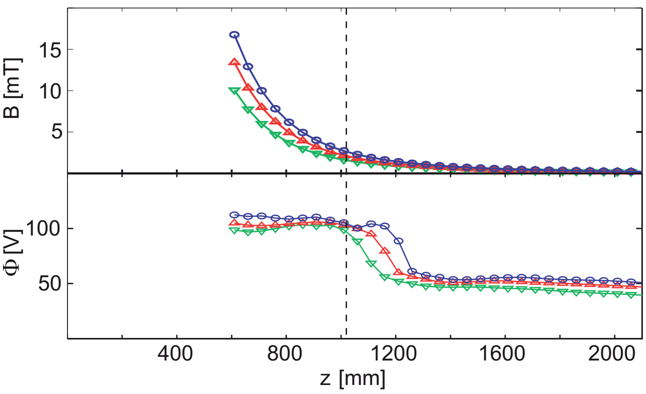

Figure 1: Three magnetic field gradient configurations (a) and the corresponding axial evolution of the plasma potential (b). The dashed lines indicates the position of the expansion of the volume.

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Part of the VINETA program is carried out under the auspices of an EFDA Fusion Researcher Fellowship.

ITER

ITER Cooperation Project

Head: Dr. Hans Meister

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 via contributions to the International Tokamak Physics Activity and by participating in the various Task Forces and Topical Groups of the EFDA Workprogramme.

Introduction

2009 brought yet another major design review for ITER. Due to the complex manufacturing procedure for the vacuum vessel components an alternative design was proposed and assessed. This included also a major review of the design of the blanket modules. However, because of the impacts a change in the design would have meant for many other components, it was decided to keep the original versions. After these decisions were made, the draft ITER Baseline was presented to the ITER Council in November. Unfortunately, it could not be finalised, as there are still some controversial discussions ongoing about the final schedule and costs.

The ITER cooperation project at IPP passed two major milestones in 2009. In November a service contract between F4E and IPP was signed for the establishment of ELISE and subsequent experiments on this half-size ITER source for negative hydrogen ions. At the beginning of the year the Cycle consortium for the ITER ICH antenna was signed and received a grant in autumn. Progress can be reported from the ITER bolometer project, which is currently supported by national funds but still awaits the call from F4E for R&D tasks.

Additionally, IPP is contributing to various heating systems, diagnostics and in particular the preparation of the physics basis through a number of tasks within the EFDA Workprogramme.

Heating Systems

Development of RF Driven Negative Hydrogen Ion Sources for ITER

In 2009, the development of the IPP RF source – being since 2007 the ITER reference source – made a substantial step forward: the service contract between F4E and IPP with a volume of 4 M€ for 4 years for the establishment of the ELISE test facility and subsequent experiments for the extraction from a half-size ITER source was signed on 4th of November.

The design of most of the components is finished; the first procurement activities of the leading items (extraction grids, ion source) have already been started. The installation work in the refurbished experimental hall which hosted the dismantled W7-AS stellarator has also been started by transporting and positioning the spare target tank on site (figure 1). The integrated commissioning with the first pulses is expected in fall 2011. ELISE will use existing hardware from the present IPP test facilities in a wide range. Hence, during the assembly MANITU and RADI have to be closed; this is expected in spring 2011.

The early operation of ELISE is important for the success of the neutral beam injector test plant (PRIMA) in Padua, Italy, consisting of two test facilities: a full power, 1 MV test facility (MITICA, planned to be operating in 2015) and a low power, 100 kV ion source test facility (SPIDER, operating in 2013) by involving the PRIMA personnel in commissioning and experiments and to give important input for the design of the MITICA ion source which is planned to be frozen in 2013. Furthermore, IPP continued to contribute to PRIMA in the framework of an F4E grant in the design of the full size RF source, the RF circuit and the layout of source and beam diagnostics, also by training of PRIMA personnel at the present IPP test facilities.

Figure 1: View into the refurbished old W7-AS experimental hall with the first installation work for ELISE (target tank). The outer red lines on the floor indicate the position and the area of the concrete neutron shield.

The long pulse experiments at the test facility MANITU concentrated last year on the investigations of (a) the stability at high power operation, (b) the correlation of the source performance with the amount and distribution of Cs in the source, (c) the correlation of source plasma and beam homogeneity and (d) effects of magnetic fields on the source performance and beam homogeneity. Record values have been achieved in hydrogen: current densities of 330 A/m^2 (extracted) and 220 A/m^2 (calorimetric) at an RF power of 100 kW for a pulse length of 20 s with an electron to ion ratio below 1, but at a source pressure slightly larger than required. At these power levels however, the long pulse stability is still limited by an increase of the electron current.

The experiments at the BATMAN test facility which went into operation again after a longer phase of reconstruction and upgrading concentrated on studies of the effects of the magnetic field structure on the source performance. The work was supported by an ITER R&D task agreement and done in collaboration with the Indian DA responsible for the diagnostic neutral beam at ITER. First experiments with a new moveable magnet frame showed that some magnetic field in front of the plasma grid is needed not only for electron suppression, but also for achieving large negative ion currents.
The experiments are strongly supported by modelling of the processes in the boundary layer near the plasma grid where the negative ions are generated as well as of the distribution of Cs during and between the plasma pulses, also by basic experiments regarding Cs chemistry and RF efficiency at the University of Augsburg (see chapter 12). The BACON code, a self consistent PIC model, showed that at typical source parameters the amount of negative ions that can leave the plasma grid is space charge limited for the available amount of positive charges (H_x^+, Cs^+). This code was now extended by including bias effects and deuterium. The maximum achievable ion current densities (~1000 A/m^2) agree rather well with the measured extracted current densities taking into account the extraction probability of 25 % which was calculated with the IPP ion transport code TRAJAN.

ICRF Antenna Consortium and Design

The function of the ITER ICRF heating system is to couple a power of 20 MW to the plasma for pulse lengths up to 1000 s, at frequencies from 40 MHz to 55 MHz. In the frame of the ITER in-kind contribution, Europe will provide the ICH port plug with the ICH antenna. The transmission lines, including the now external matching are the responsibility of the US, while the ICRF power source are the responsibility of India.
By the beginning of the year, all European partners had signed the Cycle consortium agreement, thereby formally setting up the Cycle Consortium (CEA, ERM-KMS, IPP, POLITO and UKAEA).
Cycle submitted on 11th May a bid for the Grant "Detailed Design of the ITER ICH Antenna" in reply to the call from F4E at the beginning of the year. After F4E indicated that they wished to place a contract with Cycle, negotiations concerning the maximum cost took place and lead to a revision of the bid, with a reduced cost and scope.
The Cycle grant has been accepted by EXCO of F4E and in preparation for the signature of the Grant Agreement, IPP has signed a mandate allowing the United Kingdom Atomic Energy Authority operating as co-ordinator of the CYCLE Consortium, to sign the Grant Agreement on its behalf.

ECRH Upper Launcher

IPP is involved in the design of the ECRH Upper Launcher for ITER and will be part of the consortium being formed under the lead of KIT. Also, IPP staff made the case for including counter ECCD in the ITER baseline in order to retain experimental flexibility in contrast to having only counter ECCD on-axis.

EFDA Tasks

IPP is coordinating the European efforts on arc detection. It is well positioned to do this with a test stand for arc detection (MXP) and integrated test possibilities on a complete system on AUG, which takes into account the plasma effects. New concepts (Guidar) as well as the further development of existing systems (optical, SHAD) are pursued in cooperation with POLITO, ERM-KMS, CEA and TNO.
Ion cyclotron wall condition experiments were performed on AUG as part of a multi-machine experimental programme with international participation. AUG provides, with its W-wall, unique information for ITER. The results of this campaign are presented in section 10 of chapter 1.
Scientists from UKAEA/JET and ERM-KMS participated in AUG experiments on the effect of local gas injection on ICRF antennas loading and density profiles in the SOL as well as on impurity sources. In standard tokamak operation, the coupling of one antenna improved by about 50 % when switching a high gas puff of 10^{22} el/s from a remote midplane valve to a valve in that antenna.
For ECRH polarisation control experiments three sniffer probes for stray radiation have been purchased and installed in AUG. The results from first experiments are described in chapter 1.

Diagnostics

ITER Bolometer Diagnostic

With many years of experience in the development of bolometer detectors IPP proposes to take the lead in a consortium with the Hungarian Association (RMKI) and the Karlsruhe Institute of Technology (KIT) for the full development of the ITER bolometer diagnostic. The contract for the consortium will be signed shortly by all partners. However, the official call for tender by F4E on this topic is still pending. In order to continue the R&D activities started previously in the framework of tasks of the EFDA Technology Workprogramme IPP successfully applied for national funding. 5.7 M€ have been awarded for the period 10/2008 – 03/2012 for detector development, building and testing of prototypes and the development of the diagnostic integration in ITER. Using these funds, a new team has been set up which is now working on the continuation of the R&D activities. In 2009, results have been achieved in several areas of investigation. The cooperation with IMM (Institut für Mikrotechnik Mainz GmbH) on the development of bolometer foils is being continued and reports further success in increasing the thickness of the absorber now to 4.5 µm by galvanic deposition of Pt onto a thin SiN membrane with Pt meanders on its backside. First tests of these detectors under thermal loads have revealed that the layout of the detector foil and its holder should be adapted in order to reduce forces due to differential thermal expansion of the materials used. Detector foils produced by IMM have also been tested successfully in the tokamak ASDEX Upgrade showing enhanced sensitivity, but lower temporal resolution. Small modifications in the processes used for the deposition of the absorber can be used to change the thermal diffusion time constant and thus the temporal response of the detector. Detector foil samples featuring the new layout (see figure 2) and a reduced thermal diffusion time constant are expected at the beginning of 2010. Additionally, a sample has been irradiated up to 0.01 dpa in the reactor BR2 of the Belgian Association. The results are very promising: consistent data could be acquired during the irradiation cycle confirming that the choice of materials for the samples is in principle radiation resistant. However, the mechanical stability of the detector foils still has to be increased.

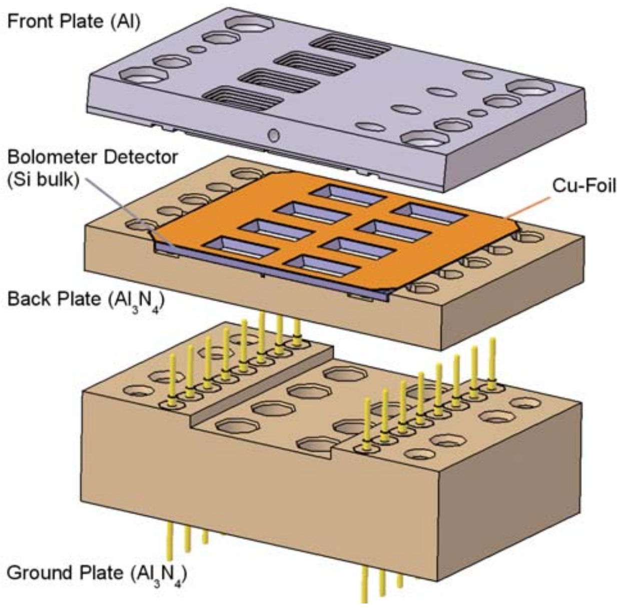

Figure 2: New layout of bolometer detector which is now placed inside a recession of the back plate without holes for screws, is protected by a copper foil and has features for unambiguous orientation at the edges.

New test stands have been set up at IPP for testing the detector foils. Firstly, a laser trimmer has been procured and taken into operation. After the optimisation of the trimming process, it will be used to adapt the electrical resistance of all meanders for one detector such that thermal drifts during the measurement are minimized. Secondly, a vacuum oven which can heat bolometer detectors up to temperatures of 450 °C has been designed, manufactured and brought into operation. It will be used to test simultaneously up to five of the samples provided by IMM at ITER relevant temperatures while performing continuous calibration measurements. A blue laser at a wavelength of 405 nm and a cw-power of up to 10 mW can be used as light source. This is an essential step towards characterising new samples under realistic conditions in order to continuously improve their quality. Work has been started to make the proof of principle that the geometric function of the bolometer diagnostic can be calibrated in situ. To this aim a light-weight robot has been procured and is now being programmed as part of a diploma thesis to reliably determine the geometric function of bolometer lines-of-sight by moving a blue laser as light source along known coordinates. The development of the integration of the bolometer diagnostic in ITER had to wait for the result of the ongoing design changes for the vacuum-vessel and the blanket modules of ITER. Now that the decision has been made to keep the original design variant, this work will continue as soon as an official Grant from F4E is awarded. Finite element analysis of diagnostic components in cooperation with RMKI is being continued and gives information on the usefulness of prototype components for ITER.

EFDA Tasks

A scintillator-Faraday cup combined solution has been studied as Fast-Ion Loss Detector for ITER. In collaboration with TEKES, 3D simulations of the α-particle load on an up-to-date ITER wall were used to estimate detector signals.

A feasibility study to determine the edge bootstrap current via Zeeman splitting of Li or Na showed that Li is better suited than Na, that a close to toroidal viewing geometry delivers the highest radial variation for the ratio of σ/π intensity for given current profiles, and that the expected photon numbers are too small for a conventional Czerny Turner spectrometer.

Within a new EFDA working group on “Data Analysis and Calibration Techniques” data analysis challenges for present and next generation fusion devices were identified and an overview of present data analysis methods was drawn. Most urgent data analysis methods for next generation fusion devices were identified and candidate solutions were proposed.

For spectroscopic erosion measurements in ITER, the relevant atomic data has been reviewed and the detection limit calculated. The latter is sufficiently low for measurements of C, Be and W.

Additionally, EFDA supported diagnostic hardware upgrades at AUG for the SXR, bolometry, Thomson-scattering and CXRS diagnostics. Enhanced time and/or spatial resolution will be used to provide essential data for the analysis of various plasma scenarios in view of ITER to study e.g. fluctuations, disruptions and transport.

ITER Support

Physics Integration

Most of the experimental programme of ASDEX Upgrade is oriented towards the investigation of plasma scenarios required for the operation of ITER. These results are presented in chapter 1. In this section, the results of some specific investigations are presented, which are conducted within the framework of the EFDA Workprogramme.

Experiments on plasma rotation showed a clear decrease in core plasma rotation when ECRH power was added to NBI heated discharges which seemed to occur only above a critical gradient in the T_e profile.

The disruptions of the last two years have been analysed and classified according to their physical causes. Discriminant analysis discerns successfully between non- and pre-disruptive states. A disruption prediction algorithm based on a neural network has been updated and applied to recent discharges. ASDEX Upgrade plasmas during vertical displacement and following disruption have been simulated with the DINA code in order to test the capability of the halo model to reproduce the measured evolution of the halo current for legitimizing the use of DINA to predict ITER halo currents.

Sawtooth oscillations in the central temperature, caused by MHD instability, can be stabilized by fast ions which is particularly important for ITER. The effect of fast particles from NBI and ICRH was studied in AUG. The first destabilisation results with ECCD are obtained.

The Langmuir probe diagnostic has been enhanced for fast T_e measurements in the SOL. In collaboration with many European Associations studies of fluctuations and transport were performed. Some results are presented in chapter 1.

A new Langmuir-probe array with 128 probe tips has been installed in TJ-K. In the presence of shear flows, long-range correlations mainly in the potential but also in density were observed. The energy transfer to the zonal flow comes mainly from small scale fluctuations and is non-local.

PWI Task Force

In the framework of ITPA and the EU PWI TF different processes leading to fuel retention in tokamaks, such as codeposition and implantation in C, Be and W have been investigated and quantified in laboratory experiments. In 2009 the special emphasis was on high fluency retention in W and effects due to additional radiation damage by neutrons. It could be shown that at fluencies exceeding 10^{27} D/m^2, equivalent to more than 2500 full ITER discharges at the vessel walls, the retention saturates and does not increase further. Neutron damage, simulated by the irradiation with MeV W ions, enhances the retention due to additional trapping sites in the W lattice. An extrapolation to tritium retention in ITER was performed on the basis of the analysis of the underlying retention processes and a scaling of plasma conditions in front of the PFCs to ITER. The inventory due to implantation and bulk retention in an all-W device saturates at about 50 g tritium without neutron damage, and will also not reach the 700 g tritium limit within the lifetime of ITER if a damage level of 1 dpa in W is taken into account.

Further ITER-specific tasks with a total of 5.4 ppy Priority Support were acquired in the fields of fuel retention, tritium removal, dust generation, material transport, high-Z materials, mixed material behaviour, and disruption and ELM mitigation. Results from these tasks are included in chapters 1 and 6.

Trainee Programmes

The EnTicE Project (European Network for Training Ion Cyclotron Engineers), part of the Euratom Training Scheme, continued successfully in its third year. One trainee was hired in replacement of a trainee who had obtained a permanent position at IPP, while another trainee was hired by ITER.

Two trainees at IPP participate in the new Euratom training scheme LITE.

IPP also takes part in the FUSENET project, a European Fusion Education Network (FUSENET) for education in fusion science and technology. The project consists of eleven focused work packages, with a total budget of 2 M€ and brings together a broad representation of the European fusion community. IPP leads one workpackage and one task and participates in several other workpackages.

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Plasma-wall-interactions and Materials

Plasma-facing Materials and Components

Head: 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

Deuterium Release after Implantation into Single- and Polycrystalline Beryllium

Temperature-programmed desorption (TPD) measurements of deuterium implanted at various ion energies into single and polycrystalline beryllium were performed in order to gain a deeper understanding of the retention and release mechanisms of D in Be. Prior to implantation the samples were repeatedly sputter-cleaned and annealed. In-situ X-ray photoelectron spectroscopy showed a constant but small amount of beryllium oxide as the only remaining surface impurity.

A high and a low desorption temperature regime was found. After implantation to fluences below 10^{21} m^{-2} deuterium only starts to desorb at temperatures above 600 K. An implantation energy-dependent shift in desorption temperature of this high temperature desorption peak was observed after implantation to fluences around 3×10^{19} m^{-2}. Such a peak shift was reproduced in TMAP7 simulations by variation of the distance from the surface of atoms implanted at different energies rather than by changes in the activation energy for detrapping. The threshold fluence for the appearance of the low-temperature desorption region around 460 K after implantation of 1 keV D ions into polycrystalline Be was determined to 1.2×10^{21} m^{-2}. The fact that the threshold fluence is the same for single and polycrystalline Be leads to the conclusion that the evolution of the supersaturated regions, in which the D is trapped after implantation to high fluences, is not substantially influenced by possible trapping at grain boundaries or fast diffusion along them. Furthermore, the comparison of desorption spectra from single and polycrystalline materials showed that trapping at grain boundaries – if possible at all – is less strong than the trapping at ion-induced defects which occurs in both kinds of materials already upon implantation to low fluences.

Influence of Beryllium Containing Redeposited Layers on Tritium Retention

The influence of redeposited beryllium-containing layers on tritium retention in plasma-facing materials was investigated in collaboration with the National Institute for Laser, Plasma and Radiation Physics, Bucharest. Thin beryllium films (several hundreds of nm) were deposited onto tungsten (W) and carbon samples in Bucharest by means of a thermionic vacuum arc discharge procedure. The samples were in the following implanted with D ions (200 eV, 10^{19} $Dm^{-2}s^{-1}$) at IPP. The amount of retained D was measured by nuclear reaction analysis (NRA) and thermal desorption spectroscopy (TDS). For room temperature implantation, NRA depth profiling showed that most of the D was retained in the Be film without significant diffusion across the Be-W or Be-C interface. Consequently, the retention properties at 300 K do not depend on the substrate material, but rather on the intrinsic structure of the deposited layers. TDS spectra showed a major D desorption peak from the Be film at about 470 K and several additional minor peaks around 550, 700 and 850 K, respectively. Increasing the implantation temperature basically leads to decreasing D retention and correspondingly disappearing D desorption peaks below the implantation temperature. However, it should be noted that the peaks above the implantation temperature sometimes slightly increased compared to those found in TDS spectra of samples implanted at 300 K. Implantation at 620 K leads to formation of a Be-C mixed layer at the Be-C interface, whereas Be-W mixing at samples with W substrate was not significant at this temperature. During TDS, samples were heated up to 1000 K. Due to this thermal treatment, the Be film on the C substrate becomes fully intermixed with C with a stoichiometric ratio of Be:C of ≈2:1, which suggests formation of a Be_2C phase. In comparison, Be-W mixing for Be layers on W substrate was still insignificant even after TDS with the same maximum temperature. From the results one infers that Be-carbide will be easily formed under reactor exposure conditions and hence further investigations of D retention in the Be-C system are required. Although W-beryllide alloy formation might not be as significant as Be-carbide formation, influence of such beryllide formation on D accumulation in W bulk materials might become important at temperatures above those investigated in the present studies. The film deposition system in Bucharest has been further upgraded and fabrication of Be-C or Be-W "co-deposition" films is now available. Investigations of film properties and hydrogen retention properties in such co-deposited layers are presently underway.

Influence of the Molecule Structure on Sticking of Low-energy Hydrocarbon Species

One of the most critical issues for the use of carbon in ITER is the erosion of plasma-facing components and the tritium retention resulting from redeposition of hydrocarbon films. The predictions for the amount of redeposited tritium are based on transport calculations which rely on proper plasma-wall interaction models. Key quantities entering these models are the energy and species dependent sputter yields of the wall materials due to energetic particles and the sticking and reflection coefficients of impinging species. Since experimental data on these quantities for hydrocarbon species are very sparse most plasma-wall-interaction models rely on estimates based on binary collision (BC) codes such as TRIM.

However, these BC codes are incapable to take the molecular structure of the impinging particles into account. To derive a more reliable understanding a joint experimental and theoretical approach was initiated. The sticking properties of various hydrocarbon molecules are investigated in the MAJESTIX particle-beam experiment with special emphasis on the low energy regime (E<150 eV). These experiments are accompanied by molecular dynamics simulations of the deposition and sputtering process. The dependences of sticking coefficients and sputter yields were computed as functions of projectile energy, angle of incidence and impacting species. The simulations reveal the relevance of the molecular structure for energies below 50 eV. In figure 1 the sticking coefficients of several impinging molecules (C, CH_3, CH_4) are shown as function of energy. Single carbon atoms have a sticking of around 0.9 throughout the energy range of 5-100 eV. In contrast the sticking of CH_4 drops to almost zero for low energy, with a pronounced threshold at around 50 eV. A similar reduction of the sticking coefficient is also present for CH_3. Fitting formulas were established describing the computed dependencies, providing a compact and accessible description of the simulation results. Sticking coefficients based on TRIM simulations match the MD results for high energies (>100 eV), where the intramolecular binding energies become small compared to the projectile energy but deviate by up to two orders of magnitude for low energies in the case of CH_4, thus potentially yielding misleading (co-)deposition estimates.

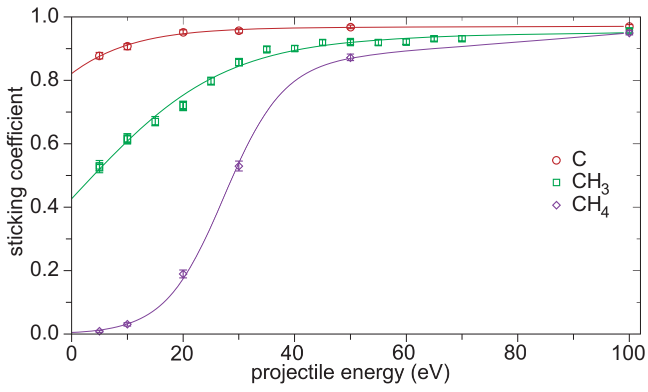

Figure 1: Energy dependence of the sticking coefficient of selected hydrocarbon species for perpendicular incidence. Symbols are model results from MD simulations and the lines are fits of a sigmoidal function to the model results.

Interaction of Nitrogen Plasmas with Tungsten

The use of nitrogen seeding to reduce the edge plasma temperature has recently been successfully applied in ASDEX Upgrade. While the plasma performance was significantly improved compared to other seeding species like Ar or Ne, questions remained as to the interaction of nitrogen with a tungsten first wall. Formation of thick layers with reduced melting temperature and increased physical sputtering was a concern. Therefore dedicated laboratory experiments have been performed to investigate the interaction of W surfaces with N plasmas. Tungsten coated Si samples were exposed to N ions from plasma and ion gun sources at energies from 20 eV to 10 keV and W surface temperatures from 300 to 750 K. After exposure to the N plasma with fluences of up to several 10^{23} N/m^2 the N content in the samples was measured by nuclear reaction analysis. The sputter erosion was determined by measuring the thickness change of the W layer by RBS. The formation of W nitride phases was investigated in separate XPS experiments where the samples were implanted in situ with keV N ions. XPS measurements showed the formation of W-nitrides with W 4f peak shifts similar to those found in literature. W-nitrides become unstable at elevated temperatures and decompose by degassing the N. This instability was also predicted by thermodynamic modelling calculations of the W/N system. The W implantation experiments showed that the N content in the W surface quickly saturates, once the N concentration within the implantation range has reached the stoichiometry of W-nitride (50 % N). The total amount of N in the surface depends on the N energy since the implantation range increases with increasing N energy. Due to accumulation of N in the W surface the observed partial sputter yield of W was significantly reduced compared to the yields expected for a pure W surface. Therefore, with respect to W sputtering N is a better seeding species compared to noble gas elements which only accumulate in the surface at sub % levels which results in observed partial sputter yields equal to those for pure W surfaces. In conclusion the use of N as a seeding species together with a W wall poses no problems with respect to the interaction with the first wall. Moreover the use of N leads to lower W erosion compared to noble gas seeding with Ne or Ar.

Migration of Materials in Fusion Devices

Additional contributions to material migration in ASDEX Upgrade, JET, and ITER are reported in the respective sections of this annual report.

Tungsten Transport in ASDEX Upgrade

Net erosion and redeposition of tungsten in the ASDEX Upgrade divertor were investigated in collaboration with the Finnish Association TEKES by analysis of marker tiles after the full-W campaign 2007. The inner divertor and the roof baffle were net W deposition areas. Net erosion of W was observed in the whole outer divertor, with the largest erosion close to the outer strike point. Only a small fraction of the tungsten eroded in the main chamber and in the outer divertor was found in redeposits in the inner divertor. The global tungsten transport shows a different behavior than the carbon transport: While for carbon erosion is balanced by deposition in the inner divertor, tungsten exhibits strong erosion in the outer divertor and only little redeposition in the inner divertor. A large fraction of eroded W is either redeposited at unidentified places in the main chamber or forms dust.

Investigation of Local Transport in the Outer Divertor of AUG by Injection of $^{13}CH_4$ Isotope-Marked Methane

One of the key issues in designing the ITER fusion experiment has been the selection of suitable materials for the plasma-facing components. Currently both carbon and tungsten are envisaged for the power-load-bearing surface regions in the device. The major concern with the use of carbon is its tendency to form hydrocarbon molecules, leading to co-deposition of tritium in the vessel structures. However, the transport mechanisms of hydrocarbons and layer formation on tungsten surfaces are still not adequately known.

Correct inclusion of ion drift effects in impurity transport models such as implemented in the ERO code package is of crucial importance for predictive modelling of respective plasma-surface interactions in the ITER reactor. The origin of such drifts and their effect on local carbon transport and deposition was investigated experimentally by comparing deposition patterns obtained from experiments with opposite magnetic field directions (end of experimental campaigns 2007 and 2008 respectively). Measurement of the ^{13}C deposition pattern on retrieved tiles from the vicinity of the puffing location was performed in 2009 by means of nuclear reaction analysis. It turned out that the deviation of the deposition pattern from the magnetic field orientation at the surface in the 2008 experiment with reversed B-field was opposite to that of the 2007 experiment. This provides conclusive evidence for the presence of E×B drifts and provides the necessary data base for benchmarking of respective transport models.

