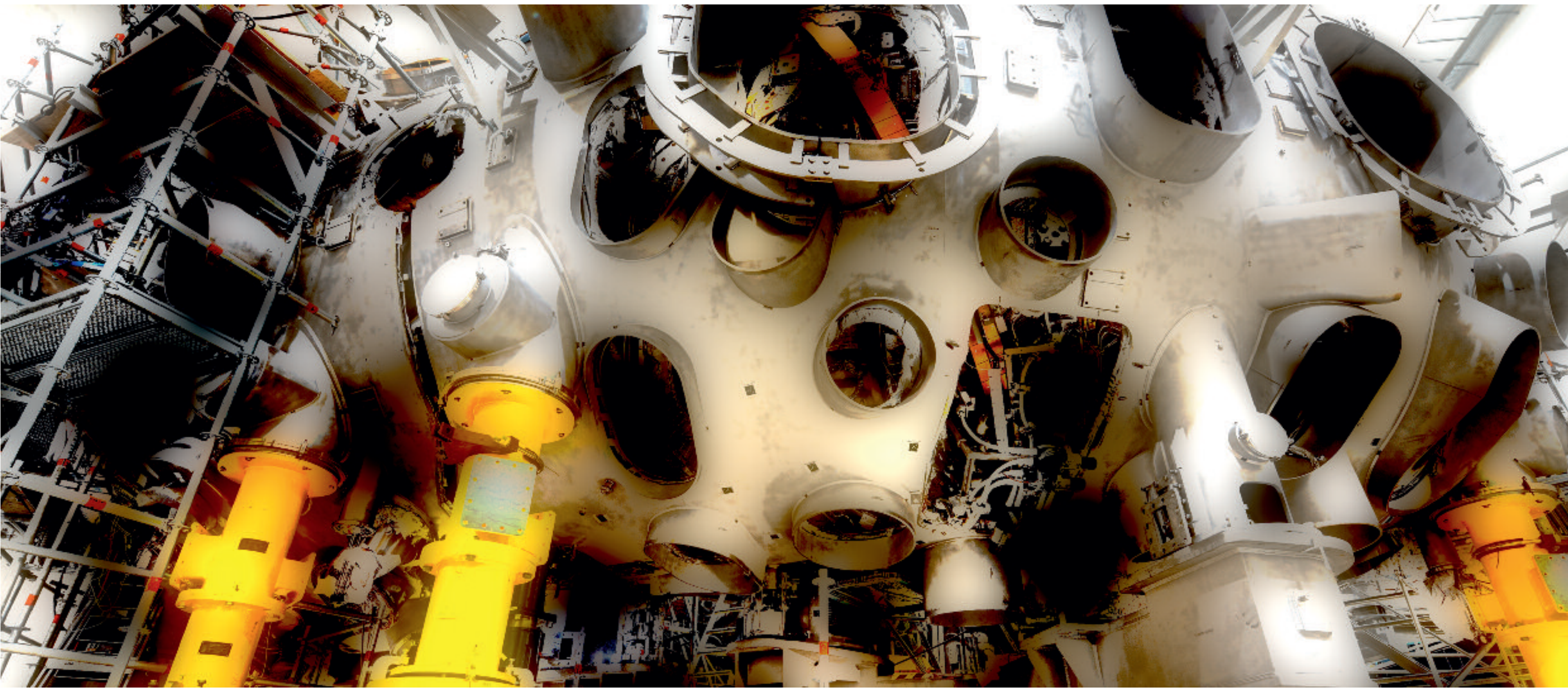
Max-Planck-Institut
für Plasmaphysik

Annual Report 2011



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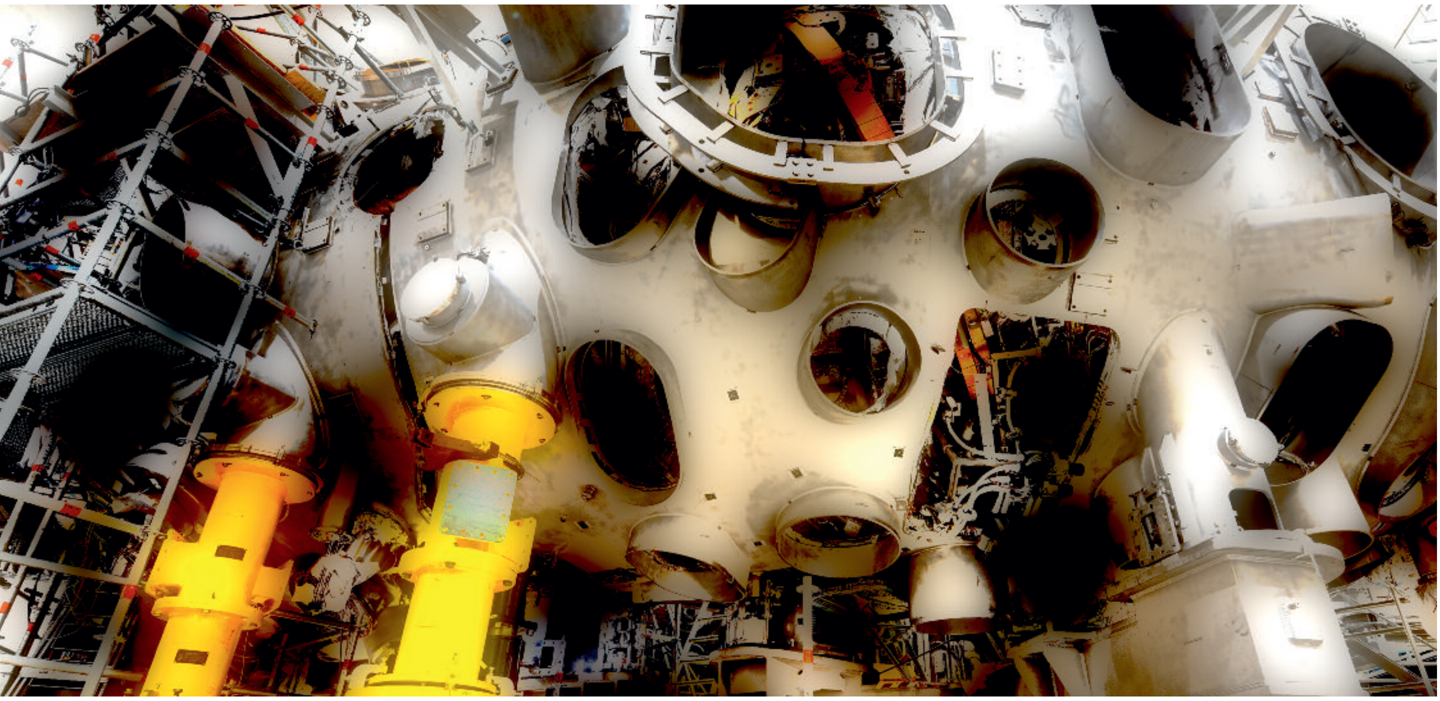

Photo: Christian Lünig | www.arbeitsblende.de

By the end of 2011, all five modules had been placed on the machine's foundation and enclosed in a steel outer shell 16 metres in diameter. Wendelstein 7-X, to be commissioned at the Greifswald branch of Max Planck Institute for Plasma Physics in 2014, has attained its final form.

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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.


Photo: IPP, Stefanie Graul

By the end of 2011, Wendelstein 7-X, the large superconducting stellarator under construction at the Greifswald branch of Max Planck Institute for Plasma Physics had attained its final form. The last of five modules had been positioned in the experimental hall. The ring, consisting of superconducting coils, mechanical support structure, plasma vessel, and the cryostat vessel surrounding the coils are thus now complete. Besides such obvious advances, many other equally important tasks are still ongoing. The ports are being installed. They connect the plasma vessel through the cryostat with the outside world and are needed for observation and heating of the plasma, and exhaust of heat and gas. The large number of ports – 254 altogether – and the precision required for their assembly make this a very demanding work package. In addition, the plasma vessel still has to be equipped with a wall structure designed to absorb the plasma loads. These are highly specialized elements that have to be exactly aligned to the outer contour of the plasma. While fabrication of these elements had been completed, preparation for installing them was just starting. Completion of assembly of Wendelstein 7-X is now only two years away. The focus is thus shifting towards construction of diagnostics and heating systems. This effort is being supported by Professor Dr. Thomas Sunn Pedersen, who just at the right time moved from Columbia University in New York to Greifswald to head the diagnostics department. In the future he will be in charge of the physics of the plasma boundary.