Deuterium Inventory in Tore Supra

As in previous years, the Materials Science department was substantially engaged in the analysis of DITS samples (Deuterium Inventory in Tore Supra). In the last campaign, the long existing discrepancy between hydrogen gas balance measurements during discharges and post-mortem surface analysis in Tore Supra could be reduced by a factor of 2. Large deuterium amounts were found in the gaps between the carbon tiles particularly in erosion dominated areas. In 2009 additional 60 samples were analysed at IPP by ion beam analysis. Quantitative data evaluation is ongoing. In addition, IPP produced a set of benchmark samples to allow a quantitative comparison of the different TDS analyses used in the participating laboratories.

Tritium Inventory – Understanding and Control

Many of the project activities devoted to the understanding and control of the tritium inventory are reported in section "Helmholtz-Russia Joint Research Group: Hydrogen Isotopes Retention in First-Wall Materials" at the end of this chapter.

Hydrogen Trapping in Pre-damaged Tungsten

Deuterium retention in pure tungsten has been observed to be fairly low, but some uncertainty remains regarding the influence of damage caused by 14 MeV fusion neutrons. Therefore, the production of n-induced defects was simulated by tungsten self-implantation (5.5 MeV, R_p=400 nm, 300 K) at three different fluences which correspond to three damage levels of 0.04, 0.4, and 1.2 dpa (displacements per atom) in the maximum of the damage profile. The damage levels were calculated using SRIM-2008.03. Depending on the assumed threshold energy for displacement of W atoms, E_{th}, the estimated damage in ITER at the end of its lifetime is between 0.4 and 0.7 dpa. After the tungsten pre-irradiation, some of the samples were heated at 1200 K for 2 h in order to investigate the annealing of radiation-induced defects. Both sets of samples were either implanted with 200 eV deuterium ions at two different fluences or exposed to high-fluence deuterium plasmas. The D-irradiations were performed at about 300 to 350 K or 470 K, respectively. For comparison, D-implantation into undamaged tungsten was investigated accordingly.

The deuterium depth profiles were measured by means of NRA using the D(^{3}He,α)p reaction. The total deuterium retention was obtained from TDS measurements. The surface morphology was investigated by SEM/FIB. The results indicate that deuterium is mostly retained in traps created by the pre-irradiation. This increases the D retention strongly in comparison with undamaged W.

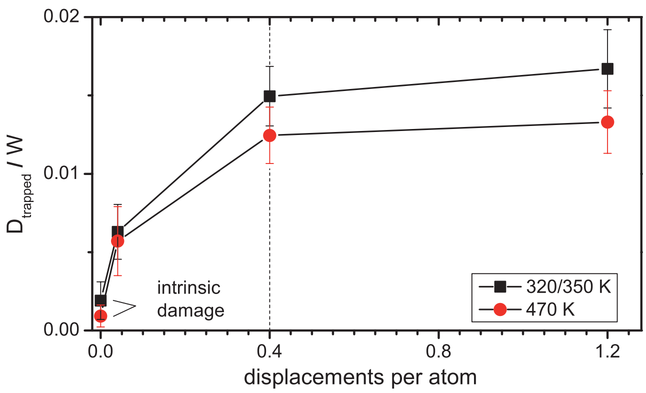

Figure 2: Average D concentration in the damage region vs. dpa for polycrystalline W irradiated at 320/350 and 470 K. The damage levels were calculated with SRIM-2008.03 using a threshold energy of 68 eV. The vertical dashed line indicates the estimated end of lifetime damage in ITER.

The D inventory does not grow linearly with dpa, but reaches saturation at 0.4 dpa with a D/W-ratio of 1.6 % (see figure 2). TDS spectra reveal that the ion pre-irradiation produces traps with desorption temperatures of ~530 and ~820 K. The lower temperature corresponds to D detrapping from interstitial-type dislocation loops, the higher one to deuterium detrapping at vacancy clusters. Around 30 % of the retained D is trapped in the high-energy defects. The NRA and SEM results suggest that in order to keep deuterium retention low and to avoid tungsten blistering, the effective temperature at the tungsten surface should be above 900 K.

Tritium Removal from Tile Gaps at Elevated Temperatures

The removal of redeposited carbon layers from ITER-like tile gap structures with oxygen plasmas was investigated in laboratory plasma experiments. In ITER such layers may significantly contribute to the total tritium retention. Since ions cannot penetrate deeply into such gap structures erosion from these surfaces is dominated by neutral reactive species. Uniform plasma-deposited amorphous hydrogenated thin films were used as a model system for redeposited films. Erosion measurements were performed on flat substrates as well as on two different 3D test structures. One design consists of 19 mm deep gaps with widths ranging from 0.5 to 4 mm to simulate ITER tile gaps. A second design was used to measure the radical reflection probability of the neutral species involved in the erosion. It consists of a flat box-like structure where particles can enter only trough a narrow slit. Measurements were performed for substrate temperatures ranging from 270 to 580 K. Erosion rates increase exponentially with the substrate temperature with an apparent activation energy of 0.25 eV. While at room temperature the radical reflection probability of the dominant eroding species is 50% it becomes higher at elevated temperatures. At elevated temperatures films are not only removed faster but simultaneously erosion penetrates deeper into the gaps. Carbon removal in remote areas of fusion experiments with oxygen glow discharges will only be efficient at elevated temperatures (> 450 K) but will be ineffective at room temperature as the radical reflection probability of the species dominating the erosion process is too small at 300 K.

Materials – Processing and Characterisation

Clarification of the Cavity Formation Mechanism of Deuterium Bombarded Tungsten with the HELIOS Device

The strong morphological changes appearing on polycrystalline tungsten (W) after hydrogen (H, D) and helium bombardment are extensively investigated utilising scanning electron microscopy (SEM) in combination with focused ion beam (FIB) preparation and related analytical techniques (e.g., electron backscattering diffraction, EBSD). The observed surface features range from spherical blisters over irregularly shaped hill-like (figure 3) to coral/sponge-like surface structures (see Par. "High Heat Flux Test Facility GLADIS"). Their occurrence depends on the material grade and the loading conditions such as hydrogen impact energy and sample temperature. The power of combining various techniques in the HELIOS device, especially the sequential cross-sectioning, is demonstrated for the example of D bombardment of W: In the course of these investigations the formation mechanism of the hill-like surface structures appearing on W surfaces after D bombardment was clarified. Figure 3 shows a SEM image of polycrystalline W after D exposure. Many of the hill-like structures, which are not present on the unirradiated surface, are elongated and correlated to the crystallographic orientation of the individual grains.

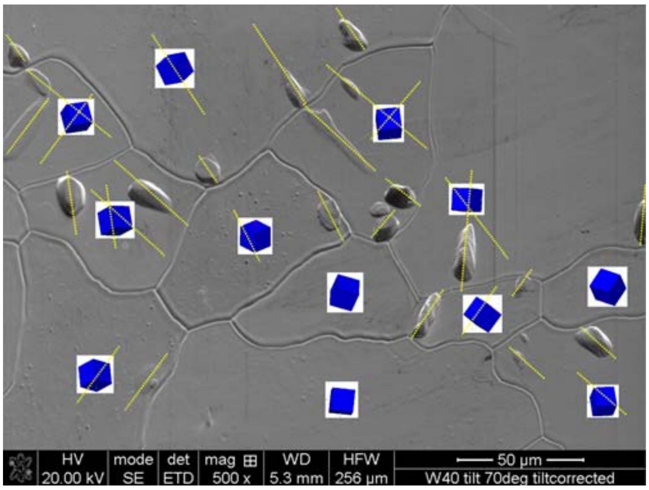

Figure 3: Polycrystalline tungsten with various elongated hill-like structures after exposure to 10^{26} Dm^{-2} (~40 eV per D) at 600 K. The orientation of the grains was determined by EBSD and is represented by the inserted cubes. Some of the projected {110} slip planes of the slip system {110}⟨111⟩ are marked by the dashed lines in the cubes as well as on the elongated structures. The surface was tilted by 70° and the image was stretched in the vertical direction in order to correct the tilt shortening.

By sequential cross-sectioning through the shown surface area with the FIB, three dimensional (3D) data of the subsurface morphology are obtained. Each observed surface structure is correlated with a cavity deep underneath the surface. The cavity is always attached to a grain boundary. 3D data are necessary to determine the lateral shift of the cavities with respect to their surface feature. The crystallographic orientation of each individual grain was determined by EBSD and is illustrated by the cubes inserted in figure 3. Correlating the crystallographic orientation, the elongation of the structures, and the position of their respective cavity, it was found that the material transport leading to the structures on the surface is caused by gliding along the slip system {110}⟨111⟩.
In addition, the EBSD study indicates that the crystallinity of the very surface is strongly distorted, even though the energy of the impacting D was below the threshold for defect creation in W. Only after removing this surface layer with the FIB, the orientation analysis with EBSD was possible.

Erbium Oxide Permeation Barriers: Characterisation and Radiation-induced Damage

Er_2O_3 thin films are proposed as hydrogen diffusion barrier and for the application as insulating and corrosion resistant coating. A thorough study was performed to investigate the influence of the deposition conditions on the crystallographic phase of the deposited Er_2O_3 coatings. A filtered cathodic arc device is used for film deposition. Deposition temperatures above 500 °C without additional substrate bias resulted in coatings in the usual cubic crystal structure. However, by deposition at lower temperatures with a bias voltage of ≥100 V, an unusual monoclinic phase is formed. It has a higher density, therefore, a stronger permeation reduction is expected, which is currently under investigation.

To simulate neutron displacement damage, 5.5 MeV Au^{2+} irradiation of Er_2O_3 thin films was performed at room temperature up to a damage level of 100 dpa. The cubic phase transformed into the monoclinic phase during the ion irradiation. Post-annealing experiments indicated that this effect is irreversible up to 600 °C. In contrast, Er_2O_3 thin films of the monoclinic phase remained stable under these irradiation conditions. TEM analysis of the irradiated coatings was performed at the Oak Ridge National Laboratory to study the effect on the Er_2O_3 microstructure. The phase transformation is accompanied by an increase in the number of crystallites and grain boundaries, which could degrade the permeation barrier property.

Future activities will be devoted to Er_2O_3 deposition by reactive magnetron sputtering and the influence of 5.5 MeV Au^{2+} irradiation on the hydrogen permeation properties.

Metal Matrix Composites

High temperatures at the interface between plasma-facing material (PFM) and the heat sink of future fusion reactors will cause high stresses due to the different coefficients of thermal expansion and the temperature gradient at the PFM interface (e.g. W/CuCrZr). This critical zone can be reinforced with a silicon carbide fibre (SiC_f) reinforced copper matrix composite (MMC). Based on thermal and mechanical investigations, an MMC consisting of 4-5 unidirectional (UD) layers and a fibre volume fraction of 14 % was chosen as an interlayer between the W and the CuCrZr. In a first step SiC fibres were coated with a thin titanium interlayer by magnetron sputtering to improve the bonding between the fibres and the copper matrix. In a second step UD layers were prepared by two subsequent electroplating processes which allow for adjusting various fibre volume fractions. The UD layers were consolidated by vacuum hot pressing at 650 °C and ~40 MPa in cooperation with MTU Aero Engines to form the MMC interlayer, which was implemented in a flat-tile mock-up for high heat flux tests (HHF). Brazing of the MMC interlayer between tungsten tiles as PFM and CuCrZr was performed in cooperation with Ansaldo.

Flat-tile mock-ups were investigated in the HHF facility GLADIS at IPP. Figure 4 shows a test component, comprised of tungsten tiles as PFM, the SiC_f/Cu MMC at the interface (marked area), and a CuCrZr heat sink with cooling channel. According to FEM simulations the highest stresses are located between the PFM and the MMC interlayer at the edge of the mock-ups. The predicted temperatures (with the highest temperature at the edge of the tungsten surface) showed good agreement with the measured temperature profile during the HHF tests.

At the highest heat flux of 10.5 MW/m^2 stable and sufficient heat transport could be demonstrated. Additional cycling tests were performed with the mock-ups at 10.5 MW/m^2. A uniform temperature distribution at the tungsten surface up to 25 cycles indicated good heat transport from PFM to the heat sink. After 80 cycles at 10.5 MW/m^2 the mock-up was investigated by metallographic and microscopic techniques, permitting the identification of failure mechanisms and defect types. In microscopy investigations good bonding between the UD layers within the MMC was confirmed. Small localized defects without crack propagation and small cracks within the matrix due to high stresses were identified as a consequence of the cyclic heat loads. These defects, however, did not lead to a failure of the full component. Hence, SiC_f/Cu is a suitable functional material to reinforce critical interfaces between PFM and heat sinks in future fusion reactors. The weak point of the flat-tile mock-up concept is the brazing between the components. Cracks and pores between W and MMC, MMC and CuCrZr, as well as cracks within the brazing foil lead, in combination with high stresses and small matrix cracks, especially at the edge of the mock-up, to an insufficient heat transport and an overheating of W tiles.

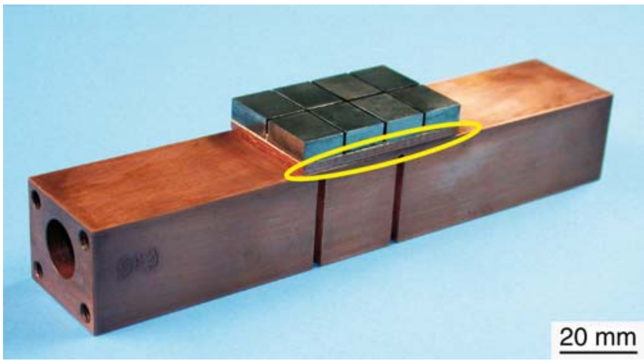

Figure 4: Flat-tile mock-up for HHF tests at GLADIS. The SiC fiber reinforced metal matrix composite is located at the interface between the tungsten tiles and the CuCrZr heat sink (see mark).

Component Behaviour

Additional contributions on component behaviour are reported in the section JET cooperation of this annual report.

Development of Tungsten-wire-reinforced Tungsten Materials

Inherent brittleness is the most crucial drawback of tungsten prohibiting its application as a structural material. In order to realize fundamentally enhanced toughness of tungsten, IPP is developing a novel tungsten-wire-reinforced tungsten matrix composite (W_f/W) utilising the well-established toughening mechanism of fibre-reinforced ceramic matrix composites. Toughness of the composite is achieved by controlled debonding and friction at the engineered fibre/matrix interfaces since this process can lead to substantial dissipation of stored strain energy. Cu-based (Cu single-layer and Cu/W multi-layer) and ZrO_x-based (ZrO_x single-layer and ZrO_x/Zr multi-layer) thin coatings were used as interfacial layers. For the purpose of interface testing, a number of dedicated single-filament mini-composites were fabricated with different coating thickness. Fibre push-out tests were carried out to explore the mechanical properties of the coated interfaces (figure 5).

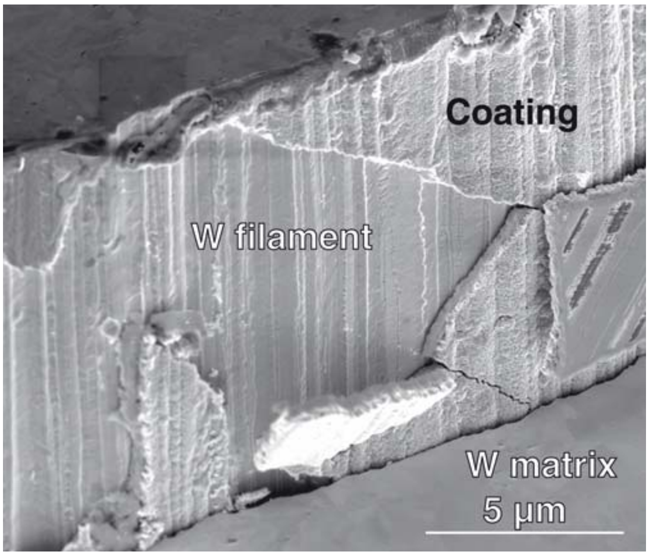

Figure 5. Surface of the pushed-out filament with the ZrO_x single-layer coating. The oxide coating cracked on both interfaces indicating comparable fracture energy values on both interfaces. The fracture surface exhibits a clear separation caused by cleavage debonding.

Fracture mechanical interface parameters were identified by means of fitting the push-out test data to theoretical models. The estimated interfacial data were as follows: debonding strength: Cu single-layer (393 MPa), Cu/W multi-layer (429 MPa), ZrO_x single-layer (385 MPa), ZrO_x/Zr multi-layer (262 MPa); fracture toughness: Cu/W multi-layer (22 J/m^2), ZrO_x single-layer (4 J/m^2), ZrO_x/Zr multi-layer (3.5 J/m^2). Cu single-layer data could not be fitted into the elastic model due to strong plasticity, but its energy absorption capability was larger than the multi-layer counterpart. These fracture toughness values satisfy the theoretical criterion of crack deflection which ensures interfacial debonding instead of catastrophic crack propagation through the bulk.

High Heat Flux Test Facility GLADIS

The successful operation of present and future fusion experiments requires increasingly reliable and well characterized plasma-facing components (PFCs). The thermo-mechanical behaviour of the PFCs strongly influences the plasma-wall interaction. For instance gas diffusion in materials, i.e. hydrogen and tritium retention and desorption, depends on the temporal and spatial distribution of temperature and thermo-mechanical stress during plasma operation. This complex set of conditions, however, can experimentally only be verified by exposing the component to realistic heat and particle fluxes. This is especially important for actively cooled divertor components, for instance in W 7-X and ITER. In the high heat flux (HHF) test facility GLADIS full-size water-cooled PFCs as well as small samples can be exposed to divertor-relevant heat and particle loads.

As part of the activities in 2009 W7-X divertor tests were continued as main task, tungsten coatings on CFC were qualified for the ITER-like Wall Project at JET (see section “JET cooperation”), and combined H/He loadings of tungsten components were performed studying surface morphology changes.

HHF tests of pre-series IV targets for W7-X focused on the qualification of repaired CFC tiles. Individual tiles were replaced at different stages of manufacturing by PLANSEE to develop a repair method for series production. Extensive HHF tests, performed up to 5,000 cycles at 10 MW/m^2, confirm the nearly original performance of such repaired tiles. For some tiles the surface temperature increased slightly due to the additional welding process during repair. Tungsten has been selected as one of the PFMs for devices like ITER and DEMO. Powder metallurgy tungsten (PM-W) is preferred for the highly heat- and particle-loaded divertor components.

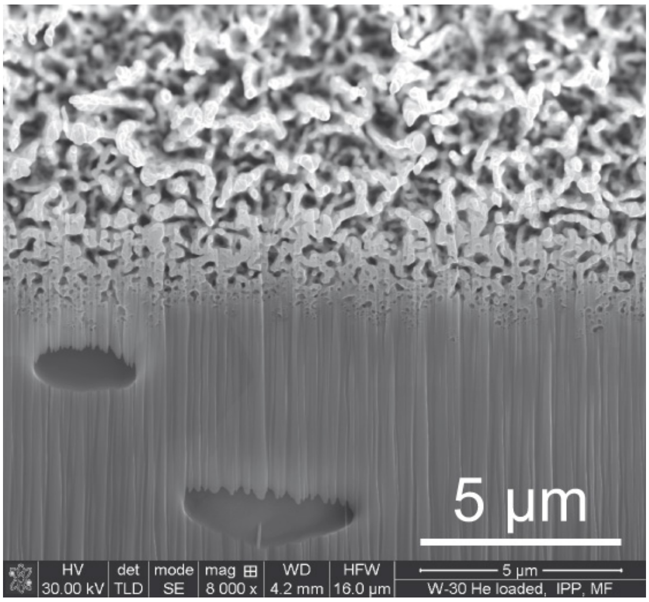

Figure 6: FIB cross-section depicting individual bubbles as well as larger agglomerates. The surface temperature increased to 2100 °C during He loading.

Various components with W as PFM have been tested with H, He and mixed beams at heat fluxes of 2-10 MW/m^2 and fluences up to $3 \cdot 10^{25}$ atoms$\cdot$m^{-2} to study surface morphology changes. For a comparative assessment of the component performance, loading was also performed on W coatings on adiabatically loaded samples. This type of PFCs is used in ASDEX Upgrade and is foreseen for JET in frame of the ITER-like Wall Project. In addition, 2 mm thick vacuum plasma sprayed (VPS) coatings on water-cooled steel substrates and PM-W components were loaded with H and He beams at 2 MW/m^2 under identical conditions to investigate the ability of W-VPS to withstand first wall operational conditions. Figures 6 and 7 show microscopy results obtained by focused ion beam preparation after exposure to He beams with a total fluence of $1.5 \cdot 10^{24}$ $He \cdot m^{-2}$. The main difference during loading is the peak temperature of the surface. The surface temperature of the adiabatically loaded sample increased up to 2100 °C after 3.5 s heating at 10 MW/m^2. This extremely high peak surface temperature resulted in the coral-like surface modification shown in figure 6.

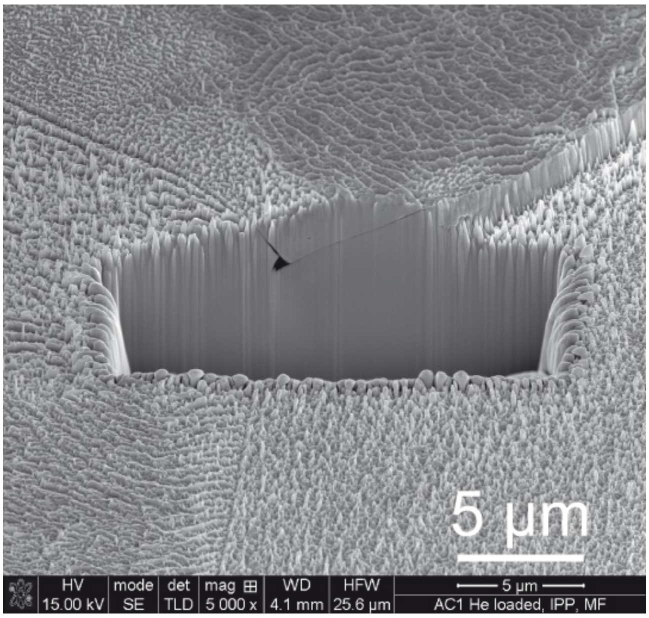

Figure 7: Different erosion patterns of individual differently oriented grains on an actively cooled sample. The surface temperature of this sample during $1.5 \cdot 10^{25} He \cdot m^{-2}$ loading was 200 °C.

This feature extends to a depth of 2-3 µm, which is far beyond the 70 nm penetration depth of the incident He particles. In contrast, for tungsten experiencing lower surface temperatures physical sputtering is the only surface modification process. Such a surface is shown in figure 7.

Integration of and Collaboration in EU Programmes

EU Task Force on Plasma-wall Interaction

The contribution of the project to the EU PWI Task force has intensified in 2009 with the deputy TF leader, the new leader of the Gas Balance and Fuel Retention expert group and the leader of the Mixed Materials expert group being from IPP. PWI research within the programme is characterized by co-operation based on joint experiments (e.g. at JET, Tore Supra), which is the basis for several priority tasks assigned by EFDA. Consequently, strong contributions were made to all topics of the Task Force, amounting to 5.4 ppy Priority Support and 16 ppy Baseline Support. Within the EFDA Fusion Programme the Project provides two mid-size facilities: The High-Heat-Flux Test Facility GLADIS and the Integrated PWI Facility.

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 centers and universities with the aim to develop new materials for very demanding applications.
The fifth project year finalized the *Industrialisation* phase of the project which was devoted to up-scaling of newly developed materials and technologies and integration to mock-ups and test samples. In addition, neutron irradiation campaigns (2 doses, 4 temperature ranges) at the high flux reactor in Petten were successfully performed. In total, ~1000 different samples were investigated in thermal and mechanical tests before and after neutron irradiation.

FEMaS – Fusion Energy Materials Science (an EU Coordination Action in FP7)

Main goal of the FP7 EU Coordination Action “Fusion Energy Materials Science (coordinated by IPP) is to foster the integration of universities, research centers and in particular large-scale research facilities like synchrotrons and neutron sources into the fusion materials community. During the first project year in 2009, 65 new collaborations were established and exchange of researchers took place. The project organized a workshop with ~60 participants and a summer school on micro-mechanical testing, providing in 10 lectures an overview in this field.

Scientific Staff

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Helmholtz-Russia Joint Research Group "Hydrogen Isotopes Retention in First-Wall Materials"

Heads: Dr. Matej Mayer (IPP), Dr. Anna Golubeva (Kurchatov Institute)

This joint research group comprises scientists from the IPP, from the Moscow Engineering and Physics Institute (MEPhI), and from the Kurchatov Institute (both located in Moscow, RU). The research group is funded by the Helmholtz Association.

Permeation of D through Clean and Carbon-coated W

The ion-driven permeation of deuterium through clean and carbon-coated tungsten was investigated in the PERMEX set-up at ion energies of 200 eV and temperatures of 550-675 °C. For pure W the lag time for permeation was 4 orders of magnitude larger than estimated from literature data due to trapping in defects. The recombination coefficient on the surface and a detrapping energy of (2.05±0.15) eV were estimated from TMAP 7 code calculations. The deuterium is probably trapped in a chemisorption state on the surfaces of internal voids or pores. Scanning electron microscopy analyses of sample cross-sections proved the existence of pores, the estimated concentrations agreed with the calculations.
Carbon films were deposited on the front side of the samples, and the permeation was measured at 600 °C. The carbon film was eroded during the measurements due to sputtering, and the film was completely eroded at the end of the experiment. In contrast to pure W, the permeation flux was almost zero for the first five hours of implantation. During that time the carbon film thickness decreased from 120 nm down to about 65 nm. Then, the permeation flux started to increase and reached a maximum at a remaining carbon thickness of 10-20 nm, the maximum flux was slightly higher than in experiments without the carbon film. Subsequent bombardment finally totally removed the carbon film and led to a decreased permeation at a steady state level. A carbon film with a thickness larger than the implantation range therefore suppresses permeation.

Retention of Deuterium in Different Tungsten Grades

Deuterium retention in tungsten was investigated for incident ion energies from 3.3 to 200 eV at temperatures of 320 and 500 K for two different polycrystalline tungsten grades and plasma-sprayed W (PSW). Three kinds of defects with trapping energies of 0.85, 1.45 and 2 eV were found in all materials. The traps are associated with grain boundaries/dislocations, vacancies, and pores, respectively. The majority of D in polycrystalline W irradiated with 20 and 200 eV was found in two trapping sites with trapping energies of 0.85 and 1.45 eV. The 2 eV trap site was only important for PSW. D at 3.3 eV occupies all types of trapping sites. The D retention increases with increasing ion energy. Seeding of helium into D plasmas with a He concentration of 10 % reduces the D retention for all investigated tungsten grades. A more significant reduction was observed for polycrystalline W, while a smaller effect was found for PSW. The presence of He modifies the density of existing traps, but does not modify the nature of the traps. The He effect was more pronounced at elevated temperatures.

Release of D from High-energy Induced Defects in W

High-energy radiation-induced defects were created in polycrystalline W by a 10 keV D_3^+ beam. D desorbs from the traps in several peaks at temperatures of 390, 450, 540, 630 and 750 K. The peak at 750 K can probably be attributed to D trapped in vacancy clusters. These defects are annealed at temperatures in the range of 1073-1273 K. The peak at 630 K can be attributed to D trapped in pores formed during irradiation/annealing cycles. Scanning electron microscopy studies in the HELIOS device showed the presence of radiation-induced pores with an average size of 20 nm in a thin near-surface region. Defects corresponding to the peaks at 390, 450 and 540 K are annealed rather slowly and can be attributed to dislocations and dislocation loops, grain boundaries, and vacancies.

Influence of Impurity Layers on the Trapping of D in W

The impact of BeO layers on D retention in W was modelled by replacing Be by Al. D retention in pure and Al_2O_3-coated polycrystalline W was studied under plasma irradiation at 570 K with 150 eV/D. For thin alumina layers an increase of the amount of trapped D is observed. The influence of surface layers created by boronisations was studied by installing W samples in ASDEX Upgrade during boronisations and subsequent D irradiation in laboratory investigations. Boron strongly suppresses D diffusion into W.

Permeation of D Gas through Coated Carbon Materials

The influence of coatings on the gas driven permeability of fine grain graphite during exposure to hydrogen gas or an ECR plasma was studied. 60 and 600 nm thick a-C:D layers as well as 0.47 to 3 µm thick W coatings were deposited on fine-grain-graphite and the gas-driven permeation was measured. During plasma exposure the typical flux was 5×10^{19} ions/s·m^2. The gas permeability of graphite is determined by molecular transport through the system of open porosity, which connects the front and back surfaces of the membrane. For deposited W layers with thicknesses up to 3 µm there is no pronounced difference in the permeabilities of coated and uncoated fine grain graphite, although the mean pore size (0.6 µm) is much smaller than the coating thickness of 3 µm. The small influence of the coating is explained by incomplete coverage of the rough graphite surface with the deposit, so that the system of connected porosity remains open.

Scientific Staff

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Plasma Theory

Theoretical Plasma Physics

Heads: Prof. Dr. Sibylle Günter, Prof. Dr. Per Helander

The project “Theoretical Plasma Physics” is devoted to first-principle based model developments and combines the corresponding efforts of the divisions Tokamak and Stellarator Theory, of three independent Junior Research groups, and of the HLST Core Team of the EFDA HPC initiative. To exploit synergies between astrophysical and fusion plasmas, a collaboration between IPP and the Max-Planck-Institut für Solar System Research (MPS) has been started.

Tokamak Physics Division

Head: Prof. Dr. Sibylle Günter

Tokamak Edge Physics Group

A significant effort went into benchmarking various versions of SOLPS (as part of an ITM activity); further developing SOLPS (in collaboration with CNRS-Paris, State Polytechnical University of St Petersburg); and the development of a new kinetic approach.

A number of test cases have been run with both the SOLPS4 version of the code (as used by ITER) and the newer SOLPS5 version of the code. For pure hydrogen cases good agreement was obtained; for cases with C a significant source of the observed differences was traced to the use of older atomic physics rates used in SOLPS4 compared to the use of more recent ADAS data in SOLPS5.

The SOLPS6-B2.6 project has proceeded to convert the core solver of B2.6 to the newly developed more flexible data structure and numerical scheme necessary to support adaptive grids. The new B2.6-structured version of the code contains all components necessary for the solution-driven grid adaptation algorithm. It can adapt the grid resolution at run-time within the constraint of a logically structured grid. First runs on benchmark cases for this code show promising results.

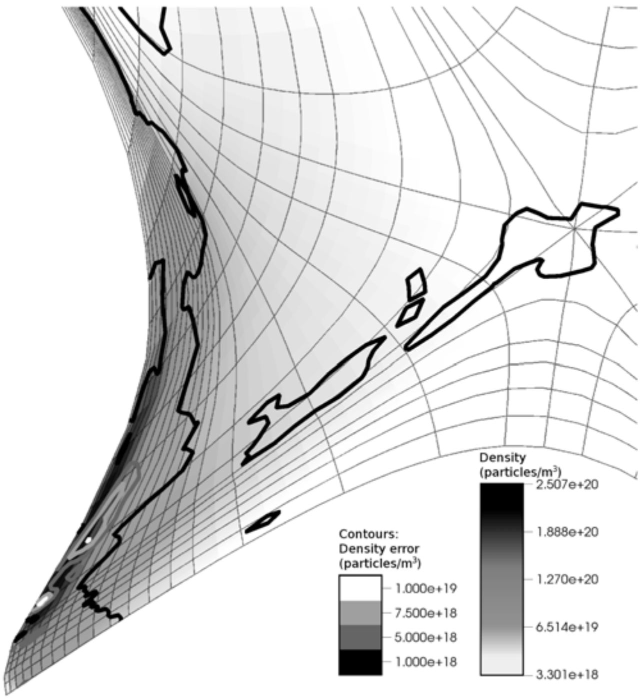

Figure 1: Ion density solution of a B2.6-structured simulation on a solution-adapted grid with 1056 cells. Contours show error with respect to the reference solution obtained on a grid with 8580 cells.

The integration of the new high resolution finite volume scheme is underway, resulting in the code version B2.6-unstructured supporting fully unstructured grids, which will be available in 2010. Work on a kinetic module for the B2 fluid code has progressed. Separate programming units describing parallel electron dynamics in the SOL, including the Debye sheath and Coulomb collisional relaxation, are presently available. Before the two units can be combined, however, further programming is planned, aiming at increasing the speed and stability of the unit describing Coulomb collisions.

Significant effort from the group has also gone into the EFDA Task Force on Integrated Modelling (IMP1 and IMP3), the EFDA Goal Oriented Training Program in Theory (GOTiT) and the FP7 EUFORIA project.

MHD Theory Group

Heat Transport across Magnetic Islands

The stability and time evolution of neoclassical tearing modes (NTMs) strongly depends on the flattening of the temperature at magnetic islands. For robust predictions, it is therefore essential to gain insight into the experimental heat transport processes. Diffusive heat transport across magnetic islands has been modelled for ASDEX Upgrade and TEXTOR discharges and the simulation results were compared to the electron temperature measured by electron cyclotron emission imaging (ECE-Imaging). The experimental data was reproduced very precisely which allows to draw conclusions for the effective heat diffusion anisotropy, $\chi_{||}/\chi_{\perp}$, at the magnetic island. The anisotropy values obtained with this method are by two orders of magnitude lower than expected according to the Spitzer-Härm theory, which is a strong indication that heat transport across magnetic islands is governed by the heat flux limit.

Resistive Wall Mode (RWM) Studies

In the OPTIM code, which deals with feedback stabilitsation of RWMs, the scheme accounting for the influence of a time delay between sensors and actuators has been improved. The matrix describing the feedback controlled RWM model is represented as a power series in the delay time. The coefficients of this power series can be computed to arbitrary order (however, with strongly increasing numerical effort). The previous first order scheme is superseded. The old scheme was quite accurate for delay times of about 0.1 ms, whereas the new scheme allows for delay times up to about 1 ms, depending on the modelled situation. A feedback benchmark study between the VALEN and STARWALL/OPTIM codes has been carried out. The behaviour of the feedback controlled system in dependence of the gain and the toroidal phase shift of the feedback response have been compared for a simple test case. Reasonable agreement between the two code packages has been found for growth rates and rotation frequencies of the modes.

3D Computations of Non-axisymmetric ITER Equilibria

Three planned Test Blanket Modules (TBMs) and 18 toroidal field coils break the axisymmetry of the ITER magnetic field. The plasma response to these non-axisymmetric fields was studied quantitatively. To this end, self-consistent, three-dimensional, free-boundary equilibria of type ITER scenario 4 were computed with the 3D free-boundary VMEC/NEMEC code for various volume averaged β-values (β=2.24 %, 3.66 %, and 4.67 %). The resulting 3D equilibrium magnetic fields were then compared with the corresponding axisymmetric fields on which the vacuum perturbation fields were superimposed. The observed plasma response to the ripple and TBM perturbation fields is negligibly small. Comparing the flux surface geometry and the magnetic field ripple, only negligibly small differences were found. The observed maximum ripple differences are smaller than 10 %. Therefore, no significant effect concerning particle losses is expected for self-consistent 3D equilibrium fields.

Kinetic MHD and Fast Particle Physics

The drift-kinetic code HAGIS has been extended to follow fast particles across the separatrix. Direct comparisons of the simulated fast ion losses and the experimental Fast-Ion-Loss-Detector measurements at ASDEX Upgrade were carried out. Multi-mode simulations (TAEs, BAEs, ACs) with realistic distribution functions revealed the details of the coupling mechanisms in real and velocity space. Not only the radial overlap of two modes controls their saturation amplitudes but also the orbit width of a specific class of fast particles that are resonant with both modes. This leads to a resonant coupling of the two modes although their frequencies are very different. The physics of IRCH driven BAE modes at ASDEX Upgrade was investigated using the LIGKA code. Diamagnetic and trapped particle effects lead to a downshift of the mode frequency which is consistent with experimental measurements. Furthermore, in the presence of steep background density and temperature gradients the strong ion Landau damping of the BAE branch can be considerably decreased by diamagnetic effects. A numerical calculation of the resonant and non-resonant fast ion contribution showed that the mode drive is mainly due to the drift precessional resonance and that the existence criteria for a gap mode are fulfilled.

Linear MHD Stability Analysis

A comparative stability analysis between ASDEX Upgrade and DIII-D was carried out for a series of hybrid scenario discharges. In ASDEX Upgrade the confinement enhancement with power is due to an increase in pedestal confinement while it is due to an increase in core confinement for DIII-D. Linear MHD stability diagrams were calculated for one pair of low and high plasma β discharges for each ASDEX Upgrade and DIII-D plus a pair of high vs. low triangularity cases in DIII-D. The strong stabilizing effect of high triangularity on the plasma edge was demonstrated in the j-α-diagrams for DIII-D while no significant change of the stability threshold with normalized β_N was found. The latter finding can be explained by an increase of the pedestal width with increased NBI heating power in ASDEX Upgrade and no major change in the pedestal confinement in DIII-D with β_N. The relative position of the experimental reference points to the stability threshold confirms the peeling-ballooning model for edge localized modes (ELMs).

Stability Analysis of Vertical Displacement Events

The development of a non-linear, higher order finite element code has been continued. The aim is to predict growth rates and non-linear behaviour of the generalized positional instability of a plasma in the presence of finite resistivity structures like the passive stabilizing loops (PSL) of ASDEX Upgrade. Results underline the importance of taking into account the temporal changes in the current distribution in PSLs. Particularly near the transition from a resistive to an ideal wall instability the resulting effects on the growth rate are substantial. Present efforts aim at the implementation of projection boundary conditions which eliminate the artificial stabilizing effect of the computational domain boundary and at modifying the code for cases of finite plasma pressure.

Non-linear MHD Studies

The effect of an externally applied resonant magnetic perturbation (RMP) of single helicity on the plasma particle transport has been investigated based on two fluid equations. A sufficiently large RMP was found to flatten the local electron density profile around the rational surface as expected. With small or moderate amplitude of RMP, however, the local electron density is increased if the plasma rotates in the plasma current direction with a frequency larger than the electron drift frequency. In the opposite limit, the electron density is decreased and its local gradient may even become positive for a given constant perpendicular particle diffusivity.

Reconnection in Semi-collisional, Low-, Plasmas

Reconnection of semi-collisional, low-β plasmas has been studied numerically using a two-field description of the plasma including electron pressure effects (and hence kinetic Alfvén wave dynamics). Two model problems have been considered: the tearing unstable Harris sheet (with the global parameters of the Geospace Environment Modelling-challenge case) and – exemplary for a driven reconnection situation – two coalescing islands, starting from a non-equilibrium situation. The qualitative differences observed between spontaneous and driven reconnection cases and their scaling behaviour are best understood by considering the reconnection rate as a triple product of outflow Mach number, outflow to inflow channel width ratio, and magnetic energy density at a height above the *X* point.

Transport Analysis Group

In the field of electron particle transport, theoretical and numerical studies focused on the dependence of density peaking on magnetic shear and collisionality in various turbulent regimes, ion temperature gradient (ITG) modes, and trapped electron modes (TEM). Consistently with previous results, the predicted density peaking decreases with increasing collisionality in the presence of ITG turbulence, while it is roughly independent of the collisionality in the presence of TEMs. While the density peaking is predicted to increase in the collisionless limit with increasing magnetic shear for all turbulent regimes, it does so for realistic collisionalities only in the presence of TEMs, while it becomes roughly independent of shear in the presence of ITG modes. These theoretical results provide a qualitative explanation of the differing experimental observations in L-mode and in H-mode plasmas. The impact of electromagnetic effects on the transport of light and heavy impurities in tokamak plasmas was investigated by means of linear gyrokinetic calculations with the code GYRO and of analytical derivations with a fluid model. Diffusive and convective contributions were separated and both ITG and TEMs were analysed. The dominant contribution from magnetic flutter transport is of a pure convective type but smaller than 10 % of the E×B transport. A significant impact on the impurity transport due to an increase of the plasma normalized pressure parameter β is observed in the case of ITG modes, while the effect remains weak for TEMs. Under realistic conditions of high β plasmas in H-mode with dominant ITG turbulence, the impurity diffusivity is found to decrease with increasing β in qualitative agreement with recent observations in tokamaks. The toroidal momentum transport in the presence of TEMs was studied by means of quasi-linear gyrokinetic calculations. The Coriolis drift term has been implemented in the gyrokinetic code GS2 specifically for the completion of this work and has been successfully benchmarked against independent implementations in the GKW and GYRO codes. In the presence of TEMs, despite of a weaker symmetry breaking of the eigenfunctions with respect to the case of ITG modes, a pinch of toroidal momentum is produced under most conditions. The toroidal momentum viscosity was also computed and found to be small as compared to the electron heat conductivity but significantly larger than the ion heat conductivity.

Kinetic Theory and Wave Physics Group

An analytic study with the aim of understanding the relevance of aberration effects on the propagation and absorption of waves in the electron cyclotron frequency range has been carried out. Deviations from a paraxial (beam-tracing) description can arise in the presence of strong absorption combined with spatial dispersion. These effects, however, are rather small for realistic (e.g. ITER) parameters. A feasibility study of electron cyclotron heating in reversed field pinch plasmas has been performed using the TORBEAM code and has shown that high current discharges are accessible to standard heating schemes.

The quasilinear solver SSFPQL of the full wave package TORIC has been extended to include a model of fast particle losses in the Fokker-Planck equation (with the byproduct that the numerical scheme has also been considerably improved). A synthetic neutron diagnostic has been implemented. This allows an investigation of synergy effects between ICRH and NBI heating. A model for the evaluation of the quasillinear ion heating operator (using the wave fields calculated by TORIC), to be implemented in Monte Carlo simulations, has been developed. Within the framework of a collaboration with the MPI für Sonnensystemforschung, a novel routine has been developed for the solution of systems of partial differential equations coupled to ordinary differential equations, its new feature being the possibility to handle ill-posed problems by extracting only a partial information on the solution. This procedure is intended to be the engine of a steady state quasilinear solver for ion cyclotron heating of the (fast) solar wind.

Neoclassical processes under the conditions typical of the edge of H-mode plasmas (strong electric field, density and temperature gradient lengths comparable with the poloidal gyroradius) have been studied employing the delta-f code HAGIS. In particular, the bootstrap current and the Pfirsch-Schlüter current have been determined. Deviations of the numerical results from the standard neoclassical theory valid for smaller gradients have been found, but they are less strong than according to recent theories regarding the effect of orbit squeezing in such electric fields.

A model for the treatment of a magnetic island in a gyrokinetic flux tube spectral code has been derived and implemented in the turbulence code GKW together with the appropriate diagnostics. First results confirm the non-linear coupling between microinstabilities and large scale electrostatic fluctuations (of the size of the angular extension of the island) previously found in PIC simulations.

Development of Mathematical Tools

Large scale instabilities not immediately terminating a discharge often result in periodic non-linear perturbations of the plasma (sawteeth, fishbones, ELMs, NTMs). A low-dimensional description of their dynamics is desirable to qualitatively understand their reaction to changes in the driving parameters (e.g. heating power) or to illustrate the possible action of control techniques (e.g. pellet injection for ELM mitigation, etc.). The model system considered depends on three parameters and shows a rich variety of bifurcation phenomena. Sawteeth solutions occur if the system is singularly perturbed.

Turbulence Theory Group

Progress was made on a wide front in both analytical and computational efforts. Gyrokinetic theory was extended to the strong E×B flow regime in a way not dependent on the use of a local frame, compatible with the global MHD component of the general dynamics. Global gyrokinetic electromagnetic turbulence simulations with a particle in cell (PIC) model were demonstrated. Extensive results were obtained by a local gyrokinetic flux tube model for edge turbulence. Edge equilibrium flows and associated MHD phenomena were captured by total-f gyrokinetic computations. A new conformal coordinate system was derived for the X-point region. Additional theoretical efforts were begun to study turbulent collisionless reconnection under collaboration with the MPS institute and for non-linear drift wave dynamics.

Gyrokinetic Study of Core Turbulence

The major development is the clear demonstration of global electromagnetic turbulence with a PIC model, a longstanding aim in the field. A model is only properly global when it treats the entire volume within a given boundary flux surface. Many models are full-radius in the sense of limitation to large toroidal mode number. Others avoid treating coordinate singularity at the magnetic axis. NEMORB, the electromagnetic successor to ORB5 has managed to avoid both constraints. Turbulence is found in intermediate scales between the toroidal minor radius and the ion gyroradius, but with energetic contact to both large scale MHD and to small scale microturbulence. The fluctuations in the parallel current, shown in figure 2, are free of noise. The advances of previous years with the ORB5 code in long-term collaboration with CRPP/Lausanne have been incorporated into NEMORB within the ongoing collaboration.

Thermodynamic saturation of turbulence depends on the existence of an energy sink into which free energy liberated from the gradients can flow. It is necessary but not sufficient to have free energy conservation in the collisionless part of the system. Physically, this dissipation is done by collisions. The gyrokinetic collision operator includes spatial diffusion. In practice, collisional scales are not reached by the resolution of computations for core turbulence, so the energy is contained by subgrid dissipation. In a fluid model this is artificial viscosity. In a PIC model it is done via thermostatting. Successful implementation of this into NEMORB allows turbulent saturation to be well represented.

The ITER core is expected to be electromagnetic according to the normalized parameters governing turbulence, chiefly the ratio of the drift frequency of E×B eddy vorticity to the transit frequency of Alfvén responses along the magnetic field lines around one poloidal circuit. Although the original Cyclone benchmark was electrostatic the actual case was deeply electromagnetic, as found in our previous gyrofluid studies. NEMORB allows study of this dynamics without assuming particular relationships between the turbulence and global MHD phenomena. Turbulence is a highly non-linear dynamical system in which much of the energy resides for significant time in components which do not involve instabilities. It is now possible to determine which component of the overall system play the leading role. Subsequent advances in the computational implementation will allow ITER sized systems and together with theoretical advances a unified computation involving the MHD background.

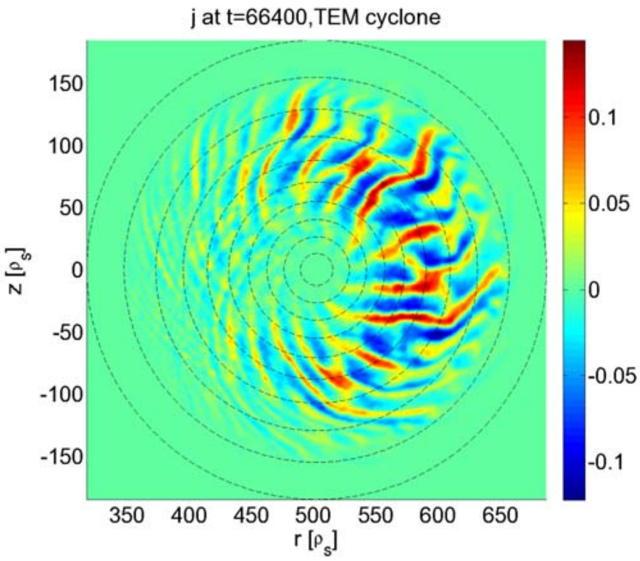

Figure 2: Contours of the parallel current in the poloidal plane. Large scale structures are found which persist for a few eddy turnover times. The dynamics is free of small-scale fluctuations due to the thermostatting which provides the PIC equivalent of subgrid dissipation which is required for proper thermodynamical behaviour. The distances are in units of the ion gyroradius.

Gyrokinetic Study of Edge Turbulence

A large series of edge turbulence parameter scalings was run with the fluxtube delta-f gyrokinetic model delta-FEFI. Detailed diagnostics now show the runs routinely satisfy energetic consistency, critical for edge turbulence due to the coupling to mesoscale MHD. The new studies have uncovered strong differences in the sensitivity to both magnetic and E×B velocity shear compared to the gyrofluid model GEM run at the same parameters. The annulus total-f edge model FEFI was advanced to capture neoclassical flows and bootstrap current in the presence of self consistently evolving profiles. Canonical toroidal momentum was found to be as well conserved as particles, energy, and entropy (about 10^{-4}). Addition of a conservative collision operator produces bootstrap flows and currents.

A new conformal coordinate system was derived for turbulence studies in the vicinity of the X-point in a separatrix equilibrium. The mathematical properties were explored in detail besides having this built into an annulus gyrofluid model GEMZ. The conformal property avoids coordinate deformation, facilitating multigrid computation as well as better representing turbulence, which is close to isotropic at small scales.

Fundamental Theory

The origin of the FEFI code is a Lagrangian field theory model by Naoaki Miyato et al. Its link to MHD is a novel development. The total-f gyrofluid model GEMX, which depends on it, is being reworked.

New analytical work was started which should allow better understanding of phenomena such as the non-linear drift wave instability and blob/filament structure in the density and vorticity. Work was also started on turbulent collisionless reconnection in collaboration with the MPS institute in Katlenburg-Lindau, using gyrofluid and gyrokinetic models.

JET

The disruption simulations of the thermal quench of JET shot #73122 have been continued. Various disruption shots have been analyzed using the new fast IR camera with respect to a broadening of the power fluxes onto divertor structures.

EFDA Task Force on Integrated Tokamak Modelling (ITM)

IPP continued to play an important role in the ITM providing a deputy leader for IMP1, the leader and a deputy for IMP3 and the leader for IMP4. Significant effort has gone into the development of the European Transport Solver (ETS) in IMP3 and its verification and validation.

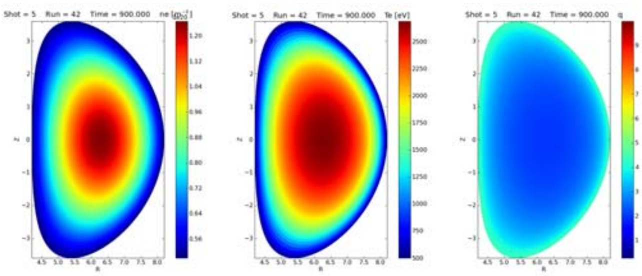

Figure 3: From left to right, the electron density, the electron temperature and the safety factor for a simulation with the ETS of an ITER-like discharge.

EFDA Goal Oriented Training in Theory (GOTiT)

IPP continued as coordinator of GOTiT, as well as leader of WP2 (High Level Courses). Three high level courses ("Optimisation and Parallel Computing" at CCFE Culham, "Single Particle Physics and Monte-Carlo Methods" at KTH Stockholm and VTT Espoo, and "Magnetic Control of Tokamak Plasmas" at the University of Naples) have been organized by IPP. The web pages for the GOTiT project have been completed. The two IPP GOTiT trainees were hired.

EU FOR Iter Applications (EUFORIA)

IPP continued as a member of the EUFORIA project funded under the 7th Framework Programme of the Commission, playing a major role in the management of the project and in the development of fusion relevant workflows based on Kepler, GRID, and HPC technologies. Presentations about EUFORIA and the ITM were made at workshops in Santander, Spain, Veli Losing, Croatia and Lyon, France.

MHD-TG

All the tasks in WP09-MHD-01 made significant progress, with clear and new results. The close collaboration between experiment and theory/modelling allowed for qualitative and quantitative comparisons between measurements and code results: not only mode frequencies, damping/growth rates and mode structures but also losses due to wave-particle interaction could be studied and interpreted in detail. This process increases significantly the validity and the reliability of the fast particle diagnostics and the numerical tools for diagnosing and predicting ITER stability boundaries and fast particle transport in a burning fusion plasma.

TTG

IPP is strongly involved in the EFDA Transport Topical Group coordinated research activities, in terms of leadership, by means of a vice-Chair position, as well as by taking active part in research projects under EFDA task agreements. In particular, ASDEX Upgrade and its Team have been involved in the research dedicated to the study of long-range correlations at the confinement mode transition, to the transport of impurities in the core, hosting experiments by external European colleagues, as well as to the physics at the plasma edge and scrape-off-layer, where it is the pole of a wide European collaboration. In addition, several diagnostics, such as the reflectometry system, the Langmuir probes, the Thomson scattering and the charge exchange recombination spectroscopy systems, have been and/or are currently upgraded in order to answer to specific needs identified within the EFDA Transport Topical Group research priorities.

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Stellarator Theory Division

Head: Prof. Dr. Per Helander

Ideal MHD

The CAS3D code has been used to (i) assess the ideal MHD stability of plasma equilibria and (ii) calculate perturbed equilibria. Within recent configuration optimisation studies done in collaboration with KURCHATOV NIFS (Russia), the global stability properties of quasi-symmetric plasmas were determined to verify the local stability properties enforced in the optimisation process. The perturbed-equilibrium option was applied to evaluate the 5/5-island size in W7-X-type equilibria that were part of a study on the effects of bootstrap current on the magnetic configuration of W7-X. The CAS3D code package has also been transferred to ANU. (Canberra) to prepare for a collaboration employing Bayesian inversion methods to constrain equilibrium and stability theory of advanced magnetic confinement experiments ahead of ITER.

Global Particle-in-cell Simulations of Electromagnetic Modes

Global linear gyrokinetic particle-in-cell simulations of the fast particle destabilized Toroidal Alfvén Eigenmodes and the Energetic Particle Modes have been performed using the code GYGLES. Current driven modes (the kink mode and the collisionless m=2, n=1 mode) have been simulated in a screw pinch geometry. Simulations of such modes in tokamak geometry require modification of the background distribution function to account for the necessary anisotropy with respect to the parallel velocity. In future simulations, it is planned to treat the polarisation density exactly using a generalized solver. Simulations with this solver can become computationally expensive because of the very large matrices appearing in the equations for the electromagnetic field. To use the generalized solver in tokamak geometry, the matrix operations in the code GYGLES have been optimized in collaboration with the HLST group in Garching.

Kinetic MHD

The EUTERPE code has been extended to be able to calculate growth or damping rates of Alfvén eigenmodes from ideal MHD perturbatively. The code has been coupled to the CKA code which calculates eigenfunctions within the framework of reduced ideal MHD. The growth rate is obtained estimating the wave particle energy transfer. First benchmarks with CAS3D-K show encouraging results.

Continuum Damping

If the gaps in the continuous Alfvén spectrum are closed, global Alfvén eigenmodes start to interact with the continuum which leads to a damping. This well-known process can be understood as phase mixing in analogy to Landau damping of plasma oscillations.