The ASDEX Upgrade tokamak completed a very successful period of operation in 2011, making full use of the extended technical capabilities – eight new internal coils and extended ECRH power. The internal coils were used to demonstrate reliable suppression of large type I ELMs in a wide operational window, as long as operating above a certain plasma density. Together with the experimental results from other tokamaks, most prominently DIII-D, this offers a potential route to suppressing large ELMs in ITER, which will be required there. In the 2012 campaign, an additional eight internal coils and more diagnostics will be available to clarify the underlying physics, which is crucial for extrapolation to ITER. Surprisingly, ELM suppression by magnetic perturbations also eliminated the ELMs usually triggered by pellet injection, thus increasing the pellet fuelling efficiency and allowing access to H-mode discharges with peaked density profiles at 1.5 times the empirical Greenwald limit. The increased ECRH power of up to 4 MW in the plasma was used to study type I ELMy H-mode discharges in a regime with dominant electron heating and low rotation, i.e. under conditions resembling those expected in ITER. Although global energy confinement is not affected under these conditions, the rotation profile is found to undergo dramatic changes, clearly hinting at torque generated by turbulence. This finding is consistent with the results of a more extended study pointing out the importance of turbulent stresses for intrinsic rotation on ASDEX Upgrade.

Fusion research targets a coherent solution for confinement at the plasma edge, for controlled power flux onto the limiting walls and for materials able to sustain high heat loads with low hydrogen retention properties. Following the appointment of Professor Dr. Ulrich Stroth end of 2010, research in these fields has been merged to fully exploit synergies. Improved diagnostics and more flexible plasma heating schemes were used to study the role of the plasma parameters for the development of the H-mode and to highlight the importance of the neoclassical radial electric field for transport barrier formation. Turbulent drive of large-scale flows has been identified as an additional player. Power from the separatrix is radially transported to the wall by intermittent fluctuations, and for the first time electron and ion temperatures inside these structures have been measured and successfully compared with turbulence simulations. Work on plasma-wall interaction, material modification under plasma exposure and development of new plasma-facing materials and their characterisation was continued. Of special interest were erosion, migration and redeposition of materials and impurities in ASDEX Upgrade. Formation of mixed materials was investigated with respect to the ITER-like wall in JET by an integrated approach that tightly links plasma transport with surface evolution. The EU coordination action, FEMaS (Fusion Energy Materials Science), which was coordinated by IPP, was brought to a successful end in 2011.

Just before the end of August, JET was ready to start operation with its ITER-like wall. Already during one of the first attempts plasma was produced and controlled for 15 seconds. The initial few months of exploitation have been very rewarding. IPP scientists have been involved – often in a leading role – in many key experiments of JET Campaigns C28 & C29. One of the most important results is confirmation that hydrogen retention with the ITER-like wall is greatly reduced in relation to the previous carbon wall.

The ITER cooperation project at IPP continues its activities on the major topics: The ELISE test facility, a major step on the way to the ITER neutral beam injection system, is being built and will start operation in 2012. R&D on the bolometer diagnostic for ITER continues, as does the work on the design of the ICH antenna within the CYCLE Consortium. Among the smaller contracts with F4E are the running R&D activities on a dust monitor, a code benchmark for 3D ELM studies, which was successfully completed, and development for the "Plasma Control System Simulation Platform", which has just started. In addition to these directly ITER related projects, IPP in particular contributes to the ITER physics basis by the scientific work performed on ASDEX Upgrade where the programme strongly concentrates on the most urgent ITER needs.