While the conventional way to calculate continuum damping is to introduce an artificially small resistivity, a computational approach to the problem has been developed which is based on the Riccati method with a suitable path of integration in the complex plane. It is shown that the approach can be transferred to the Galerkin method used in three-dimensional ideal MHD codes like CAS3D and CKA. The new approach turns out to be more efficient with respect to resolution and computation time. So far, calculations have been carried out for large aspect-ratio equilibria with a few Fourier harmonics only. However, it is possible to extend the approach to fully realistic 3D equilibria from VMEC or similar codes. The calculated eigenfunctions and damping rates may serve as an input to kinetic MHD hybrid models like CAS3D-K, making it possible to bypass the problem of having singularities on the path of integration to evaluate the continuum damping accurately.

Monte Carlo Code Development

The ANTS (plasmA simulatioN with drifT and collisionS) code was validated using a wide range of benchmarks.
As a first application, the code was used to compute the thermal load on the vessel components of W7-X caused by losses of NBI particles. The simulations used a geometrical description of the vessel and its components obtained from ANSYS CAD data. It was established that, for intermediate values of , and realistic operational parameters, power flux densities beyond the design limits are delivered to sensitive components of the vessel. In cooperation with Chalmers University (Göteborg) the ANTS code and auxiliary codes were extended to simulate runaway electrons in tokamaks, and have been employed to compute particle losses due to the Dynamic Ergodic Divertor in TEXTOR.

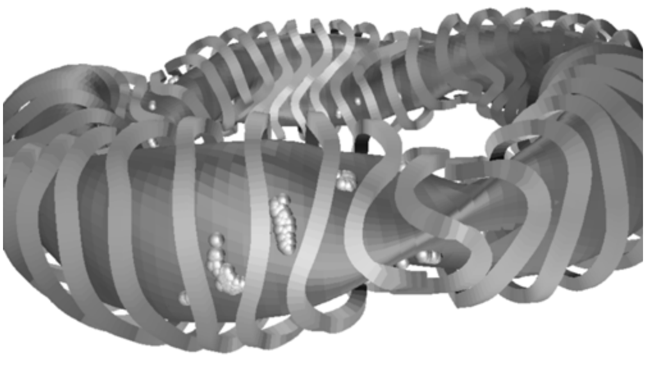

Figure 4: Sample strike points of energetic NBI ions as computed by ANTS.

Gyrokinetic Particle-in-cell Simulations

In collaboration with the Garching Computing Centre, the global three-dimensional gyrokinetic PIC code EUTERPE has been extended. The physical model now includes multiple kinetic particle species and electromagnetic perturbations.

As a first test, a global Alfvén eigenmode for a cylinder configuration was found and compared with similar results from GYGLES. Moreover, pitch-angle scattering collisions have been implemented for all species and tested by calculating neoclassical transport in a tokamak and comparing with results from the DKES code. EUTERPE can thus be used as a nonlocal neoclassical δf-code. An investigation of the influence of collisions on trapped electron modes in tokamak configurations is under way. Also a new equilibrium module has been written which allows the output from a newly developed mapping program. As an application of EUTERPE, utilizing the recently developed averaging solver and needing a global code, the Rosenbluth-Hinton initial-value problem for zonal flows has been simulated for different stellarator configurations (LHD, W7-X, HSX) including an external electric field (as e.g. given by neoclassical theory). The influence of the field on the residual zonal flow level has been investigated. The time development for LHD showed GAM oscillations consistent with the simple GAM estimate but additional oscillations with a much lower frequency were also found. For W7-X, only oscillations with a frequency different from the estimate were observed while for the HSX configuration, GAMs were damped out very quickly. It was found that a realistic electric field can increase the residual level by about a factor of two compared with the case without field for LHD and W7-X, while for HSX the field had only a minor influence.

Geometry Dependence of ITG Turbulence

Using the nonlinear gyrokinetic code package GENE /GIST turbulent transport has been studied in a variety of stellarator designs. The goal is to understand the geometry dependence of ITG microturbulence. This dependence not only makes the transport different in different devices, but also different in different flux tubes on the same flux surface. By using a set of flux tubes on a given flux surface, a picture has been constructed of the two-dimensional structure of the microturbulence. This structure can be related to various geometric quantities, such as the curvature, local shear, and effective potential in the Schrödinger-like equation governing linear drift modes.

Rotation in Stellarators

It has been shown that gyrokinetic turbulence, whether electrostatic or electromagnetic, usually cannot affect the large scale radial electric field and plasma rotation in non quasi-symmetric stellarators. If the magnetic field is perfectly quasi-symmetric, however, rapid rotation is formally allowed for, but leads to the appearance of a non quasi-symmetric centrifugal force and electric field within each flux surface. Since this field is not quasi-symmetric, particle orbits are no longer well confined and the confinement is degraded.

Pfirsch-Schlüter Impurity Transport

Neoclassical "Pfirsch-Schlüter " transport of impurities in a stellarator has been studied. Contrary to the tokamak case, where the only contribution to the neoclassical particle fluxes comes from friction, in a stellarator there is an additional source of transport due to anisotropy between parallel and perpendicular pressure. This term is small but causes the transport to be non ambipolar. Thus, the impurity transport behaves approximately as in a corresponding tokamak, but the radial electric field does not.

NBI Current Drive

Standard calculations of neutral beam current drive consider only the beam driven current and the accompanying electron response (the so-called Ohkawa current) while ignoring any reaction of background and impurity ions. A more accurate approach which fully accounts for parallel momentum conservation of the beam particles with a plasma containing an arbitrary composition of ion species was developed employing a formulation which may be considered a generalisation of the classical Spitzer problem to treat the case of arbitrary collisionality. This approach, which has also been used successfully to account for momentum conservation in calculations of the bootstrap current and ECRH current drive, makes use of a mono-energetic parallel transport coefficient to characterize an "effective trapped particle fraction" which is collisionality dependent. Implementation in the Greifswald 1D transport code has shown, however, that the NBI driven current calculated using this approach is only modestly increased (by 10-20 %) for reference W7-X scenarios due to a partial cancellation of the various new physical effects which it includes.

Progress in ECCD Calculations: Parallel Momentum Conservation and Collisionality Effects

A simple and fast numerical model, which approximates a weakly relativistic solution of the Spitzer problem in the collisionless limit with parallel momentum conservation, has been implemented in the ray-tracing code TRAVIS developed at IPP. Additionally, the fully relativistic solver SYNCH (developed for the collisionless limit) has been included. For benchmarking against other codes (in particular the ray-tracing code TORAY with the high-speed limit model and the Fokker-Planck code CQL3D), the ECCD for the ITER reference Scenario-2 was calculated. Comparison of the results confirmed sufficiently high accuracy of the models implemented in TRAVIS. To include the finite collisionality effects, two different models were applied: a somewhat heuristic momentum-correction technique and a field-line-tracing technique (NEO-2 code). Preliminary calculations of the ECCD efficiency in a circular tokamak lead to the conclusion that in regimes where the collisional detrapping time is comparable to the bounce time, particle acceleration due to the magnetic mirroring force plays an important role in the generation of ECCD.

Predictive and Analysis Transport

Two techniques used for calculating the thermal neoclassical transport matrix (convolution of mono-energetic transport coefficients D_{ij} with a local Maxwellian) have been benchmarked within the International Collaboration on Neoclassical Transport in Stellarators. The plasma profiles for testing have been created at IPP for LHD using predictive transport modelling with neoclassical transport coefficients provided by the convolution based on a database of D_{ij} for this device and conventional interpolation in 3D parameter space. Then the resulting plasma profiles are analyzed by the LHD team using the neoclassical database DCOM/NNW, which implements a Monte Carlo code for creating discrete data sets and neural network techniques for interpolation during convolution with a local Maxwellian. The outcome of the transport analysis, the derived thermal diffusion coefficients and the radial electric field demonstrate very good agreement with the original prediction despite the quite different approaches used.

A new module for calculating the neutral beam current drive (NBCD) has been implemented in the transport code used for W7-X. The NBCD module solves the generalized Spitzer problem with the linearised collision operator for all plasma species, thus providing overall momentum conservation. Simulations with this new module have been carried out to assess heating scenarios using 'negative ion' NBI (n-NBI) at high densities $(1.8\text{-}3.0)\times10^{20}$ m^{-3}. The n-NBI is formed from negative Hydrogen ions and has energy 150-300 keV, allowing central power deposition for high densities and thus much higher heating efficiency than 'positive ion' NBI (p-NBI), which heats the plasma edge at these densities; in the p-NBI system the neutrals are produced by neutralisation of positive Hydrogen ions with energies of about 55 keV. The angle between the beam line direction of the n-NBI system and the magnetic field lines is about 37°, which provides favourable conditions for generating the current drive. For comparison, the 'radial' and 'tangential' beam lines of the p-NBI system have angles of about 68° and 58° with the magnetic field lines. It was shown that NBCD calculated with momentum conservation for all species has 10-20 % higher value than that derived from a traditional approach without momentum conservation in the ion contribution to the current.

Additionally, the current drive efficiencies for different plasma heating methods at the same plasma conditions (with central temperature T_0=4 keV and density $n_0=10^{20}$ m^{-3}) have been analyzed. The current drive efficiencies for X2-mode and O2-mode ECR heating are comparable where the absorption is maximal. However, the total currents are different; their values are 26.7 kA and 8.3 kA for the X2 mode and O2 mode, respectively. The NBCD efficiency is twice that for the ECRH X2 mode and nearly constant within two thirds of the plasma radius. The total current driven by the n-NBI is 66.2 kA. This is an important result for high-density operation of W7-X when O2-mode ECCD is not sufficient to control the bootstrap current or when NBCD is the only means of current drive in regimes above the O2 cut-off density.

Benchmarking of 3D-equilibrium Codes

The persistence of good flux surfaces in 3D stellarator configuration with finite beta is an important question. For its treatment 3D equilibrium codes like HINT2 or PIES have been developed relying on different numerical schemes for solving the equilibrium problem. As their results are usually similar but differ in details, a benchmarking activity among the laboratories NIFS, PPPL and IPP has been initiated to investigate and compare the codes HINT2 and PIES for reference W7-X and LHD configurations at high beta.

W7-X Configurations with Net Currents

The impact of non zero bootstrap current and its compensation with ECCD in W7-X reference configurations has been investigated in detail. Two scenarios for the so-called standard configuration with 5MW ECRH power at $n_0=10^{20}$ m^{-3} were investigated with regard to equilibrium and stability properties. In the first scenario, the bootstrap current was allowed to freely evolve on the L/R time scale of about 40 s, whereas in the second scenario proper ECCD was applied to compensate the final bootstrap current. In the latter, the time evolution is on the time scale of the internal skin time of about 1s and steady state profiles are reached after about 6 s. For both scenarios, interchange stability is maintained during the evolution. Only in the final state of the case with ECCD compensation a small ideal interchange unstable region is observed in the central part of the plasma where $\iota'<0$. Otherwise global stability is maintained in the final states. Further work is underway to investigate how the evolution in equilibrium, stability, and transport properties couple.

Equilibrium Recovery from Magnetic Diagnostics for W7-X

Based on a database of about 10,000 magnetic equilibria, a first study on the prospect of recovering equilibrium information from the foreseen magnetic equilibrium diagnostics has been started. The diagnostics considered consist of two diamagnetic coils near the two main symmetry planes, four saddle coils and 19 segmented Rogwoski coils. Initial results show that the plasma energy can be recovered rather accurately. However, recovery of profile information on the basis of magnetic diagnostics is more difficult. For example, first studies based on a principal component analysis of the profiles in the database showed that the second principal components could only be recovered with an error of at least 20 %. More sophisticated analysis and recovery techniques based on Bayesian Theory and Integrated Data Analysis need be tested to see whether this can be improved.

Edge Transport Modelling Using EMC3-EIRENE

The 3D edge transport code EMC3-EIRENE has been used for a variety of problems.

Particle handling capability of the W7-X divertor: The particle control capability of the W7-X island divertor was examined and assessed numerically. The large islands and the high densities expected within them under high recycling conditions in W7-X effectively prevent the recycling neutrals from fuelling the plasma core. This indicates that high density plasmas in W7-X would necessitate additional central particle fuelling. In this case, the island divertor must be capable of pumping out the externally fuelled particles to maintain global particle balance. Simulations have shown that an efficient particle pumping requires a close positioning of the strike point to the chamber entrance, which, however, conflicts with power handling. To solve this problem, additional thermal shielding plates are considered and their compatibility with particle exhaust has been assessed numerically. In addition, a systematic sensitivity study of plasma and neutral transport to the island topology modified by plasma currents and finite-β effects has been initiated to find optimum particle pumping conditions in both configuration and plasma parameter space.

Simulatons for AUG: The EMC3-EIRENE code was implemented at ASDEX-Upgrade. After a successful benchmark with SOLPS for a 2D configuration limited by an axisymmetric inner heat shield, the code was applied to simulate 3D limiter plasmas and has been compared with Li-beam and ECE diagnostics. Moreover, EMC3-EIRENE has been adapted and optimized for the poloidal divertor configuration and successfully tested for a divertor discharge in AUG.

Impurity modelling during ITER start-up: For the low temperature, high transport plasma conditions in the initial phase of the ITER start-up process, the main radiating Be ions are typically driven deeply into the core before getting fully ionized, adding large core contributions to the Be radiation. These contributions have been estimated by a 1D diffusive transport and ionisation model for the radiating Be ions using realistic constant values of plasma density, temperature and diffusion coefficient in the core. The 1D model was represented by appropriate boundary conditions at the SOL upstream boundary, thus avoiding a time-consuming iteration between the SOL and the core transport.

Alpha-particle Orbits in Presence of Resonant Magnetic Field Perturbations Shielded by the Plasma

In tokamaks, resonant magnetic perturbations (RMPs) are often efficiently shielded by the plasma, which results in the elimination of islands produced by RMPs within a few ion gyroradii of resonant magnetic surfaces. Resonant unperturbed drift surfaces of alpha particles depart from the resonant magnetic surfaces by much larger distance. As a result, the effective radial magnetic field experienced by their resonant drift orbits is much larger than for the field lines. This effective field is only one order of magnitude smaller than in the vacuum. Nevertheless, even this much smaller reduction of drift-surface islands makes losses of passing alpha particle being negligible in ITER.

Effect of the Toroidal Current on the Island Position in W7-X

The VMEC/MFBE code package has been used to investigate the effect on toroidal current on the island position for the standard W7-X configuration. For given β of 4 % and varying toroidal currents from 0 kA to 64 kA, the o-point of the top island (located near the divertor) in the bean shaped cross section is shifted up in z-direction by about 10 cm and by -10 cm in r-direction. A linear dependence of the shift on the toroidal current was found.

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Max Planck Junior Research Group "Turbulence in Magnetized Plasmas"

Head: Priv.-Doz. Dr. Wolf-Christian Müller

Fundamental Properties of Turbulence

The investigation of fundamental statistical characteristics of turbulent plasma flows is of interest for physical systems which range from nuclear fusion plasmas to geo- and astrophysical turbulence. Lagrangian analysis of three-dimensional large scale direct numerical simulations of magnetohydrodynamic (MHD) and Navier-Stokes turbulence involving the Lagrangian energy spectrum has led to a better understanding of non-linear energy transfer in MHD turbulence by allowing the identification of weak and strong non-linear interaction mechanisms. This aspect is crucial for a validation of present theories of MHD turbulence.

The Eulerian investigation of anisotropic MHD turbulence has revealed a surprising isotropy of inertial range scaling invalidating all currently discussed theories of such flows. Dynamic anisotropy appears, nevertheless, by a direction dependent Reynolds number.

The direct analysis of non-linear turbulent interactions by examining all existing wavenumber triads of numerically simulated turbulent systems has shown that non-linear energy dynamics of 3D MHD turbulence is spectrally local in wavenumber – in contradiction with the prevailing view found in the literature.

Compressible Turbulence

Understanding compressible MHD turbulence is key to describing magnetized turbulent flows observed in astrophysical plasmas. Within the Cluster of Excellence 'Origin and Structure of the Universe' which supports this project financially, the efforts to study supersonic and super-Alfvénic turbulence focus on turbulent dynamics which are probably of importance for star- and structure-formation in the interstellar medium.

The development of a compressible 3D-MHD simulation code (KT-MHD) has been completed, allowing for numerical investigations of statistically steady-state turbulence in various configurations. In a recent benchmarking against current cutting-edge compressible MHD codes, the KT-MHD code has shown excellent results in combination with high numerical cost efficiency. The validity of compressible extensions to established turbulence models such as in Fleck's model for compressible turbulence is currently scrutinized. This includes spectral scaling properties of the turbulent velocity, the kinetic energy, and the density weighted velocity. Additionally, the contributions of conservative vs. non conservative spectral flux terms within the turbulent cascade are considered.

Large Scale Magnetic Structure-formation

A previously found universal scaling relation which links magnetic helicity with other important spectral quantities of three-dimensional MHD turbulence like kinetic and magnetic energy, as well as kinetic helicity has been examined with regard to its significance for astrophysical problems. The relation, for the first time brings out the contribution and importance of kinetic helicity in the inverse cascade process of magnetic helicity.

Based on direct numerical simulations of MHD turbulence, an explanation to large scale magnetic structures like radio relics in clusters of galaxies has been suggested. It is proposed that forced turbulence initiates the structure formation in radio relics while the finally observed large scale magnetic structure is a result of decaying turbulence, which dominates after the forcing ceased to exist. In planets, stable magnetospheres might be a result of inverse cascade of magnetic helicity which is responsible for large scale magnetic structure formation, after the initial magnetic fields are created through a dynamo process.

Turbulent Magnetoconvection

Magnetic dynamo action in a three-dimensional, turbulently convecting plasma has been studied using direct numerical simulations. This study addresses the need for the fundamental understanding of the dynamo mechanism by pushing the field of dynamo simulation forward in several ways. To this end, the Boussinesq equations for magnetoconvection are solved; this paradigm departs from the fully incompressible case by allowing compressibility to have certain limited effects on buoyancy, while at the same time preserving numerical efficiency. Also special boundary conditions (called pseudo-Rayleigh-Bénard) designed to allow natural flow formation have been implemented. These boundary conditions provide an alternative to the frequently studied, more restrictive Rayleigh-Bénard setup. Two particle relative dispersion, diffusion, and magnetic field line stretching are observed using Lagrangian tracer particles, a new and valuable technique in this setting. This project is financially supported in the framework of IPP's collaboration with the Max-Planck-Institut für Sonnensystemforschung in Katlenburg-Lindau.

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Helmholtz University Research Group "Theory and Ab Initio Simulation of Plasma Turbulence"

Head: Prof. Dr. Frank Jenko

The main goal of our research is to better understand the important unsolved problem of turbulence in magnetized plasmas. To this end, we also employ and extend ideas from fluid turbulence, non-linear dynamics, and statistical physics. Spanning a wide range of approaches, from simple analytical models to simulations on massively parallel computers, we address both fundamental issues as well as applications to specific experiments. Beyond this, we hope that our research helps to improve the general dialogue and cross fertilisation between plasma physics and neighbouring fields of science.

Global Simulations with the GENE Code

After having completed the development of a global version of the non-linear gyrokinetic continuum code GENE, the code was benchmarked carefully both linearly and non-linearly. In particular, extensive comparisons with the ORB5 code have been undertaken successfully. GENE has then been used to determine the scaling of linear growth rates and non-linear transport levels with the ratio ρ^* of the thermal ion gyroradius and the minor radius of the device. It was found that for medium size tokamaks like ASDEX Upgrade, there are moderate differences (of the order of 10 %) from the local (small ρ^*) limit, while for larger tokamaks like JET or ITER, differences tend to be negligible. Moreover, in flux driven (as compared to the more usual gradient driven) simulations, ballistic radial heat flux avalanches were observed. A closer examination will show if these features are sufficiently strong to break the so-called gyro-Bohm transport scaling.

Turbulent Transport of Energetic Particles

Recent experiments at various tokamaks (including, in particular, ASDEX Upgrade) indicate that there might be a significant interaction between fast ions and the background turbulence, in contrast to past expectations. The most convincing evidence along these lines so far is a study by W. Heidbrink and co-workers at DIII-D. As it turns out, these developments are supported by new theoretical insights. Using a combination of analytical and numerical investigations, it was discovered that the electrostatic cross-field diffusivity of energetic ions falls off only inversely proportional to the particle energy, while its magnetic counterpart is even energy independent. While these results seem to be able to explain the DIII-D measurements, to determine their applicability to AUG will probably require better profile data in future experiments. Interestingly, we were also able to transfer these findings to the problem of cosmic ray scattering in the solar wind turbulence. This way, a general scaling theory of cosmic rays could be derived.

Role of Turbulence in Laboratory Dynamos

In 1999, the first successful laboratory experiments of dynamo action could be performed at Karlsruhe and Riga. These flows were quite constrained, however, corresponding to a more or less kinematic situation. A few years ago, a new generation of dynamo experiments started operation, among them the Madison Dynamo Experiment, using basically unconstrained flows. So far, only one of these was successful, however, after having adapted the flow geometry. By means of magnetohydrodynamic (MHD) simulations in a bounded, spherical system with mechanical forcing, the influence of the turbulence strength (as characterized by the fluid Reynolds number) on the dynamo onset condition (as characterized by the critical magnetic Reynolds number) has been studied for the Madison experiment. It was found, among other things, that with increasing Reynolds number, the onset is delayed due to more vigorous turbulence both on large and small scales. At higher Reynolds numbers, the role of the small scale fluctuations becomes dominant, and one finds a small-scale dynamo whose critical magnetic Reynolds number saturates at a level which is 2-4 times above that which can presently be reached by the experiment. Several suggestions for modifications of the Madison experiment have been put forward and are about to being tested.

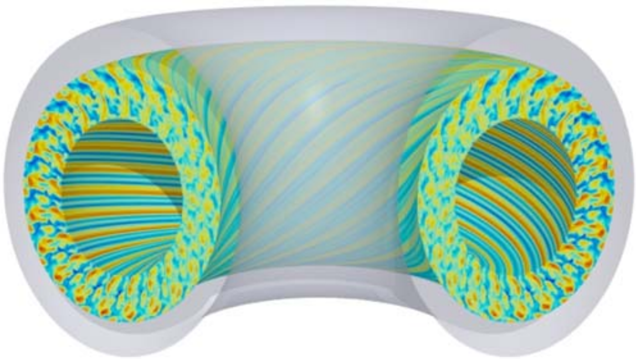

Figure 5: Snapshot of a gyrokinetic turbulence simulation in toroidal geometry using GENE.

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Helmholtz Junior Research Group "Computational Material Science"

Head: Dr. Ralf Schneider

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

The multi-scale model was extended further to study the flux dependence of chemical erosion. The basic idea is that due to the shielding of the carbon atoms lying in lower layers only few surface layers are accessible to the incoming hydrogen ions. This puts an upper limit on the released carbon flux. The model agrees very well with the experimental trends. The chemical erosion model has been coupled with the TRIM code treating collisional cascade effects. The hydrocarbon molecule formation probability is determined from the analytical model of Mech and the release probability is determined from the collision cascade physics within TRIM.

Silver Cluster Dynamics Using a GPGPU

A model has been developed to simulate the Ag cluster dynamics on an Ag substrate using Monte-Carlo methods. The code has been parallelized using the GPGPU (General Purpose Graphic Processing Unit). The results follow the experimental trends for the temperature dependence of cluster size distribution.

Kinetic Modelling of Complex Plasmas

Kinetic modelling of plasmas with PIC (Particle-in-Cell) methods was done in close collaboration with experiments at the Ernst-Moritz-Arndt University in Greifswald within the Transregio TR-24 project. In the simulations of capacitive RF oxygen discharges the formation of negative ions and their dynamics was studied. The simulations helped to understand observed double structures in the optical emission spatio-temporal profiles. The primary emission peak, taking place during the first quarter of the RF cycle, is produced due to dissociative excitation by the electrons expelled from the electrode by the growing sheath, whereas the secondary structure is due to an electron avalanche (visible as background pedestal in the electron velocity distribution in figure 6) started by electrons produced in detachment collisions of the negative ions with the neutrals close to the electrode, when the sheath drop is maximal. In figure 6 the plasma potential, charged species densities, electron velocity distribution function after ¼ of RF cycle and the 844.6 nm line spatio-temporal excitation profile obtained from the PIC simulation are presented. The spatial-temporal emission pattern, obtained in the simulations agrees very well with the one observed in the experiments.

In addition, the charging of a spherical, conducting dust grain confined in the sheath potential close to the wall was simulated. The ion drag force resulting from dust grain collisions with the streaming ions was calculated self-consistently. This force is critical for a realistic description of the dust particle dynamics and transport in fusion plasmas.

A newly developed 2D (rz) PIC MCC code was used to study two different ion thruster concepts - Stationary Plasma Thrusters (SPT) and High Efficiency Multistage Plasma Thrusters (HEMP-T), in particular the plasma properties in the discharge chamber due to the different magnetic field configurations. Special attention was paid to the simulation of plasma particle fluxes onto the thrusters' channel surfaces and the resulting erosion. In both cases, PIC proved itself as a powerful tool, delivering important insight into the basic physics of the different thruster concepts.

PIC simulations of sparking in the accelerating structure of the Compact Linear Collider (under development at CERN) were done in collaboration with the group of Kai Nordlund (Univerity of Helsinki) to simulate the surface damage self-consistently.

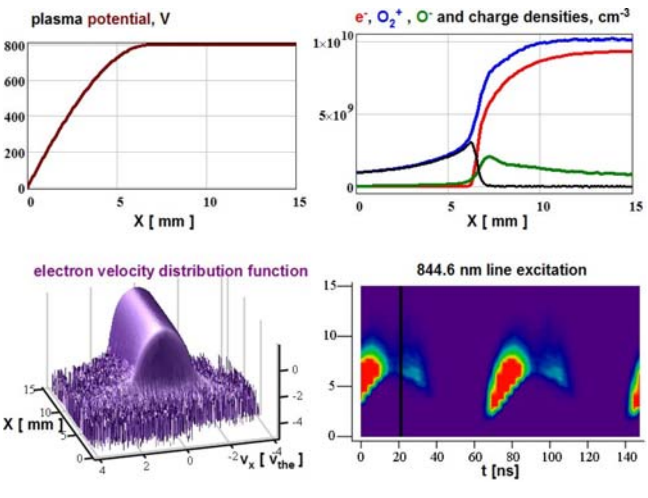

Figure 6: Plasma potential, charged species densities, electron velocity distribution function after ¼ of RF cycle and 844.6 nm line spatio-temporal excitation profile.

Scientific Staff

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Guests

A.R. Sharma (Emory University Atlanta), F. Taccogna (University of Bari), D. Tskhakaya (University of Innsbruck), I. Bizyukov (Kharkov University).

EURYI Research Group "Zonal Flows"

Head: Priv.-Doz. Dr. Klaus Hallatschek

The group focuses on the properties and interaction of large scale flows, a critical agent determining the level and deleteriousness of turbulence. Whereas in slab geometry only stationary zonal flows (ZF) exist, in toroidal systems, the coupling to pressure fluctuations allows oscillating geodesic acoustic modes (GAMs).

Geodesic Acoustic Mode Studies: Propagation and Geometry

The ability of GAMs to propagate radially can cause the formation of global eigenmodes or the nonlocal excitation of flows. The propagation is associated with the fluctuation energy flux of the GAMs, which on one hand is due to the magnetic drift of fluctuations in ion direction, and on the other due to plasma polarisation. Up-down symmetry leads to a neoclassical cancellation of both terms, leaving only finite Larmor-radius corrections at relatively large wave numbers where the GAMs are damped. However, an up-down asymmetric equilibrium such as a single null geometry yields GAM propagation even for long wave lengths. For warm ions, the curvature drift term dominates, whence the propagation direction corresponds to the ion drift direction at the position opposite to the X-point, i.e., GAMs propagate inward for ion drift toward the X-point and vice-versa. Reminiscent of the sensitivity of the H-mode to the ion drift, this fact inspires further search for a possible link with that phenomenon.

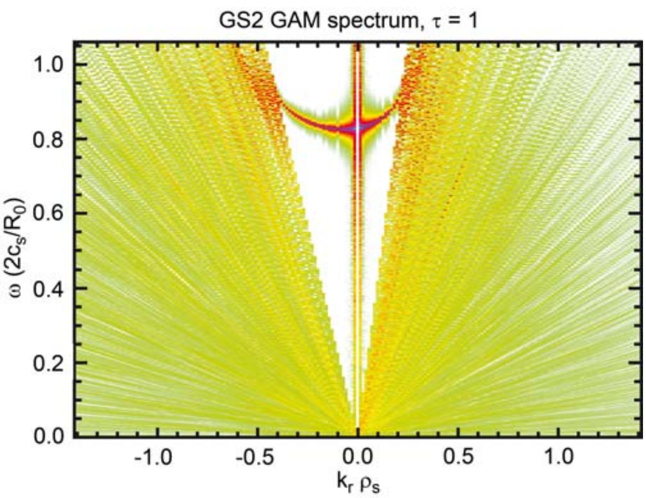

Figure 7: Example gyrokinetic GAM spectrum (GS2) for shifted circle geometry with. Propagation at long wavelengths is evident from the finite slope at zero wave number.

Zonal Flow Studies: Reynolds Stress Functional

The Reynolds stress response to ZFs determines the evolution and flow structures in tokamak core turbulence. Its functional form is restricted by symmetry, the flow saturation level, and the empirical existence of a preferred wavelength. A straightforward ansatz based on a single scale and symmetry reproduces the observed stresses in self-consistent computations. However, the response functional by itself fails to produce a *lower* limit for the wave numbers. Effectively, the wave number dependent terms restrict higher wave numbers to progressively lower non-linear amplitudes. Hence, a second scale is required to damp low wave numbers, and is also sufficient to reproduce the observed behaviour.

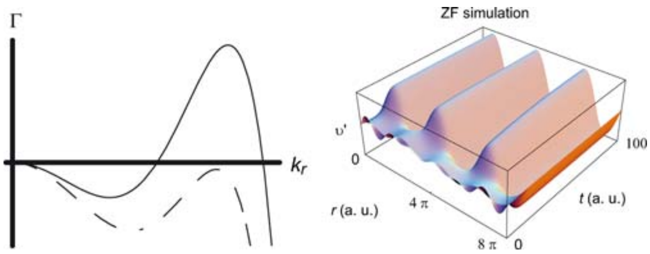

Figure 8: left: linear (solid) and non-linear (dashed) growth rate of ZFs including low wave number damping, right: self-consistent evolution of flow shear yielding a stationary final wavelength.

Zonal Flow Based Bifurcations in Drift Wave Systems

Surprisingly, well resolved NLET computer studies of resistive drift wave turbulence in a sheared slab have shown that this simple system exhibits a bifurcation of the density gradient associated with the excitation of zonal flows. For drift wave parameter the density profile transitions into a corrugated state in which it alternates between two different gradients. This seems to be the first example of a self-consistent first principles simulation of plasma turbulence exhibiting such a bifurcation. Drift kinetic effects cause a characteristic asymmetry of the flow pattern, which is currently being investigated.

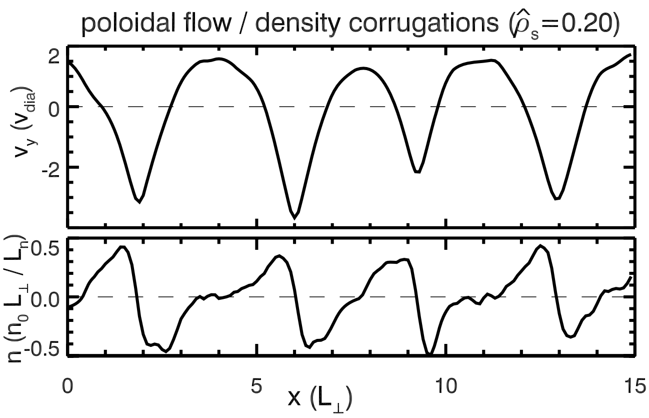

Figure 9: Flow (top) and density profiles (bottom) exhibiting a corrugated state in drift wave computation.

Scientific Staff

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High Performance Computer for Fusion Applications – High Level Support Core Team

Head: Dr. Roman Hatzky

Tasks of the High Level Support Team

The High Level Support Team (HLST) provides support to scientists from all Associates of the European Fusion Development Agreement (EFDA) for the development and optimisation of codes to be used on the dedicated High Performance Computer – for Fusion (HPC-FF) supercomputer located in the Forschungszentrum Jülich Supercomputing Centre (JSC). The HPC-FF supercomputer delivers computing power of roughly 100 teraflop/s and is optimally suited for the simulation programs in fusion. The HLST consists of a core team based at IPP Garching (Max-Planck-Institut für Plasmaphysik) and of other high level support staff provided by the Associates. At present the core team has five members and the high level support staff contributes additional seven scientists.

The HLST members are HPC experts with a background in developing large scientific applications and with particular expertise in numerical algorithms and in graphical support and visualisation.

The HLST provides support for the following tasks:

- Single processor performance optimisation,
- Parallelisation and optimisation of codes for massively parallel computers,
- Improvement of the parallel scalability of existing codes already ported to parallel platforms,
- Implementation of algorithms and numerical library routines, respectively, to improve the efficiency of codes,
- Visualisation of large data sets,
- Provision of consultancy to appointed HPC specialists from the Associates,
- Training for young scientists in the use of HPC systems and towards upcoming new computer architectures.

Further details about HLST can be found under the URL: http://www.efda-hlst.eu.

HLST Projects of the Core Team

Once a year a call is launched to invite scientists from the EFDA Associates to propose projects aimed at the improvement of existing codes and/or at development of new numerical tools which require support from the HLST. The HLST core team completed three projects which had been selected for HLST support.

BEUPACK Project

In the framework of the Broader Approach to fusion, EU and Japan have agreed to the establishment of a joint high performance computer centre in Rokkasho by beginning of 2012 (IFERC-CSC). The intent of the BEUPACK project was to prepare the fusion codes packaging for use as basis benchmark codes for IFERC procurement, and for that, get future reference data on HPC-FF as a reference system. The complete benchmark suit consists of six codes: ORB5, GENE, GEMR, JOREK, MDCASK and GYSELA.

The core team did the comprehensive coordination of the benchmarks. Realistic test cases both for weak and strong scaling had to be defined to investigate the scalability of the codes up to 4096 cores. Except of JOREK and GYSELA all benchmark results have been performed on HPC-FF by the HLST. In case of JOREK a severe technical problem had to be resolved which was caused by the hybrid MPI/OpenMP model in combination with the native MPI implementation.

GYGLES Project

The GYGLES code solves the linear gyrokinetic equations for electrons and one or more ion species in full tokamak geometry. The code revealed its limitations when it came to larger domain sizes in combination with a rigorous implementation of the polarisation density term in the quasi-neutrality equation. In such a case, the character of the matrix changed from a more dense to a more sparse type. As a consequence, the implemented algorithms for solving dense matrix equations, i.e. LAPACK and ScaLAPACK were no longer appropriate. Instead, a direct sparse solver from the IBM Watson Sparse Matrix Package (WSMP) was implemented. A memory reduction of the dominating matrix part of the code could be achieved by a factor of 20. Hence, simulations can now run on HPC-FF which would not have fit into the memory before. In addition, the scaling could be improved from 128 to 512 cores.

OPTGS2 Project

The aim of the project was a systematic study of Discontinuous Galerkin (DG) methods to find an alternative for resolving the performance bottleneck of the gyrokinetics code GS2, which arises from the implicit finite difference scheme used in the solver. Many different schemes have been implemented in a testbed.

For the one-dimensional linear advection model problem a generalized moment limiter in combination with an explicit Runge-Kutta time integration scheme preserving the total variation diminishing character of the spatial discretisation method provided the most promising results for the DG method.

Scientific Staff

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Supercomputing and other Research Fields

Computer Center Garching

Head: Dipl.-Inf. Stefan Heinzel

A major task has been the optimisation of complex applications from plasma physics, materials science and other disciplines. The prototype system for control and data acquisition of W7-X on the older and smaller device WEGA was enhanced and is used to prove the usability of control and setup tools for the physicists. The RZG is engaged in several large MPG, national and international projects in collaboration with other scientific institutions.

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), also data from institutes outside Garching, and supercomputer simulation data 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 both 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 MPG, national and international projects in collaboration with other scientific institutions.

Major Hardware Changes

The RZG operates two parallel supercomputer systems, an IBM Power6 system with 6624 processors and a fast 8-plane-InfiniBand communication network yielding a peak performance of 120 TFlop/s; and an IBM Blue Gene/P system with 16 384 PowerPC@850MHz-based cores corresponding to a peak performance of 55 TFlop/s. Furthermore, an IBM p575-based cluster of 8-way nodes and a series of Linux clusters with Intel Xeon and AMD Opteron processors are operated. Dedicated compute servers are operated and maintained for an ever increasing number of MPIs. In autumn 2009 an Intel Nehalem based Linux cluster with InfiniBand switch and dedicated I/O subsystem, with I/O server, disk storage and the global file system GPFS, was installed for FHI. It consists of 384 nodes, with over 3000 cores, a total main memory of 11.5 TB and a peak performance of 36 TFlop/s. Also for IPP a new Intel Nehalem based Linux cluster with 450 cores and a standard network was installed. In December 2009 the RZG has installed a system for developing and testing GPGPU (General-purpose Graphics Processing Unit) computing applications. The system comprises an NVIDIA Tesla S1070 unit with four FX 5800 GPUs and two CPU servers, each equipped with two Intel Nehalem quadcores. Each CPU server is attached to 2 GPUs of the Tesla unit. In the mass storage area, two old server machines were replaced by 4 new IBM Power 550 Express machines, each with 8 Power6 CPUs and 32 GB of memory. The capacity of the automated tape library Sun SL8500 has been extended to 15 PB of compressed data. Seven additional LTO4 tape drives have been installed, giving a total of 45 LTO3 and LTO4 drives.

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 authors from the respective disciplines. In what follows selected optimization projects are presented in more detail.

ASDEX Upgrade Real-time Solver

To control the plasma discharge of the fusion experiment ASDEX Upgrade, the discretized Grad-Shafranov differential equation has to be solved within the control cycle of ASDEX Upgrade, which is 1.5 ms. The so-called “Lackner solver” used so far needs 6.4 ms on the fastest processor available at RZG, which is the Power6@4.7 GHz. As a performance enhancement by parallelization was not possible due to the structure of the underlying algorithm, a new algorithm was developed at RZG which is based on fast Fourier transforms and the solution of a system of linear equations with a symmetric tridiagonal matrix. Not only that the new algorithm is much faster by itself, the sequential version yielding already the required factor of 4 compared to the Lackner solver, it has moreover the advantage to be parallelizable. An OpenMP parallelization is under progress, and it is planned to port the parallel version to a Nehalem system making use of the mkl library.

GENE Code

An important tool for the simulation of gyro-kinetic turbulence in fusion plasmas is the GENE code. After many years of successful usage of the flux-tube geometry for local calculations (local means no radial dependencies of the background equilibrium profiles), a global version of the code has been implemented in the last two years. Now the radial direction is no longer limited to constant profiles, but is capable to use realistic background profiles for temperature and density with the whole dimension represented in real space. As the envisaged global problems will use many grid-points in radial direction, a parallelization of this direction has been implemented. For this purpose the gyro average and field solve procedures had to be rewritten. For scalability of the code on many cores, the crucial point was the exploitation of the banded structure of the gyro matrix. Starting from the whole matrix being fully kept locally for each task, over a parallelization of the full matrix over the processors of the x-direction we finally ended with a parallelization of the banded matrix over all ranks in the respective direction. Now the memory consumption scales proportional to O(N_radial) instead of O(N_radial^2) as was before. With this implementation the simulation of larger global problems became possible and the code can fully exploit future petaflop computers to solve physically relevant problems. The well-known local code has been tested in terms of strong scalability by runs on the Jülich supercomputer Jugene on up to 131 072 processors for a physical case of multi-scale turbulence and up to 262 144 processors for a stellarator-like case. The results are shown in figure 1.

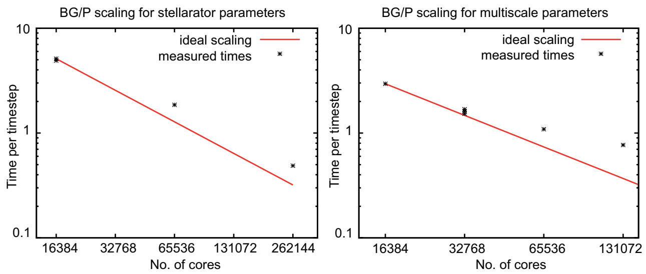

Figure 1: Strong scaling of the GENE code on the Blue Gene/P system in Jülich.

FHI-aims Code

The FHI-aims code is a new quantum-chemical code to determine the electronic structure of materials. It has been developed at the FHI and runs for different problem types on the Blue Gene/P system, on the Power6 and on the new Linux cluster with InfiniBand. A major obstacle for high scalability is the eigenvalue solver being a dominant part of the code, for which no highly-scaling library routines are available. To overcome this obstacle, a BMBF project (ELPA) was set up, in which the RZG, the FHI, the MPI for Mathematics in the Sciences, the TU Munich and the University of Wuppertal collaborate in the development of a highly-scalable parallel eigenvalue solver for petaflop machines, from which many other scientific codes would also benefit. Up to now, the algorithms from existing library routines have been reimplemented in an optimized manner, by which the performance could be heavily increased, so that it is possible to efficiently use four times as many processors as before. Future work will be related to the development of completely new parallel algorithms to obtain even higher scalability.

Visualization

Since 2009 the RZG offers central services for the visualization, exploration and quantitative analysis of (large-scale) simulation data of the Max Planck Society and the IPP (see www.rzg.mpg.de/visualisation/). This comprises provisioning of a suitable compute infrastructure as well as offering guidance for the selection, adoption and application of visualization and data analysis tools and for the instrumentation of simulation codes to the users. In addition, RZG's visualization team directly supported a number of particularly challenging visualization projects, where either the structure of the simulation data, their sheer amount, or specific visualization goals required expert knowledge on existing visualization methods or even the development of tailored software solutions.

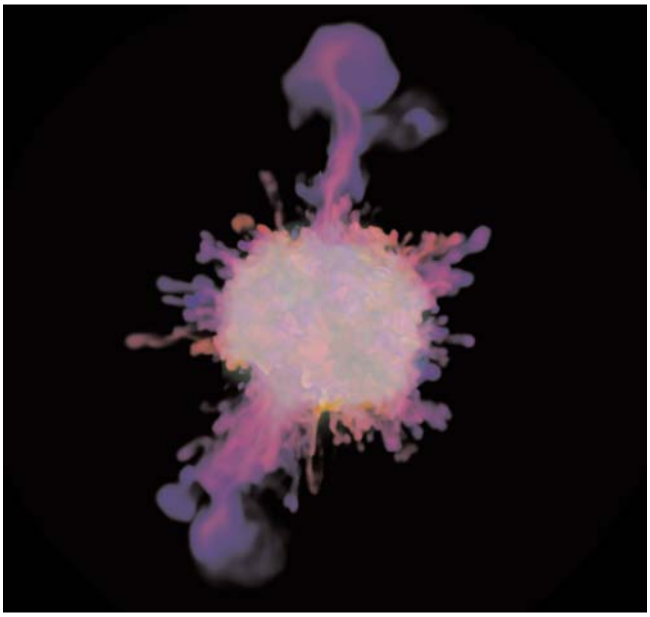

Figure 2: Snapshot of the element distribution of a 3D supernova simulation, taken at 2.5 hours after the onset of the explosion.

As a recent example for a fruitful collaboration between visualization experts and scientists from the simulation domain the visualization of the first three-dimensional simulations of large-scale mixing in Type-II ("core-collapse") Supernova explosions (N. Hammer, H.-Th. Janka & E. Müller, MPI Astrophysics, www.arxiv.org/abs/0908.3474) shall be sketched here. Employing a high-quality ray-casting method (from the VisIt software) the scalar fields representing the spatial distributions of Carbon, Oxygen, and Nickel in the exploding star were rendered individually into a red, green, and blue colour channel, respectively. The resulting single image (figure 2), which is composed of the three individual colour channels provides a quasi-realistic picture of the stellar plasma which radiates and absorbs in three different frequency bands. Employing such a technique allowed to visualize the global dynamics and morphology of the explosion on the one hand, and the detailed local chemical composition of the stellar material on the other hand, in a single image. Figure 2 shows a snapshot of the temporal evolution taken at a time of roughly

2.5 hours after the onset of the supernova explosion, when the displayed region has reached a size of about 75 millions of kilometres. Hydrodynamic instabilities drive large-scale mixing of the initially spherically symmetric progenitor star which consists of a compact nickel core surrounded by shells of Oxygen and Carbon. The prominent mushrooms and finger-like structures are composed of Nickel and Oxygen-rich material which penetrates into the outer Helium and Hydrogen layers (not shown) of the star with velocities exceeding 1000 km/s.

Projects in Collaboration

The Munich-ATLAS-Tier2 Project

As part of an active research program the MPI for Physics (MPP) participates in the ATLAS experiment, which is located at the Large Hadron Collider (LCH) in CERN Geneva. To overcome the computing challenges associated with enabling thousands of users to access and analyze the petabytes of data which will be produced by ATLAS the collaboration has turned to grid computing. A multi-tiered computing grid has been formed and extensively tested during the last decade as the LHC experiments have prepared for their long-awaited data taking phase. In Munich a Tier2 centre is supported by collaboration from RZG/MPP and the LRZ/LMU. One half of this federated centre is hosted at the RZG with the other half being hosted at the LRZ. The MPP/RZG provide approximately 200 TB of storage and over 870 CPU cores for the production and storage of simulated data as well as the storage of real data and finally for user analysis.

Throughout the last 12 months extensive stress tests of the system have been undertaken to ensure that the centre is ready to receive data from CERN and equally ready for the large-scale analysis of this data. In addition to the role of a standard Tier2 the Munich Tier2 acts as one of three centres which will perform a special role as a Muon Calibration centre. This activity requires an extremely quick cycle of data import from CERN, analysis of the data and the subsequent return of important calibration data to CERN.

On the 23rd of November 2009 the LHC accelerator started to deliver particle beams and data from the ATLAS experiment has already begun to arrive at the Munich Tier2. An exciting and challenging year lies ahead as, after many years of preparation and testing, real data taking and analysis are now underway.

The DEISA2 Project

The DEISA Consortium continues to support and further develop the *Distributed European Infrastructure for Supercomputing Applications* as an EU FP7 project from 2008 to 2011, coordinated by RZG/IPP. Activities and services relevant for Applications Enabling, Operation, and Technologies are continued and further enhanced. The very successful DEISA Extreme Computing Initiative (DECI) with annual calls for Europe's most challenging computational science projects has also been continued. In meantime, scientists from more than 180 universities or research institutes from 25 European countries with collaborators from four other continents have already benefitted from DECI. In addition, DEISA has started support for science communities as a whole, among them from Fusion Energy Research, Climate Research, Astro Sciences, and Life Sciences. DEISA is closely cooperating with PRACE which has started to install petaflop supercomputers in Europe.

HLST Project

In 2009, with support of the EU the High-Level Support Team (HLST) was set up in order to ensure support for HPC applications in the European fusion community. With the help of the RZG the core team has been established at the IPP, with the other partners residing at different other EFDA sites. The team consists of HPC experts with experiences in scientific computing, having especially a deep knowledge in the fields of numerical algorithms and visualization. The scope of tasks reaches from technical advice, training, all sorts of optimization and visualization of large data sets to the challenging task of increasing the scalability of existing parallel applications.

Bioinformatics/Computational Biology

In the context of the MIGenAS project joined by several Max Planck Institutes, the RZG has established a dedicated hardware and software infrastructure for computational biology applications. The RZG hosts various bioinformatics-related web applications and databases, offers application support for bioinformatics projects of the Max Planck Society, contributes original software development and continuously participates in research projects. Meanwhile, many computational biology projects (including research groups which were not part of the original MIGenAS consortium) are taking advantage of these centralized services and expertise.

MPGAAI – An MPG-wide Authentication-and-authorization Infrastructure

MPGAAI is a joint project of MPDL, GWDG and RZG to establish an MPG-wide corporate and federal infrastructure for authentication ("who am I") and authorization ("what am I entitled to") on the Web. Via this authentication-and-authorization infrastructure (AAI), based on the Shibboleth Framework (http://shibboleth.internet2.edu/about.html) and SAML protocol (http://saml.xml.org/about-saml), scientists and staff of the MPG can login directly with their local user accounts at their home institute (Identity Provider), and in doing so obtain access (Single Sign On) to online resources of all Service Providers within the so-called AAI Federation. Thus, users can have easy and secure access to participating publisher's protected online contents like articles, publications, databases and other services, also and especially from outside the home institute's intranet, when at home or away on business. The set-up of the infrastructure and a test-bed is currently in its final stage.

All crucial central services have failover redundancy on service level between GWDG and RZG. Start of the production service with the first pilot institutes (MPI for Solid State Research, MPI for Psycholinguistics) is expected by spring 2010.

Videoconferencing (VC)

The VC conferences duration further increased to 11,595 h (10,364 h in 2008), while the total number of calls 12,929 (12,095 in 2008) stayed almost constant. The Gatekeeper worked without breakdowns. There are 408 registered endpoints, where up to 75 have been active at the same time. Presentation sharing using H.239 is in regular use, while EFDA-TV is favoured by EFDA people. The HD (720P so far) capable Codian MCUs of the DFNVC Service delivered a very reliable and high-quality performance. Today 7 High-Definition Systems, 15 old Standard-Definition Tandberg systems and about 90 Polycom software clients are in regular use. The booking system covering 29 rooms worked stable throughout the year.
In 2010, unifying the GUIs of the seminar rooms for central manageability will be continued. The development and implementation of the ITU H.460 standard into the Open-Source Gatekeeper environment used by RZG has been supported. Necessary updates of major parts of the 7-10 years old and partly unreliable AV-infrastructure in the lecture halls (D2 in Garching and Seminar room 1 in Greifswald) have been planned, but have been postponed by the directorate due to budgetary problems. Only the old XGA beamers will be replaced by 1080P ones in Q1 2010.

Data Network

The data network is 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 most of the connections between centralized switches are at a speed of 1 Gigabit/s (Gigabit Ethernet technology) and a few have even been raised to 10 Gigabit/s on demand, numbers increasing. With this structure security and integrity of data have also been improved because eavesdropping is almost impossible.
For logical security based on the functionality of the internet protocol suite TCP/IP a packet filter firewall combined with stateful inspection at the access point to the internet (a Cisco 6509 router with hardware-based firewall module) 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.

In the beginning of the year Internet connectivity via DFN was upgraded to a capacity of 3 Gbps to keep pace with the ever growing bandwidth demand. RZG now participates in the eduroam initiative via DFNRoaming. This allows our users to make use of the wireless networks of other institutions also participating in eduroam. Wireless LAN solutions of several vendors are evaluated to replace the existing WLAN islands by a unified system consisting of powerful 802.11n-devices. A prototypical installation is planned in building D2.

Data Acquisition and Data Bases for Plasma Fusion Experiments

The fusion experiment W7-X, built in Greifswald, is designed for pulse lengths of half an hour. Especially, these long pulses require new methods and techniques in data retrieval and storage. This is the task of the XDV group at RZG in Garching. These long pulses also require new techniques to make the scheduling and operation of the pulses and their parameters for the physicists and operators a manageable task. Together with the control group in Greifswald the XDV group concentrated on the development of structures and procedures that can be used for pre-planning of pulses and the configuration of the machine. In addition, tools have to be provided, that give the user an easy and intuitive access to pulse scheduling and configuration. Some of these applications are already available in a first version.
On the prototype of the complete control and data acquisition system on the existing but simpler device WEGA more components for control and data acquisition were integrated in the last year to give a better performance picture of the complete system. Some of the necessary tools to define and operate the system are already available and the experience in using these tools will be a valuable input for their further development.

Staff

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* *IPP Greifswald*

Energy and System Studies

Head: Dr. Thomas Hamacher

The group for energy and system studies started to develop a fusion power plant model. The model should especially answer questions about the dynamic behaviour future fusion power plants in the electricity grid. The group found competent industry partners to work in this area. The EFDA-Times model was further developed and at the beginning of 2010 first reliable results are expected. The successful development of urban energy models continued.

Power Plant Models

Fusion Power Plant Model

The project Power Plant Models was started in the second half of the year 2009. The main goal of this project is to develop a dynamic model of a fusion power plant with all heat, material and other energy flows. With this model we want to analyze among other things how fusion power plants could take part in controlling and stabilizing a power grid with a higher fraction of intermittent renewable energy sources. As an option we want to include the possibility to use a thermal storage with a capacity of a few GWh. In a first step the performance of the plasma is represented by simple parameterisations and the main focus is on the structure and the dynamics of the thermal part of the power plant. Therefore we are developing a model of this part with MATLAB. In parallel some components like for example the blanket or the divertor will be modelled in higher detail so that the analysis of the heat flow in these components yields more insight. Fusion processes lead to high heat flows on components, which request materials that can resist high thermo mechanical loading and have less erosion due to plasma particles. Especially material resistance against heat flow is an object of development other industries are focused on. In this field we have a cooperation with industry partners where we want to find out which developments of materials could be used in other areas like for example in the aerospace industry.

Fusion Costs

In order to gain a better understanding of the future role of fusion power, we examine the economic aspects of a future fusion power plant from the point of view of a profit-driven investor. Since fusion power plants are capital intensive, long-term projects and future markets may be characterized by fluctuating power prices due to intermittent supply of renewable energies, investment risk is a key factor for a commercial fusion power plant. We use stochastic modelling of production and finance to cover the particular nature of future energy investments. Our models indicate that in volatile markets, greater reliability and flexibility in production can both increase the value of fusion power electricity, which may even compensate for the sometimes higher cost of fusion power.

Global Energy Models

European Supergrid

An increasing share of renewable energies in the European electricity mix is projected. Due to the variability of wind and solar supply backup, storage and transport capacities are necessary for their integration. In a linear optimisation ideal generation sites are determined. Major generation sites for a highly renewable case are shown in figure 1, where electricity transport through a powerful grid is allowed for. In a scenario-based analysis the role of transport and storage can be assessed: a European supergrid reduces the need for backup by 50 %, while the usage of large interdiurnal storage (~35 TWh) allows more substantial reduction of the backup capacity. Intermediate steps of today's energy supply to a highly renewable supply are under investigation.

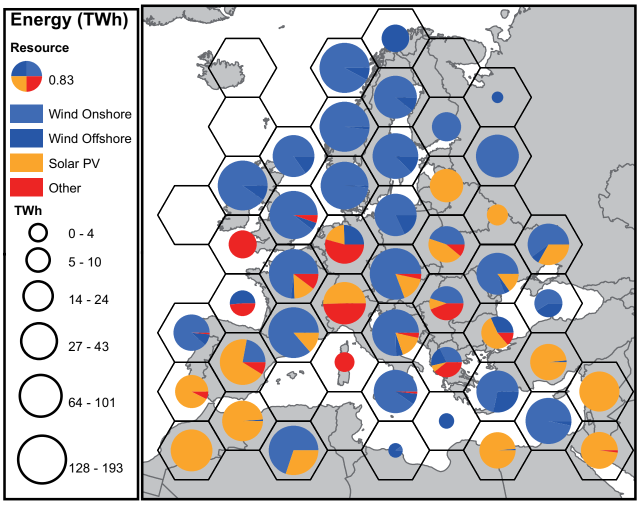

Figure 1: Energy mix for a scenario with maximal share of renewable energies and a powerful electricity transmission network.

EFDA-TIMES Model

One of our central activities is to access the potential role of fusion power in the future energy system. Since commercial fusion power plants will not be available before the mid of this century, this issue can only be addressed in a global long term picture. In order to understand under which conditions fusion energy will contribute to the electricity market starting from 2050 onwards, various scenarios have been evaluated. Independent of fusion investment costs fusion enters the market in scenarios with an emission restriction and conservative estimates of Uranium availability, see figure 1. However, a substantial reduction of demand growth would also lead to a prolongation of Uranium availability and, thus, fission could suppress the entering of fusion power plants. These issues, however, will be investigated in more detailed scenario analyses in the near future. A comprehensive publication of these studies will be available this year.

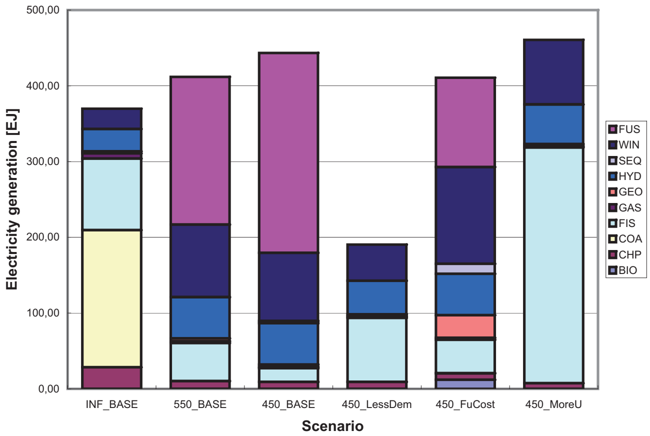

Figure 2: Electricity generation mix in 2100 for various scenario assumptions (emission restrictions in ppm, LessDem = demand growth reduced by 50 %, FuCost = doubled fusion investments costs, MoreU = unlimited Uranium resources).

Multi-agent Modelling

A model of the German electricity market was developed. Based on a multi-agent approach this model simulates the interaction of different market participants (utilities). The power commitment and the electricity production are decided according to their merit order on an hourly basis. The development of power plant mix is a result of the individual investment decisions of each utility. The investment strategies are based on a 'simultaneous investment, finance and production program' which optimizes the power plant mix on a long term and is calculated once a year. The realisation of the plan for the first year and the continuing electricity trading lead to a direct feedback of their investment decision, which allows an improved investment plan in the next years.

Energy and Cities

Greifswald

The working group develops an integrated climate protection concept for Greifswald. This is funded by a program of the Federal Ministry for Environment. The greenhouse gas inventory for the city of Greifswald has been updated for the year 2008. A comparison with results of 2003 shows no CO_2-emission decrease during the last 5 years. But the allocation of emissions within the use of energy has changed. Energy consumption and CO_2-emission for heating has decreased because of heat insulation measures at the building stock. Electricity consumption and resulting emissions have strikingly increased in the same time period. This is a trend which is noticeable not only in Greifswald, but the most cities in Germany. An urban energy system model for Greifswald was finalized. This linear optimisation model was developed with the model generator TIMES. The model is used to analyse different scenarios of the future energy supply and demand within the city of Greifswald.

There are two different types of scenarios. One type deals with the different possibilities to reach self-determined objectives (e.g. a CO_2-Cap), the other one analyses the reactions of Greifswald's energy system by changing economic parameters. An edificial database was built up by using Geographical Information Systems. This provides the possibility to analyse the heat demand for Greifswald on house level. Therefore energy supply systems, like district heating or gas, can be analysed very detailed. As a result spatial distribution of total and specific heat demand was identified and visualized. Those information can be used to determine efficient CO_2 saving measurements, e.g. priority areas for different energy supply systems.

Salzburg

One aim of our group is to think about the energy system of a whole city. The first challenge was to set up a good physical description of all the buildings, which means quite different building types like residential buildings as well as shops, offices or industry. But as we are able to work on the single buildings we can set up our energy models in a high geographical resolution (raster cells with 250 m × 250 m). That allows us to localize the development of the heat demand dependent on refurbishment and energy prices and think about optimal supply structures.

Oldenburg

The group participates in the project "energy efficient city of Oldenburg", financed by the federal ministry of education and science. Our part of the work is to identify concrete potentials for efficiency improvements in Oldenburg. The approach is twofold: An integral energy model contains the four demand sectors households, industry, services and traffic and allows comparison of modelled measures. The development of a highly geographical resolved building database is the basis of realistic measures in the heat demand structure.

St. Roman

Facing the characteristics of rural energy systems and the competition of food versus energy an optimisation model of rural energy systems was developed. Apart from energy potentials, energy demand and conversion technologies the most relevant agricultural system components are included. In order to achieve transferability the model is based on public spatial data. The high geographical resolution enables to represent the interdependencies of local structures and local energy systems. The project was financially supported by the Friedrich Schiedel Foundation for Energy Technology.

Scientific Staff

M. Bartelt, P. Böhme, F. Botzenhart, S. Braun, M. Busch, T. Hamacher, T. Hartmann, N. Heitmann, P. Hennemann, J. Herrmann, D. Köther, P. Kurz, C. Linder, P. Mühlich, K. Schaber, I. Schadinger, M. Sommerer.

Electron Spectroscopy

Head: PD Dr. Uwe Hergenhahn

The electron spectroscopy group at IPP investigates fundamental processes associated with the photoionisation of atoms, molecules and clusters as well as the decay of the resulting excited states. Moreover, it develops new instrumentation for the application of electron spectroscopy. The latter is a widely used technique for studying surfaces, material properties and solid state phenomena; good examples are provided by the chapter "Plasma-wall-interactions and Materials" in last year's Annual Report.

The group performs its experiments using synchrotron radiation at the BESSY II source in Berlin and, in part, at the free electron laser in Hamburg. The focus in 2009 has been on electron-electron coincidence studies with two different instruments: Auger electron-photoelectron coincidences from small molecules have been studied with an instrument consisting of a large hemispherical analyser and a set of time-of-flight electron spectrometers. Secondly, ICD-electron-photoelectron coincidences from weakly bonded clusters were investigated with a new apparatus that makes use of a magnetic bottle spectrometer.

New Set-up for Coincidence Spectroscopy

Coincidence electron spectroscopy gives insight into reaction dynamics which is not available from conventional non-coincident electron spectra. Photoelectron-Auger electron coincidence spectra allow the different intermediate states that are inevitably convoluted in the normal Auger spectrum to be resolved. In earlier experiments on this topic, CO was studied. Here, the potential curves of both the inner shell ionized state and the doubly charged final states are bound or metastable, respectively. While the principal mechanisms responsible for the structure in the Auger spectrum, including the vibrational fine structure, are now well understood in the case of CO, the studies have recently been extended to systems with repulsive potential curves, namely CH_4 (repulsive final state) and CH_3F (repulsive intermediate and final state).
In the following we will focus on our second major area of activity: Non-covalently bonded clusters. In this field, the experimental detection of Interatomic/Intermolecular Coulombic Decay by our group has created a lot of attention. In this non-local autoionisation process, the emission of an inner valence electron is followed by a relaxation and a transfer of the released energy to a neighbouring atom or molecule, where an outer valence electron is emitted. A doubly positively charged cluster is left behind. Although first studies on rare-gas clusters were successful with conventional electron spectrometers, we have found that for molecular clusters the acquisition of a coincidence electron signal is essential for the unequivocal detection of ICD. A recent study in collaboration with the Becker group at the Fritz-Haber-Institute demonstrating ICD in water clusters (see Nature Physics, **6**, 2010) has convinced us of the suitability of magnetic bottle spectrometers for this experiment. The magnetic bottle has potentially a much higher detection efficiency (solid angle up to 4π sR) and allows detection of very slow electrons (below 1 eV kinetic energy), both not achievable with our previous set-up used for the molecular studies.

We therefore decided to construct a new magnetic bottle instrument adapted to the needs of cluster experiments (see figure. 1). This apparatus, which also contains a new expansion and reaction chamber, was designed, built and tested during the course of 2009. A magnetic bottle spectrometer consists of two main parts: a permanent magnet producing a strong and inhomogeneous magnetic field at the interaction region and a flight tube to the electron detector. The latter is a chevron-type MCP assembly with a phosphor screen, which allows online monitoring of the spectrometer alignment. Electrons generated in an ionisation event are originally emitted in all directions, but will be forced to move towards the entrance aperture of the drift tube by the inhomogeneous magnetic field. Once the electrons enter the drift tube, they are guided by the field lines of a weak, homogeneous magnetic field to the detector.

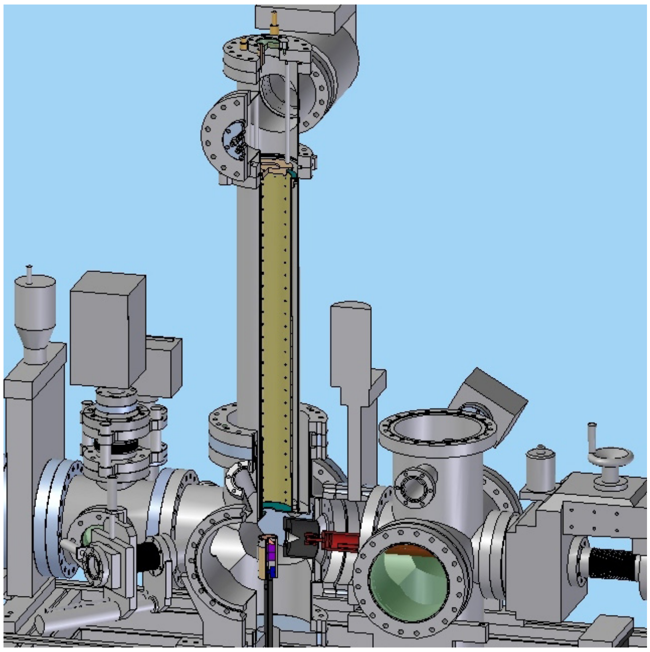

Figure. 1: Three-dimensional model (cut) of the new spectrometer and vacuum chambers. From right to left: expansion chamber with cluster source; reaction chamber with skimmer and magnetic bottle spectrometer; additional chamber housing a QMS.

It is possible to apply an additional electric field in the drift tube in order to slow down the electrons and thus increase the energy resolution. With the help of calibration spectra the energies of the detected electrons are deduced from their times of flight. A drawing of the main apparatus parts is shown in figure 1.

First Results

In the following, new results from recent beam times will be briefly presented:

Rare gas clusters are generated in a supersonic expansion process through a conical nozzle (at tip of cluster source). Compared to our old set-up, a higher pumping speed in the expansion chamber and the use of an improved skimmer shape resulted in a much higher degree of cluster formation. The new design of the spectrometer (vertical) has further advantages: The mounting system for the permanent magnet is modular, which allows for an easy exchange of magnets (below interaction zone) with different sizes, corresponding to different interaction volumes seen by the spectrometer. In future experiments the spectrometer will be used under UHV conditions, where baking is essential. To this end the coil which generates the homogeneous magnetic field along the drift tube (extending vertically, above interaction zone) is now placed outside the vacuum and can be removed. A gate valve allows to isolate the expansion chamber for maintenance work on the cluster source.

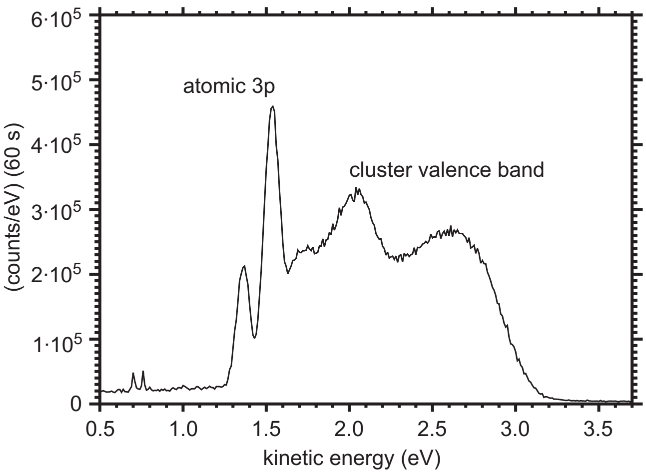

Figure. 2: Outer valence photoelectron spectrum of a free Ar cluster jet of mean size ⟨N⟩=190 atoms. The photon energy used is 17.3 eV.

A conventional photoelectron spectrum of Ar clusters obtained with the new magnetic bottle is shown in figure 2. On the right hand side of the figure, the spin-orbit splitting of the remaining uncondensed atomic Ar can be seen. From the width of these lines the resolution of the spectrometer was determined to be ΔE/E=1/20. (An interesting feature of figure 2 – the peak at ca. 2 eV kinetic energy – is assigned to an interband transition in the Ar clusters. In spectra recorded at various photon energies it shifts in binding energy, i.e. it shows dispersion, similar to spectra from bulk samples. Thus, the data not only show that band dispersion occurs in a free cluster but also that bulk-like electronic properties are already present in clusters of only a few hundred atoms.) A study of ICD with the new set-up was carried out for neon. Clusters of around 630 atoms and of around 65 atoms were ionized by photons of 51.2 eV in energy, which is well above the Ne inner valence ionisation threshold of 48.5 eV. Both electrons involved in the ICD process were recorded. The energetic correlation of two-electron events for neon clusters with a mean size of ⟨N⟩=630 is shown in figure 3.

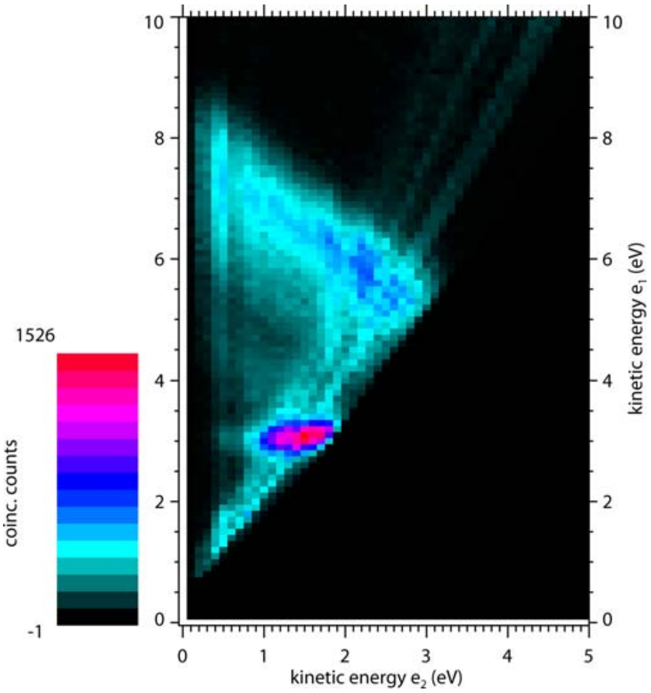

Figure. 3: Coincidence plot of neon clusters, ⟨N⟩ ca. 630. The intense peak is assigned to ICD; the diagonal at higher e_1 energies to electron collision.

A narrow and intense peak at (3, 1-1.7 eV) can clearly be seen; this is caused by coincident detection of a photoelectron with the corresponding ICD electron from a neon cluster. With this coincidence plot we are now able to confirm the hypothesis that the ICD spectrum of large neon clusters does not continue down until zero eV, but occurs within a fixed energy range. Apart from ICD we observe another feature: a broad diagonal lying along a line of constant total energy of the two electrons detected (approx. 7.5 eV). These electrons are generated by intracluster electron collisions, in which the energy is shared continuously between the two recorded electrons. For the 65-atom clusters (not shown here) the ICD peak is similar; the diagonal feature is much weaker, but still visible and shifted to slightly lower energy as expected from the larger Coulomb repulsion in the final state.

Scientific Staff

M. Mucke, M. Förstel, T. Arion, T. Lischke (1-11/2009), A. M. Bradshaw, U. Hergenhahn.

University Contributions to IPP Programme

Cooperation with Universities

Author: Dr. Axel Kampke

Many important goals in plasma physics, technology and materials science have to be attained on the way to a fusion power plant. Since this process will last another generation, IPP attaches great importance to training young scientists. Close interaction with universities in teaching and research is therefore an important part of IPP's mission. Moreover, joint projects with several universities form an integral part of IPP's research programme.

Teaching and Mentoring

Since fusion-relevant physics and engineering are not the most prevalent subjects in Germany's academic landscape, IPP is interested in sparking students' interest in high-energy plasma physics and other fusion-relevant fields. Teaching at universities therefore has a sound tradition at IPP. In 2009, 32 members of IPP conducted 115 contact hours at 15 universities or universities of applied sciences in Germany, neighbouring countries and overseas: in Augsburg, Bayreuth, Berlin, Greifswald, Munich, Stralsund, Tübingen and Ulm, in Innsbruck, Mol, Ghent and Vienna, and in Kyushu. Recently, IPP and the University of Ulm prolonged their mutual cooperation in teaching, including a practical course at IPP in Garching.

Country	Postgraduates		Postdocs	
	male	female	male	female
Australia			1	
Chile		1		
France			3	
Germany	38	3	12	
Hungary	1			1
India				1
Italy	4	2	1	1
Netherlands			1	
New Zealand	1			
Portugal			1	
Romania			1	1
Russia		1	1	
Sweden			1	
Slovenia			1	
Ukraine			4	
United States of America			1	1
	44	7	28	5
	51		33	

Table 1: Countries of origin and sex of the 51 postgraduates and 33 postdocs at IPP (31.12.2009).

Lecturing at and cooperation with universities are supplemented by 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 – in 2009 for the 24th time at Greifswald. Most of the 62 participants were from Europe – Austria, Finland, France, Germany, Hungary, Italy, Portugal, Rumania, Russia, Switzerland, and Ukraine – some even from China, Ethiopia, and South Korea.

Some of them are taking part in the "European Doctorate in Fusion" programme. A "European Doctorate" title is awarded to PhD students in parallel to a conventional one. This requires spending a significant part of the work on their subject at another European university or research centre. The European Doctorate in Fusion was initiated two years ago. At present institutions in Germany, Italy (EURATOM Association Consorzio RFX Padova and the University of Padua), and Portugal (EURATOM Association IST) are about to join this programme.

The international character of fusion research is also reflected in the countries of origin of graduate students at IPP: one-fifth of the postgraduates and approximately two-thirds of the postdocs are from abroad. Table 1 shows the distribution with respect to country and sex of the 51 postgraduates and 33 postdocs at the end of 2009. In the year 2009 a total of 64 postgraduates were supervised, 13 of them successfully completing their theses.

Joint Appointments, Grown and Growing Cooperation

IPP cooperates closely with some universities in the form of joint appointments. By the end of 2009 there were joint appointments only with Greifswald University: Prof. Klinger and Prof. Helander as Scientific Fellows and Prof. Grulke, whose junior professorship was extended into 2011.

In 2008, IPP and the Technical University of Berlin reached an agreement that provides two joint appointments in the fields of plasma astrophysics and plasma physics/stellarator optimisation, respectively. Both positions are expected to be filled in 2010.

In December, IPP and the Technical University of Munich contracted to intensify cooperation: Three joint professorships were agreed on fusion-relevant research fields of plasma edge and divertor physics, plasma-wall interactions, and numerical methods in plasma physics. Moreover, Prof. T. Sunn Pedersen, future head of IPP's Stellarator Edge and Divertor Physics Division, intends to develop an electron-positron plasma experiment at the FRM-II reactor.

The best example of very close cooperation without joint appointments is that with Stuttgart University by virtue of its essential contributions to the development of heating systems for W7-X as well as for ITER within the Helmholtz Virtual Institute, Advanced ECRH for ITER.

The development of a negative-ion source for the neutral-beam injection for ITER – awarded the Schrödinger Prize 2006 by the Helmholtz Association – is being continued with Augsburg University. The collaboration, even in lecturing and practical courses, has a sound tradition.

Networking

In addition, IPP uses specific instruments developed by the Max Planck Society, the Helmholtz Association, Deutsche Forschungsgemeinschaft (DFG), Leibniz-Gemeinschaft or the German government for more intensive networking with universities on a constitutional basis – partly in conjunction with non-university research partners and industrial partners.

Organisation of or participation in graduate schools:

- the International Max Planck Research School on Bounded Plasmas at Greifswald in cooperation with Greifswald University,
- the International Leibniz Graduate School for Gravity Waves and Turbulence in the Atmosphere and Ocean started 2008 in cooperation with Leibniz Institute of Atmospheric Physics, Kühlungsborn, Leibniz Institute for Baltic Sea Research, Warnemünde, and Rostock University.

Young investigators groups:

- Helmholtz Young Investigators Group, Computer-aided Materials Sciences, headed by Dr. Ralf Schneider, in cooperation with Greifswald University,
- Helmholtz Young Investigators Group, Theory and Ab Initio Simulation of Plasma Turbulence, headed by Dr. Frank Jenko, in cooperation with Münster University,
- European Young Investigator Award Group, Zonal Flows, headed by Dr. Klaus Hallatschek,
- Helmholtz Russia Joint Research Group, Hydrogen Isotopes Retention in First-Wall Materials for ITER and Fusion Power Reactors, headed by Dr. Matej Mayer as Helmholtz Principle Investigator and Dr. Anna V. Golubeva from Moscow Engineering and Physics Institute.

Research partnerships:

- participation in the DFG Collaborative Research Centre Transregio 24, Fundamentals of Complex Plasmas, together with Greifswald University, Kiel University and Leibniz Institute for Plasma Science and Technology, Greifswald,
- Helmholtz Virtual Institute, Advanced ECRH for ITER, together with the University of Stuttgart and Karlsruhe Institute of Technology (merging of the former and Karlsruhe Research Centre and University of Karlsruhe).

Participation in Clusters of Excellence in the context of the German government's Excellence Initiative in cooperation with Ludwig Maximilian's University and Technical University Munich:

- Munich Centre for Advanced Photonics, together with Universität der Bundeswehr München, Max Planck Institute of Quantum Optics, Max Planck Institute for Extraterrestrial Physics, Semiconductor Laboratory and Max Planck Institute of Biochemistry as scientific partners and Siemens AG/Healthcare as industrial partner,
- Origin and Structure of the Universe, together with Max Planck Institute for Astrophysics, Max Planck Institute for Extraterrestrial Physics, Semiconductor Laboratory and Max Planck Institute for Physics and the European Southern Observatory.

A few years after its formation IPP joined the European Fusion Development Agreement as a EURATOM Association. When the decision was made to build ITER, it became clear that training of young scientists and engineers had to be intensified. A European Fusion Education Network (FUSENET) was therefore formed in FP7. FUSENET consists of 14 EURATOM associations – one of them IPP – and 22 universities from 18 European countries. FUSENET shall provide education material and training opportunities in fusion science and technology covering all education levels, from secondary school through Bachelor and Master level to PhD.

University of Augsburg
Lehrstuhl für Experimentelle Plasmaphysik

Head: Prof. Dr.-Ing. Ursel Fantz (acting)

The research at the University of Augsburg is centred on diagnostics of molecular low temperature plasmas and plasma surface interaction studies for which several different low pressure plasma experiments are available. Focus is laid on the development and application of diagnostic methods for negative hydrogen ion sources. The work is carried out in close collaboration with several divisions of IPP.

Low Temperature Plasmas

For basic investigations on atomic and molecular processes in low temperature plasmas and for the development and benchmark of different diagnostic methods in a wide range of plasma parameters, several plasma experiments are available. The low pressure plasmas cover a pressure range of 0.1 - 1000 Pa in rare gases and in molecular gases (hydrogen, nitrogen). Plasma parameters are routinely measured by emission and absorption spectroscopy, Langmuir probes, microwave interferometry and energy resolved mass spectrometry.

A new experiment has been built which allows for a comparison of the rf-coupling efficiency at 13.56 MHz of capacitive and inductive discharges in a quartz tube of 1 inch in diameter and 20 cm length. Focus is laid on low power operation (5 to 50 W) of rare gas discharges in the pressure range of a several hundred Pa. Of special interest is the efficiency of producing radiation in the spectral range from 250 to 750 nm for lighting purposes.

Hydrogen and deuterium plasmas are systematically investigated in a planar coupled ICP experiment at 27.12 MHz. Special emphasis is given to the dissociation degree and the composition of the different ion species in order to benchmark the existing hydrogen dissociation and ionisation model (see Annual Report 2008). This correlation is of relevance in negative hydrogen ion sources which operate at pressures below 0.3 Pa and are less accessible by diagnostics such as mass spectrometry. Since Helicon type discharges are an option for efficient plasma generation at this low pressure a flexible Helicon setup went into operation. Higher electron and thus hydrogen ion densities as well as higher dissociation degrees are expected than for ICP discharges.

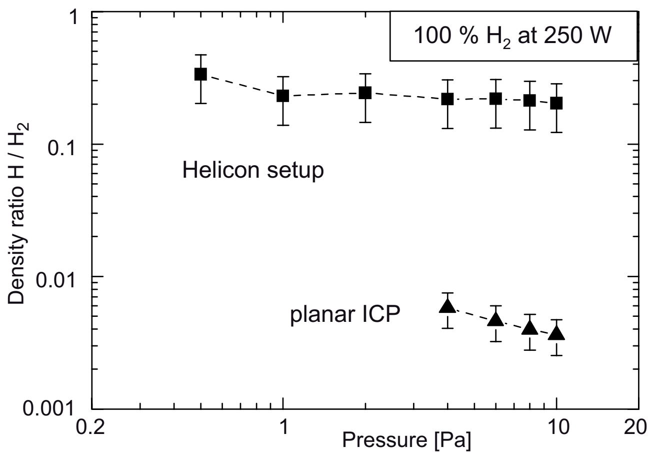

Figure 1: Comparison of atomic to molecular density ratios of hydrogen plasmas in ICP and Helicon type discharges at same rf-power.

First results are shown in figure 1. At present the discharges are driven at 13.56 MHz in thin and long tubes (diameter: 5 or 10 cm; length: 40 cm). Comparisons with tubes of about 25 cm in diameter and 20 cm length at 2 MHz, representing the geometry and excitation frequency of ion sources, will be carried out next year.

A collisional radiative (CR) model for nitrogen molecules has been added to the already available models for atomic and molecular hydrogen, helium and argon using the flexible YACORA solver. The model is benchmarked with measurements of nitrogen radiation in an argon arc discharge with known plasma parameters. Figure 2 shows molecular band emissions of two prominent nitrogen transitions ($C^3\Pi_u \rightarrow B^3\Pi_g$ and $B^3\Pi_g \rightarrow A^3\Sigma^+_u$) in comparison with results from the CR model and a simple corona model. Obviously the corona model does not reflect the measurements. With the CR model the C→B transition is reproduced very well whereas for the B→A transition further investigations are needed.

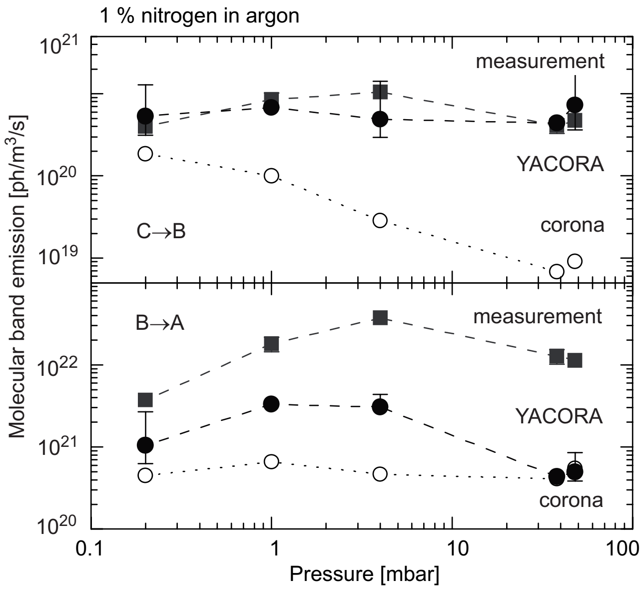

Figure 2: Measured radiation of the 2. pos. system (C→B transition) and 1. pos. system (B→A transition) of N_2 compared with results from the corona model and the collisional radiative model YACORA.

Diagnostics for Negative Hydrogen Ion Sources

The development of diagnostic methods applicable to the negative hydrogen ion sources at IPP for the ITER neutral beam injection has been continued. Since the cesium dynamics and the correlation with the negative ion production is one

of the key issues in these ion sources the activities are centred on this issue. Cesium is used for lowering the work function of the surface for effective production of negative ions by surface conversion of positive hydrogen ions and atoms.
As reported last year, white-light absorption spectroscopy for monitoring the cesium density in vacuum and in plasma operation is available at an ICP discharge. This year focus has been laid to simplify the setup for direct application to the negative ion sources at IPP. With the more compact tunable diode-laser absorption system the signal-to-noise-ratio is increased and a much better spectral resolution is achieved as shown in figure 3 for similar Cs densities. In vacuum conditions the results are being compared with results from the Surface Ionisation Detector (SID) as well as with emission spectroscopy data in plasma operation. Good agreement among these diagnostics is obtained.

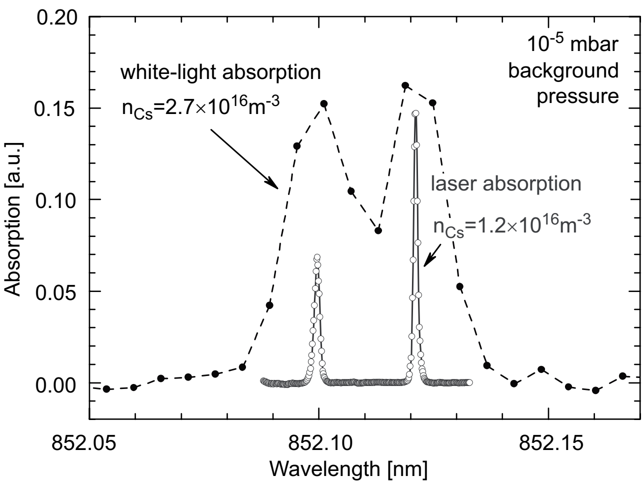

Figure 3: Improvement of the cesium absorption spectroscopy (852 nm resonance line, D2-line) by using laser absorption instead of the white-light absorption technique.

Since the behaviour of the work function of cesiated surfaces during plasma operation are much more relevant for negative ion production than in vacuum operation, the existing diagnostic based on the photocurrent method has been modified to allow for measurements in a pulsed plasma mode. As shown in figure 4 a lower work function during cesium evaporation in hydrogen discharges has been detected than in vacuum operation in which a systematic degradation is observed.
Using the developed diagnostics for cesium, the reproducibility of Cs evaporation from the standard IPP ovens could be improved. The evaporation rate (typically 10 mg/h at 150 °C oven temperature) is strongly correlated to the Cs degradation by the non-avoidable impurities in 10^{-5} mbar vacuum pressure. It has been shown that Cs dispensers such as the alkali-metal dispensers predominantly used at EPP might be an alternative; however for the Cs amount required in ion sources extensively high heat-currents are needed. Lately, new cesium-alloy dispenser became available which show promising first results. Measurements of the Cs dynamics in vacuum and in plasma operation and of Cs desorption from coated surfaces show clearly that most of the cesium reacts with the impurities from the background gas. Hence Cs is bonded chemically to the surfaces and the physical behaviour of Cs is defined by its compounds. To measure Cs compounds, mass spectrometry has been installed recently.

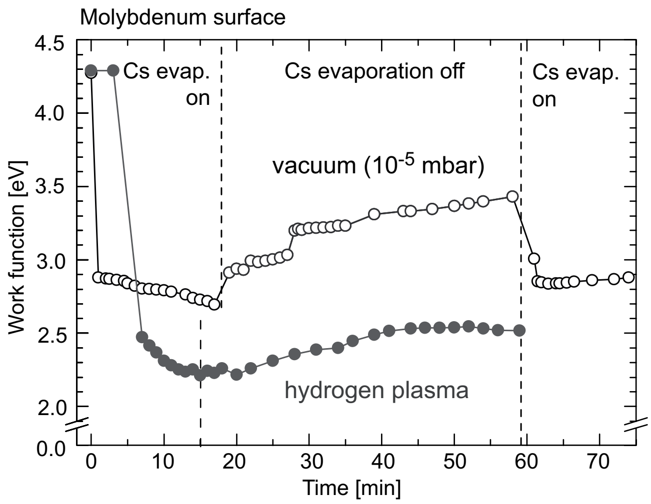

Figure 4: Change of the work function of Cs on Mo with and without Cs evaporation in vacuum (10^{-5} mbar) and during hydrogen plasma operation (pulsed ICP).

In order to investigate possible alternatives to cesium, the laser photodetachment diagnostics has been realized in an ECR plasma experiment. A trigger loop was developed to allow averaging at reproducible plasma conditions. The detection limit is at 2 % $n(H^-)/n_e$. A biased meshed grid is being used to separate the hot plasma region from a cold plasma region in which the destruction of negative ions by electron stripping is minimized. By implementing a surface into this region the generation of negative ions on different surfaces can be quantitatively investigated at relevant ion source parameters.

Diploma Theses

R. Friedl: Spektrale Intensität der N_2-Strahlung in einer Argon-Niederdruck-Bogenentladung für den Einsatz als Lichtquelle.

Scientific Staff

U. Fantz, P. Starke, S. Briefi, W. Böhm, D. Ertle, R. Friedl, T. Maier, P. Schmidt, F. Vogel, C. Wimmer, O. Wybranski.

Humboldt-University of Berlin Arbeitsgruppe Plasmaphysik

Head: Prof. Dr. Gerd Fußmann

With the retirement of Prof. G. Fußmann, the research activities conducted by the plasma physics group at the Humboldt Universität were shut down in August 2009. This section presents a selected review of our research including results from the PSI-2 plasma generator and electron beam ion trap (EBIT) experiments.

Introduction

The plasma physics group was established in 1992 as Berlin Branch of the IPP. Its head became simultaneously appointed professor for experimental plasma physics at the Humboldt Universität zu Berlin. Since its establishment, the group was engaged in experimental and theoretical investigations in Berlin and joint work at the fusion machines in Garching. The division was re-formed in 2004 and split into two parts: One part was associated to the university. The second has moved to the Greifswald Branch of IPP and continues to participate in the Wendelstein 7-X stellarator project.

Two major experimental facilities were operated in Berlin: The linear plasma generator PSI-2 and an electron beam ion trap (EBIT) device. EBIT produces and stores highly charged ions of up to the heaviest elements in the periodic table. The scientific emphasis of EBIT was on atomic physics research and applications to fusion-relevant hot plasmas. The PSI-2 generator produces stationary plasmas with parameters very close to the conditions found in the boundary region of nuclear fusion devices. The PSI-2 project focused on basic plasma physics, development of new diagnostic techniques, and plasma-material interactions relevant to fusion experiments. An additional effort was dedicated to the study of ball like plasmoids produced on water surfaces at atmospheric pressure (for further information on this topic, see Annual Reports 2006 and 2007).

Plasmagenerator PSI-2

The PSI-2 generator provides a 2-m-long, large volume (10 liter) steady state plasma column with typical electron densities in the range 10^{17} to 10^{19} m^{-3} and temperatures 1 to 10 eV. The plasma is produced by a current (up to 1000 A) flowing between a heated cathode and a hollow anode. It is confined by a magnetic field (0.1 Tesla) and guided into a target chamber for diagnostic measurements or plasma-surface interaction studies. A neutralizer plate at the end of the generator terminates the plasma in the axial direction.

(i) Plasma flow in front of a target: This item is essential for the interpretation of probe measurements, but is also of great relevance for nuclear fusion plasmas in contact with limiters or divertor plates. Theoretically, the problem was first addressed in 1949 by D. Bohm who has predicted that the Mach number $M=u/c_s$ (u streaming velocity of the ions, c_s ions' speed of sound) approaches unity in front of a target. This is the basic content of the so-called Bohm criterion used in plasma physics. To confirm Bohm's criterion by experiments, the flow behaviour of Ar^+ ions was studied in front of a target using LIF techniques and Langmuir probes (spatial resolution $\Delta z \approx 0.5$ mm). The results (figure 1) show that, close to the target (z=0), the Mach number indeed approaches unity in agreement with the prediction. An unexpected feature is the short distance ($\Delta z \approx 5$ mm) over which the final acceleration of the ions to M=1 takes place.

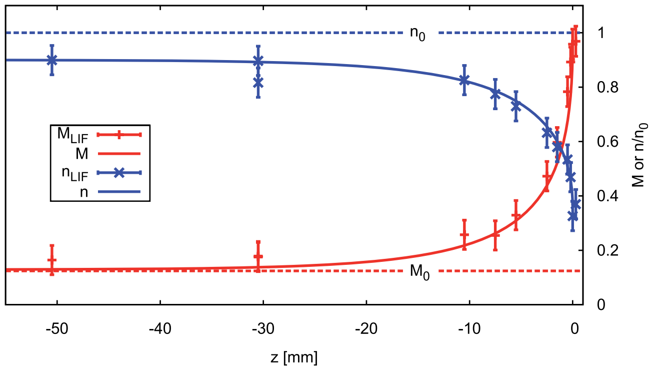

*Figure 1: Mach number and density as a function of axial position; M_0 and n_0 are the respective values for the unperturbed plasma. The solid lines represent a calculation using a theoretical pre-sheath model [Lunt et al., Phys. Rev. Lett. **100**, 175004 (2008)].*

(ii) Plasma shadow phenomena and perpendicular transport: Shadows in magnetized plasmas are a well-known phenomenon and can be seen when, for instance, a probe is moved into the plasma. In the example of figure 2, the shadow manifests as a dark region with sharp edges extending from the probe to the neutralizer plate. Note that the plasma streams from left to right parallel to the magnetic field **B**. It is clear that shadow phenomena are a consequence of the magnetic field which limits the perpendicular excursion of the charged particles to the gyro-radius. The dark shadow can thus be understood as arising from the constrained particle and energy influx from surrounding regions. A survey of electron temperature and density in the shadow revealed that T_e and n_e are only marginally reduced compared to the values found in the unperturbed plasma.

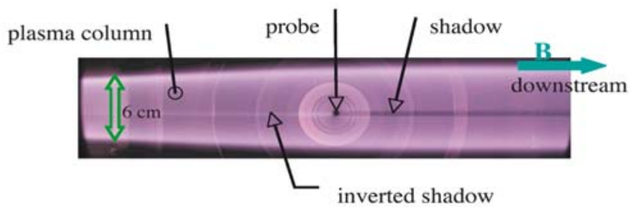

Figure 2: Plasma shadow in the PSI-2 device. The ring-like structure in the image is causes by light reflected from flanges [Waldmann et al., Contrib. to Plasma Physics 47, 1 (2007)].

Using a theoretical transport model, the measured profiles for T_e and n_e could best be described by relying on D≈3 m^2/s for the perpendicular diffusion coefficient. This D value is larger by a factor of 100 than the classical diffusion coefficient showing that anomalous diffusion prevails in the PSI-2 generator.

(iii) Chemical erosion studies: The search for new materials that could withstand the high energy and particle fluxes in a fusion reactor is an essential issue. In this context, various carbon fibre composites (CFC) are under discussion because they benefit from the fact that they neither melt nor become activated by neutron bombardment. On the other hand, physical and chemical erosion may become unacceptably high for reactor-relevant conditions. In order to quantify the effect of chemical erosion, measurements of the erosion yield have been performed in the PSI-2 generator for two different CFC materials. The samples were exposed to hydrogen and deuterium plasmas with particle flux densities Γ changing over two orders of magnitude from $2{\cdot}10^{21}$ to $2{\cdot}10^{23}$ ions/m^2 s. The data in figure 3 show that raising flux densities progressively decrease the yield. For $2{\cdot}10^{23}$ ions/m^2 s, the yield is reduced to a technically tolerable level of about 0.5 %. A result, which is highly appreciated in view of the large fluxes in a fusion reactor.

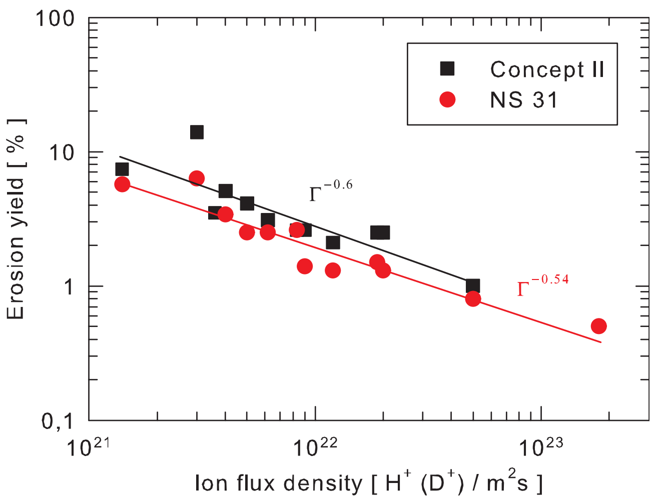

*Figure 3: Chemical erosion yield of two CFC composites as a function of particle flux density [Bohmeyer et al., Physica Scripta **T91**, 29 (2001)].*

(iv) Deposition and erosion of hydrocarbon layers: The release of hydrocarbons by chemical erosion leads to the formation of hydrocarbon films which presents a major problem in a fusion reactor because the amount of tritium trapped in these layers could become substantial. To improve our understanding of the hydrocarbon film formation, the growth rate at which a-CH layers are formed was measured in the PSI-2 generator using controlled CH_4 gas injection and heated wavers as collectors. It was found that the presence of atomic hydrogen in the plasma has a large effect on the erosion/deposition behaviour. The effect was particularly significant in hydrogen discharges leading to net erosion of the a-CH layers.

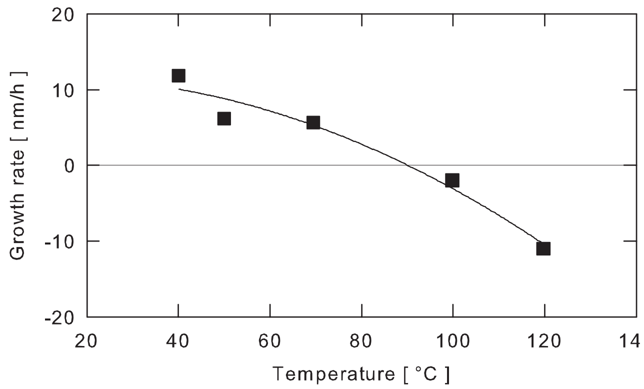

Figure 4: Film growth rate on a collector during injection of CH_4 gas into a hydrogen plasma as a function of the collector surface temperature.

As an example, in figure 4 the measured film growth rate is plotted as a function of the collector surface temperature showing that the transition from net deposition to net erosion occurs at T_t≈90 °C. The value for T_t increases with increasing hydrocarbon-to-hydrogen flux ratio, and it can be estimated that, in the PSI-2 vessel, a wall temperature of about 100 °C would be sufficient to equalize the rates for hydrocarbon deposition and erosion.

(v) Scavenger effect: Yet another method to prevent a-CH film deposition in tokamak machines is the application of scavenger atoms or molecules. Scavenger particles convert highly sticking hydrocarbons into non-sticking species which can then be removed by pumps from the device.

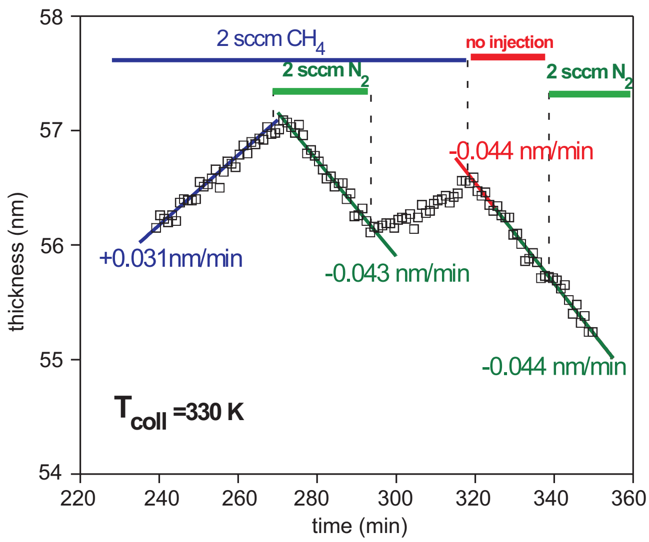

*Figure 5: Demonstration of the scavenger effect: Adding N_2 gas during CH_4 gas injection (t=270-290 min) turns deposition into erosion [Bohmeyer et al., J. Nucl. Mat. **390-391**, 560 (2009)].*

To demonstrate the effect when nitrogen is used as scavenger molecule, the film-formation process was measured on collectors placed in the pump duct region of the PSI-2 generator remote from the plasma. For pure hydrogen discharges an erosion rate of about 0.044 nm/min was measured on the collector surface. If CH_4 gas is injected into the hydrogen plasma, erosion changes into deposition with a growth rate of 0.031 nm/min (figure 5). Adding nitrogen to the plasma during a 20-min-wide frame restores the conditions of the pure hydrogen plasma, i.e. deposition has been changed into erosion. The addition of N_2 gas can thus be understood in the way that it converts all active hydrocarbons into non-sticking species.

Electron Beam Ion Trap (EBIT)

The EBIT technique employs a monoenergetic 70-µm-diameter electron beam which is accelerated and compressed by electric and magnetic fields. The trap is formed by the field of the electron beam's space charge attracting positive ions in the radial direction and the geometry of a 2-cm-long drift-tube assembly providing axial confinement. Atoms injected into the trap are successively ionized and excited within the beam by electron collisions. The resulting highly charged ions can then be observed through X-ray, UV or visible spectroscopy.
(i) Dielectronic recombination (DR): DR is an important atomic process in high-temperature laboratory and astrophysical plasmas. It is the resonant capture of a free electron by an ion, thereby forming a doubly excited intermediate state.

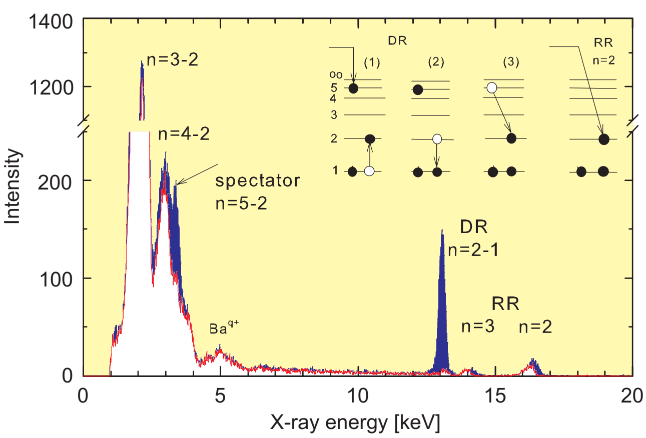

*Figure 6: 12.30-keV-beam energy (red spectrum, off-resonance) and 12.51-keV-beam energy (blue spectrum, on-resonance) X-ray spectrum of krypton Kr^{q+} ions($q \leq 34$). For the 12.51-keV-energy spectrum capture of a free electron into a state n=5 and concurrent excitation of a bound electron to the n=2 state takes place. The X-ray line at 13.1 keV is the signature of the stabilizing n=2-1 transition, while the extra photons below 4 keV (n=5-2, 4-2, and 3-2 transitions) are due to the subsequent relaxation of the spectator electron [Biedermann et al., Phys. Rev. A **56**, R2522 (1997)].*

The decay of the intermediate state to a nonautoionizing state is associated with the emission of a stabilizing photon, the signature of the DR process. In addition, if a stabilizing transition has occurred, the subsequent decay of the spectator electron leads to lower-energy relaxation transitions taking the singly excited ion to its ground state. This ion relaxation is of relevance to atomic theory and has been demonstrated for the first time at the Berlin EBIT facility (figure 6).
(ii) Dielectronic satellites and resonance lines of He-like argon: Helium-like ions are of considerable interest in fusion research because they allow by identification of a few distinct line-ratio combinations to determine the electron temperature T_e or the density of the plasma. Particularly suited for diagnostic purposes is argon, since it can be added to fusion plasmas in controlled quantities and efficiently pumped out. Using high-resolution spectroscopy and EBIT's capability to perform fast scans of the beam energy, we have measured the spectral emission pattern of He-like Ar^{16+} together with the associated satellite emission from Li-like Ar^{15+} ions. From the observed line intensity across a wide range of the exciting electron-beam energy, line-intensity ratios of individual recombination satellites (in particular the *j* and *k* satellites) to the *w*-resonance line in the He-like ion were extracted as a function of T_e.

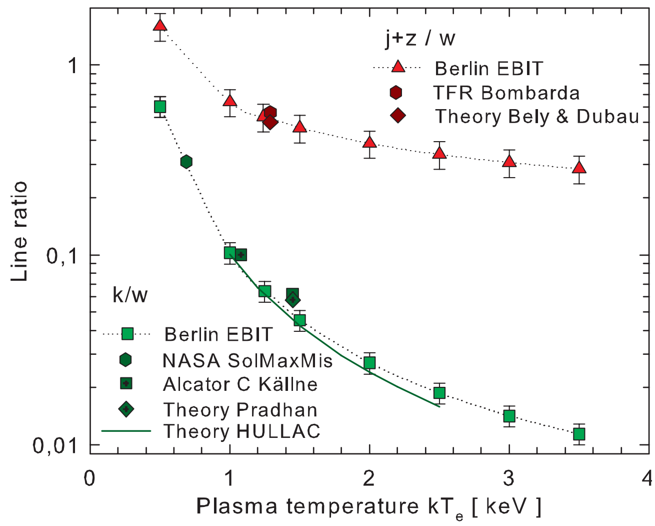

*Figure 7: Line ratios of dielectronic satellites to the w resonance line of argon. Experimental values from the Berlin EBIT are compared with measurements at tokamak facilities and calculations [Biedermann et al., Phys. Rev. E **66**, 066404 (2002)].*

The (*j*+*z*)/*w* and *k*/*w* ratios are plotted in figure 7 and compared to experimental values and theoretical calculations (*z* is the intercombination line). The strong *k* and *w* lines are particularly well suited for electron-temperature diagnostics, since they can easily be distinguished in the X-ray spectra and the line ratio is a steep function of temperature.

(iii) Extreme ultraviolet (EUV) spectra of tungsten: From investigations performed in the late 1970s at the ORMAC and PLT tokamaks and more recently at ASDEX Upgrade, it is known that the tungsten spectrum under tokamak-plasma conditions shows a bright quasi-continuum emission band between 40 and 70 Å. The nature of this band structure was unknown for a long time owing to the problem to quantify the contribution of individual ion stages to the overall spectrum. EBIT sources have the advantage over tokamaks that they can scan the ion inventory in the trap over an ionisation threshold and obtain ion stage specific spectral information. This is to be seen from figure 8 showing tungsten spectra for more than twenty individual charge states. Many isolated lines appear in the spectra, but the most interesting feature is a narrow, 2-Å-wide emission band that shifts throughout the sequence of images. The information contained in figure 8 can explain the quasi-continuum emission band observed at the tokamaks.

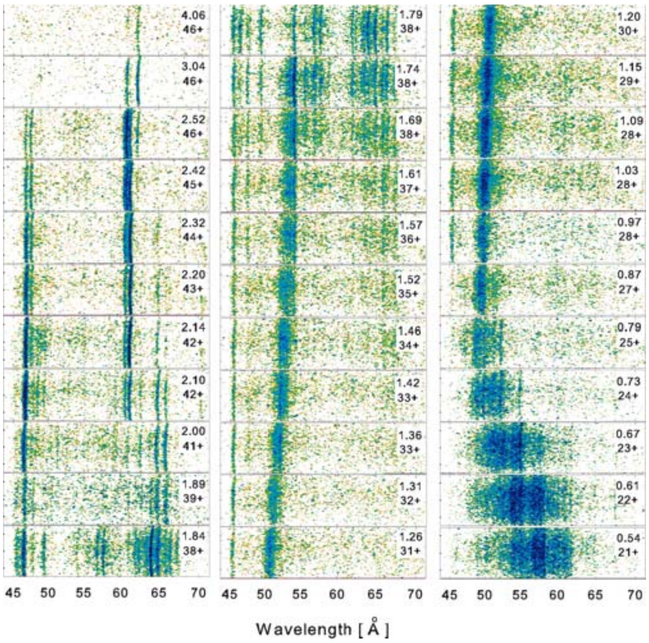

*Figure 8: CCD images showing tungsten spectra from medium-charge-state ions, from I-like W^{21+} through Cu-like W^{45+}. The labels on the right of each panel indicate the energy of the beam in keV and charge number of the highest stage [Radtke et al., Phys. Rev. A **64**, 012720 (2001)].*

(iv) Sawtooth oscillations in EBIT: An important area in electron beam ion traps and sources is the evolution of the charge state distribution during ionization. It is fundamental to the understanding of machine physics (ion confinement, evaporative cooling, etc.) and for designing experiments. In our studies at EBIT, we worked with mixtures of light (Ar or Kr) and heavy (Xe) atoms which were continuously fed into the trap from an injector while all EBIT operating parameters were kept constant. The evolution was measured by recording the characteristic X-ray emission from trapped ions. An unexpected feature in the spectra are sawtooth-like intensity variations pointing to a periodic ion expulsion from the trap (figure 9). The sawtooth effect is very sensitive to the trapping conditions, and there are thresholds for switching the activity on and off. From a theoretical point of view, the sawtooth events result from a Hopf bifurcation with two extremes in the density and temperature evolution.

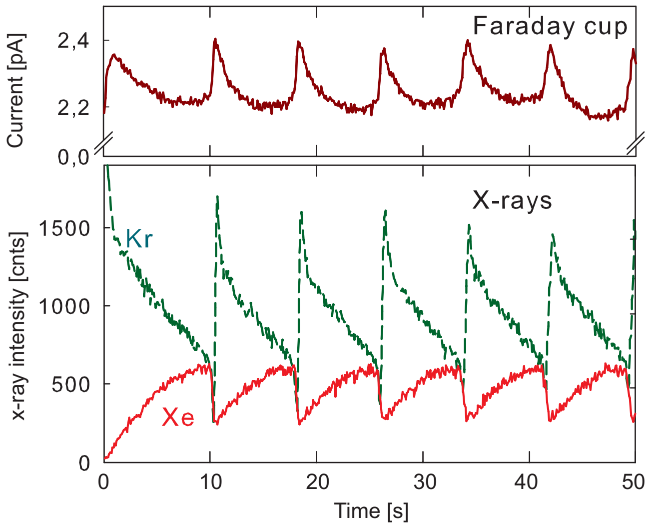

*Figure 9: Lower plot: X-ray emission of highly charged Ar and Kr ions vs. time. The feedback between the Ar and Kr ions is expressed by the mirror-like behaviour of the X-ray intensities. Upper plot: Measured current of ions expelled from the trap in axial direction. [Radtke et al., Phys. Rev. A **67**, 032705 (2003)].*

Scientific Staff (1992-2009)

F. Allen, P. Bachmann, M. Baudach, C. Biedermann, W. Bohmeyer, T. Fuchs, H. Greuner, H. Grote, E. Hantzsche, A. Hermann, D. Hildebrandt, B. Jüttner, H. Kastelewicz, I. Kleberg, S. Klose, B. Koch, P. Kornejew, M. Laux, T. Lunt, H. Meyer, B. Napiontek, D. Naujoks, E. Pasch, P. Pech, R. Radtke, H.-D. Reiner, J. Sachtleben, W. Schneider, D. Schröder, A. Stareprawo, D. Sünder, O. Waldmann, U. Wenzel, H. Wolff.

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The cooperation of IPP and Technische Universität München is concentrated on the field of thermography measurement techniques. Different infrared cameras are used at ASDEX Upgrade for contactless temperature measurement of surfaces of in-vessel components. With the temperature evolution over time it is also possible to calculate the heat flux on the monitored surfaces.

Temperature Measurements in the Lower Divertor

The divertor in a Tokamak fusion device like ASDEX Upgrade in general is exposed to high heat flux resulting in high temperatures on its surface. Although the divertor tiles are designed to withstand the presumed heat loads during normal operation, monitoring of the surface temperature and accumulated energy is a major issue. A possibility for contactless temperature measurements having high temporal resolution is the use of infrared cameras. For the lower divertor two line cameras, both cooled with liquid nitrogen, are installed outside the vessel and are observing the divertor through vacuum windows. For a ten-second-discharge they can be operated at a framerate of 3.8 kHz, which is high enough for ELM-resolved temperature measurements.

Problem of Jitter

Due to various reasons, such as vibrations of the torus or disruptions, the recorded data is affected by jitter. During normal operation this jitter accounts up to 5 pixel, which corresponds to more than 10 mm spatial displacement of the measured area.

Since the power density is calculated from the temperature evolution, this calculation is also affected by the temperature jitter for areas with spatial temperature gradients. The jitter of the temperature data can result in heat fluxes with much higher maximum values and more spikes in the temporal evolution, regarding the real power load on the divertor. Thus, the jitter has to be corrected prior to the subsequent processing of the temperature data.

Horizontal gaps between single divertor tiles are in the monitored areas of both cameras. These gaps can be used as fixed-points, because they are independent of the temperature distribution on the tiles. In order to determine the position of the gaps on the single line frames, a parabolic curve is shifted over the data. For each position the correlation between the data values and the curve is calculated and the position of maximum correlation is considered to be the centre of the gap. After the centre has been identified for all frames, they are shifted to adjust the centre with respect to a same pixel position for all frames. Because the jitter between two consecutive frames is in the subpixel range, the data size is expanded by a factor of ten with interpolation before applying the processing outlined above.

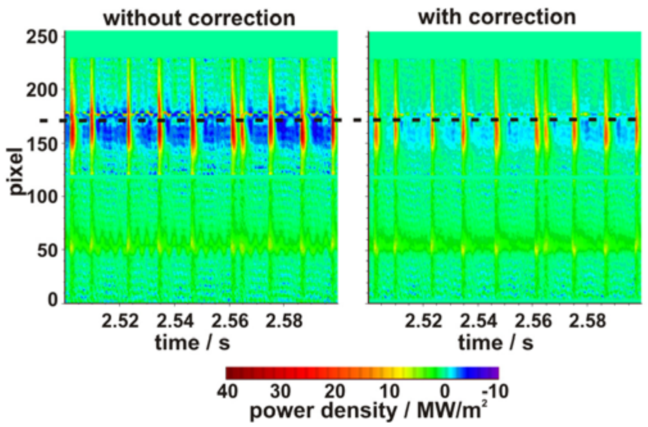

Figure 1: Calculated power density based on uncorrected (left) and corrected (right) data.

Example of Jitter Correction

Figure 1 shows the calculated power density for uncorrected temperature data on the left side with corrected data on the right side. For the pixel at the dashed line in figure 1 the power density profiles with (blue) and without (red) correction are plotted in figure 2.

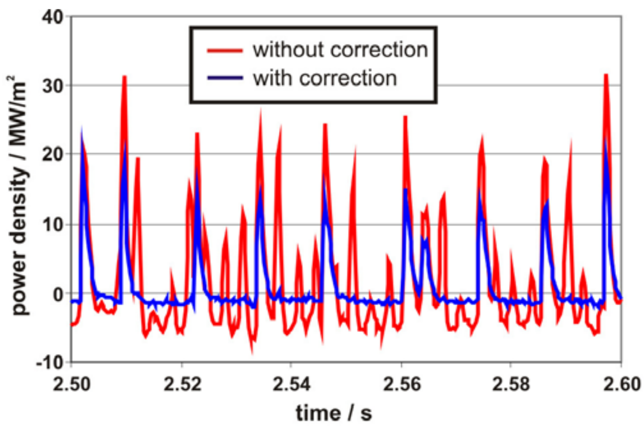

Figure 2: Power density trace with (blue) and without (red) correction of the temperature.

Without correction there are also ELM-like spikes between the real ELMs. Using the corrected data these inconsistent spikes do not occur and the height of the remaining spikes is significantly lower.

Since this method of jitter correction has shown to yield improved results it is applied routinely to the 1D thermographic data.

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The joint program between IPF and IPP on ECRH systems for AUG, W7-X, and ITER as well as contributions to the experimental program of AUG can be found on the respective pages of this report. Here is summarized the part of the program carried out at IPF: the development of new mm-wave components, 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.

ECRH in Over-dense Plasmas

In TJ-K, there exist two microwave heating systems, one with f_1=2.45 GHz and the other with f_2=7.9-8.3 GHz. For the lower frequency, intensive experimental and numerical studies of the heating mechanism have been performed. The full-wave code IPF-FDMC has been successfully used to describe the heating at f_1: It turned out that the power of the incident microwave is mainly deposited at the upper hybrid resonance. While in the simulations the single pass absorption of an incident X-wave was found to be in the order of 12 % only, the inclusion of the vacuum vessel walls strongly enhanced the absorption to 80 %. The microwave is reflected multiple times between the vessel wall and the plasma and, hence, multiple interactions with the upper hybrid resonance occur, which leads to the enhanced absorption. This fact is illustrated in figure 1, where on the left-hand side the rms-value of the wave electric field is shown for a simulation without the vessel walls and on the right-hand side, with vessel walls included.

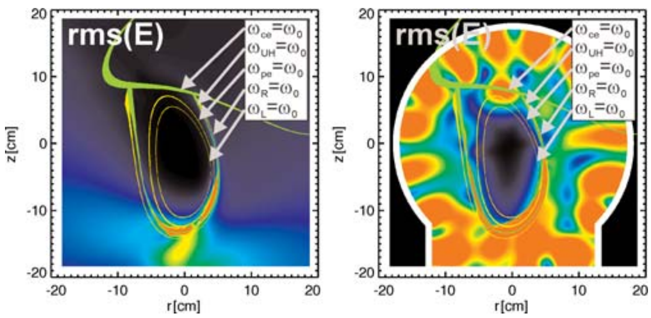

Figure 1: Results from simulations with the full-wave code IPF-FDMC for the antenna in X-mode configuration without (left) and with (right) the vacuum vessel walls included. Plotted is the rms-value of the wave electric field.

Investigations of the new operational regime, where non-resonant heating with f_1 is achieved at high magnetic fields of 300 mT, have been carried on. The non-resonant heating was found to take place only, if a plasma has been started resonantly with f_2 beforehand. The density of this starting plasma needs to be above a critical density to start the non-resonant heating.

A feasibility study of the O-X-B heating scenario at the reversed field pinch RFX-mod has been carried out. Extensive parameter studies with IPF-FDMC have been performed, where a maximum value of the conversion efficiency, within the given experimental constraints, has been successfully obtained. Again, the vacuum vessel wall was found to play an important role, although it has not such a strong impact as in TJ-K.

Global Turbulence and Confinement Studies

In 2009, investigations of zonal structures with a 128-probe array from 2008 have been continued. It was shown that externally imposed shear flows through plasma biasing enhance long-range correlations in the potential fluctuations while density fluctuations were dominated by an m=3 mode. Coherency spectra, on the other hand, also exhibit a zonal (m=0) component in the density as a consequence of the high electron collisionality in TJ-K. Under very strong shear, the m=3 mode is damped. Its energy is found to be transferred via sidebands to a Kelvin-Helmholtz (KH) mode in agreement with the modulational instability. This behaviour is consistent with the non-linear generalised KH instability.

For the reduction of fluctuation and transport levels by self-generated flows, the energy transfer mechanism is found to play an important role. For the first time, the spectral energy transfer between different poloidal scales has been measured directly. Kinetic energy is found to be transferred non-locally (see figure 2), i.e. between non-contiguous spectral ranges, from small scales ($k_{\theta 1}$>1) into the large-scale zonal flow (k_θ=$k_{\theta 1}$+$k_{\theta 2}$=0), where k_θ is the poloidal wave number. This finding is consistent with a vortex thinning mechanism, in which vortices on intermediate scales are taken over by large-scale eddies.

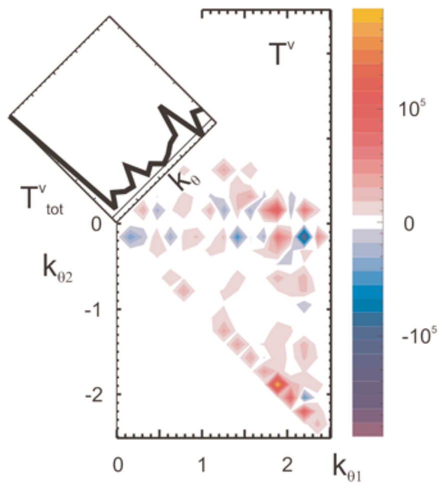

Figure 2: Bispectral analysis of the nonlinear fluid kinetic energy transfer.

A field-line tracing code has been developed, which provides relevant quantities as, e.g., field-line curvature and local magnetic shear for direct comparisons with experimental turbulence data. In a first test, measured flux surfaces and island structures were reproduced in numerical calculations.

Structures in the measured 2D plasma profiles could be correlated with the simulated island topology. A new set of magnetic diagnostics has been installed on TJ-K to investigate the topology of the diamagnetic and Pfirsch-Schlüter current system in combination with the new code.

Optimisation of Horn Antennas

The PROFUSION code (PROgrams For mUltimode analySIs, simulatiOn and optimisatioN) was extended for optimisation of horn antennas with varying aperture radii at multiple frequencies. The aperture radius of a Gaussian beam antenna is a critical value. Smaller radii cause side-lobes due to the stronger truncation of the Gaussian pattern. Larger aperture radii will result in a very complex mode mixture which could be difficult to generate. A varying aperture radius allows the optimizer to find the best trade-off for the radius.

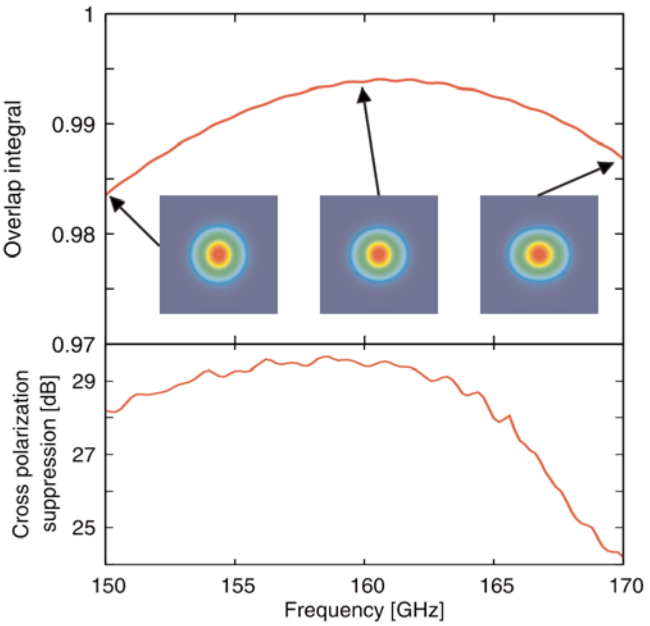

Figure. 3: Overlap integral (top) and cross polarisation suppression (bottom) of an optimized broadband horn.

The optimisation is possible at multiple frequencies, where the cost-function is averaged over the frequency points. The number of frequency points can be chosen by the user. This also allows optimisation for just 2 frequencies, e.g. for the 105/140 GHz ECRH system for ASDEX-Upgrade. Figure 3 shows the results for a horn optimized for a frequency band of 150-170 GHz. The top diagram shows the overlap integral of the apperture field and and the ideal Gaussian beam as a function of the frequency. The optimisation was done by considering 5 equidistant frequencies. The field patterns look almost identical, the decreased overlap especially at 170 GHz results mostly in a slight ellipiticy of the beam. The bottom diagram of figure 3 shows the cross polarisation suppression of the antenna. It is above 24 dB in the whole range.

Negative Refraction-index Materials and Components

The concept of Composite Right-handed-Left-handed transmission lines (CRLH) is widely used for different microwave devices such as directional couplers, hybrid junctions and leaky-wave antennas. Considering the use of this type of microwave components (frequency range 2-15 GHz) for plasma physics applications at higher power levels (up to 6 kW), the Resonant-Slot Coupled Cavity Chain provides a basis for further study.

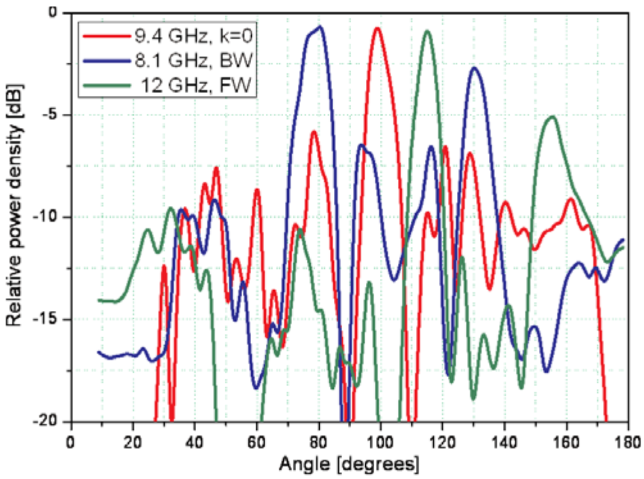

Figure 4: Measured far-field radiation pattern of the prototype structure with 49 unit cells: radiation in the backward, broadside, and forward direction.

Based on numerically approved guiding and backward-forward scanning properties of the leaky-wave antenna, the designed geometry, a square waveguide with a resonant-slot coupled cavity chain and a radiating slot was manufactured, and first measurements have been performed. In the frequency band 8-12 GHz, the transmission, reflection and far-field pattern of the antenna were measured. Initial experiments (figure 4) confirmed the frequency dependence of the direction of the antenna beam, scanning from backward via broadside to forward directions, however, with low radiating efficiency at some frequencies. Further investigations on beam quality and radiation efficiency will be performed with numerical optimisation of the geometry of the structure and radiating slot dimensions.

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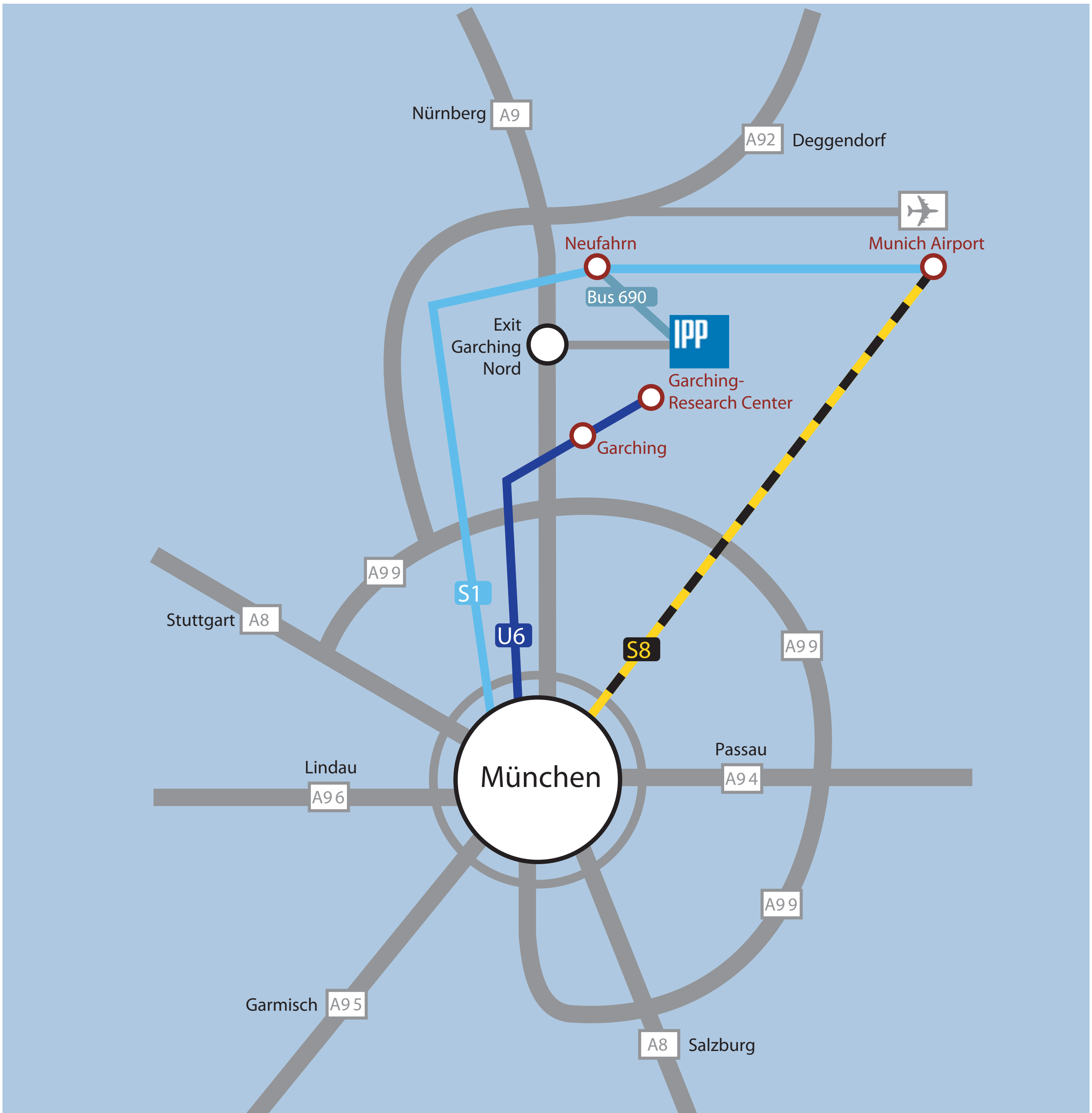
Appendix

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. 1 to the "Südbahnhof", then change to bus No. 5 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".

IPP in Figures

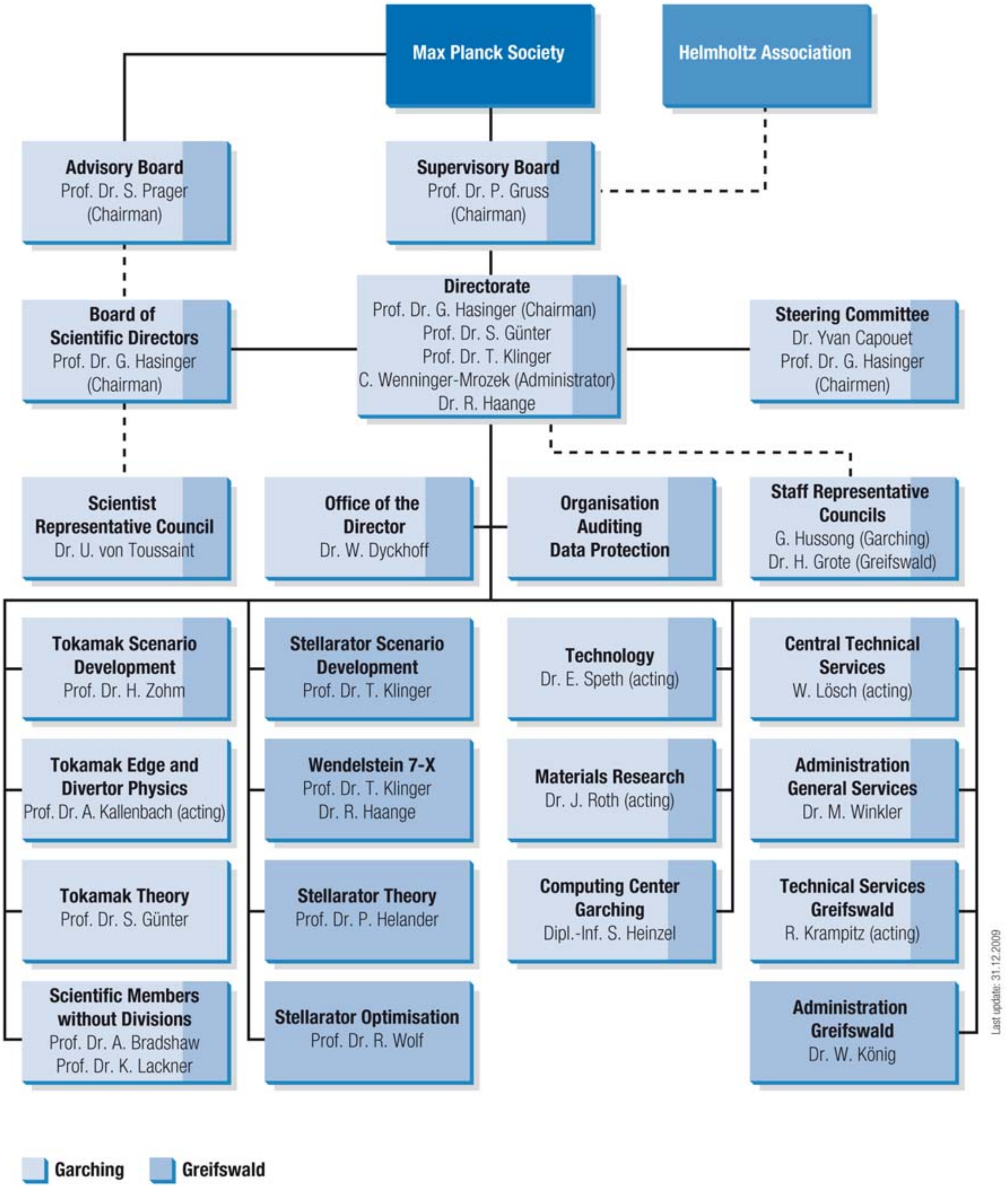
Funding

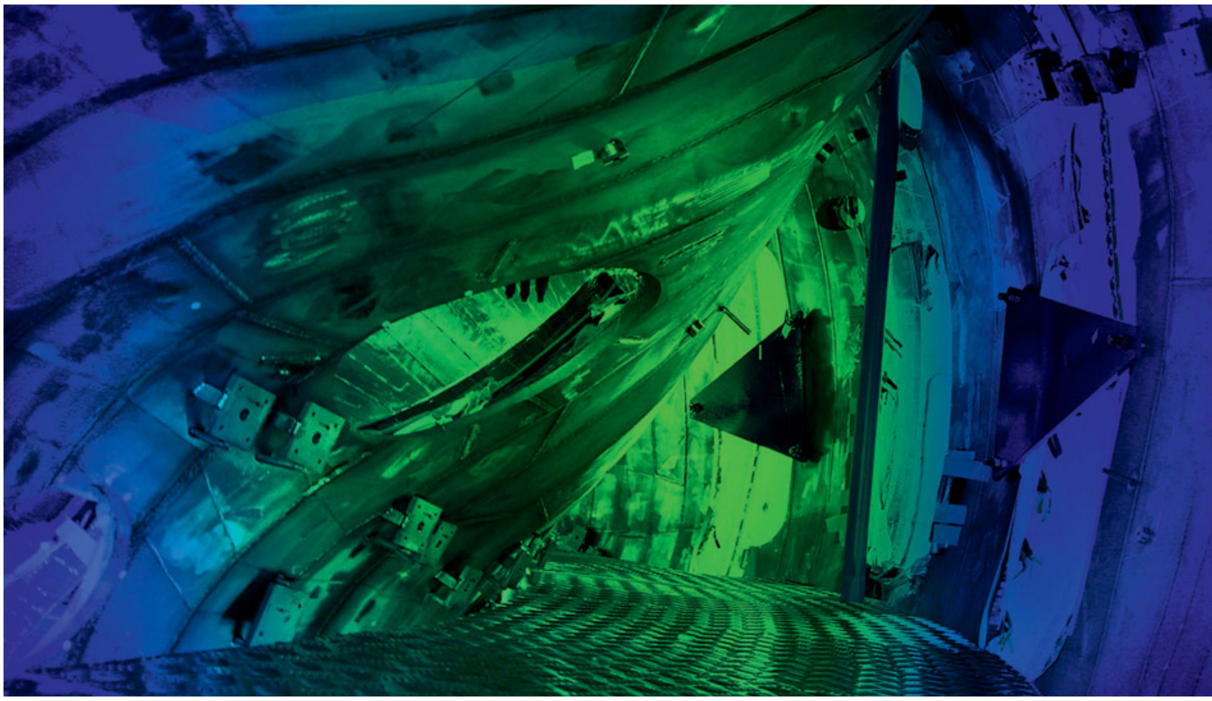
IPP receives approx. 20 % of its total budget from EURATOM. The Federal Government funds 90 % of the national expenditure for fusion research, the states of Bavaria and Mecklenburg-West Pomerania are providing the remaining 10 %. This came to total funding of approx. 149 million euros for the year 2009.

Scientific Staff

At the end of the year IPP had a total of 1172 members of staff, 451 of them worked at IPP's Greifswald site. The workforce comprised 301 researchers and scientists, 51 postgraduates and 33 postdocs. In addition, 7 guest researchers used the research infrastructure.

Organisational Structure





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Further Information

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