The most important questions, which should be answered by theory before proceeding with the design of a DEMO power plant, concern the origin and the magnitude of transport, the behaviour of the high energy He-ions produced by nuclear fusion, and instabilities limiting the sustainable plasma pressure or ablating material from the wall. For stellarators, furthermore, the shape of the plasma surface is still subject of optimization. In all these areas we are developing ab-initio numerical models and support this development with analytic theory. In 2011, these efforts have received a further boost by the joint appointment of an applied mathematician, Professor Dr. Eric Sonnendrücker to a Chair at the Technical University of Munich and as a Director at IPP. The leading role of our institute was highlighted also by the selection of two turbulent transport codes developed or co-developed by IPP as the European lighthouse projects for the initial operation of the Petaflop-class supercomputer installed this year in Rokkasho as a joint EU-Japan project. In addition to the more target-oriented research we maintain strong links with other fields of plasma science, which from 2012 onwards will be mainly conducted in the frame of the newly established Max Planck-Princeton Research Centre for Plasma Physics involving on the German side, in addition to IPP, also the Max-Planck Institutes for Solar System Research and Astrophysics, and on the American side the Princeton Plasma Physics Laboratory and the Department of Astrophysical Sciences at Princeton University. In addition, this effort is being supported by a starting grant awarded by the European Research Council in 2011 to Professor Dr. Frank Jenko who will be leading a working group on "Turbulence in Laboratory and Astrophysical Plasmas".

Max Planck Institute for Plasma Physics continues to play a pivotal role in fusion research.
On behalf of the Directorate and the Board of Scientific Directors I would like to thank all members of staff for making this possible.

Scientific Director Sibylle Günter

Content

Tokamak Research

ASDEX Upgrade

Head: Prof. Dr. Arne Kallenbach

The current ASDEX Upgrade programme concentrates on physics input to the remaining ITER design issues, the preparation and improvement of ITER operation and the design of a future DEMO prototype fusion reactor. Most prominent topics of the 2011 experimental campaign were ELM mitigation investigations with the new magnetic perturbation coils, transport studies facilitated by the ECRH II enhancement and the characterisation of the optimized, broad limiter ICRF antenna.

1 Overview

1.1 Status of the Machine

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). It has an ITER like arrangement of the poloidal field coils and a versatile heating and current drive system comprising of 20 MW neutral beam heating (NBI), an ion cyclotron resonance system (ICRF) with up to 6 MW coupled power and 5 MW installed power of electron cyclotron resonance heating (ECRH). Alternative ECRH coupling scenarios were successfully implemented to facilitate low q_{95} operation (X3 heating at B_t=1.8 T, I_p=1.1 MA) and central heating with high electron densities (O2-mode for high cut-off density). These low single-pass absorption scenarios required the implementation of dedicated sniffer probes for machine protection and in case of the O2-heating the installation of holographic mirrors on the high field side, which have been equipped with thermocouples to allow feedback-controlled steering of the ECRH beams on the mirrors. New real-time diagnostics for density profile, mode localisation by ECE T_e measurements, equilibrium reconstruction and ECRH beam tracing (real-time TORBEAM) were brought into operation to prepare the feedback stabilisation of neoclassical tearing modes, which is ready to start for the 2012 campaign. Optimization of power supply configurations allowed to extend the maximum simultaneous heating power to 23 MW, demonstrating high P/R H-modes with nevertheless moderate divertor peak power loads below 5 MW/m^2 achieved by feedback-controlled radiative cooling with nitrogen.

1.2 Results from the 2011 Experimental Campaign

AUG operated continuously from December 2010 till end of July 2011, with the exception of two short unscheduled vents caused by a leak and a damaged tile, costing three weeks outage time in total. The experimental program was prepared from more than 200 proposals, almost one third of which had an external collaborator as first author. The program was structured in five Task Forces, including a new Task Force ‘Transport’ supplying a close link to theory. About 1000 successful plasma discharges were performed for shot requests based on the experimental proposals. The highest priority in the 2011 campaign was given to the ELM mitigation studies with the new set of eight magnetic perturbation (MP) coils (or ‘B-coils’), since the decision about a corresponding ITER system is regarded an urgent issue. ELM mitigation was achieved above a critical density quite independent from the magnetic configuration, heating power or plasma rotation. The ELMs are replaced by repetitive small scale instabilities, which have low loss energies but are sufficient to keep the tungsten concentration in the core plasma low. The observations in AUG differ so far considerably from previously reported ELM mitigation scenarios in DIII-D or JET. No evidence for penetration of the field perturbation inside the pedestal was found for H-mode conditions, since neither rotation breaking nor mode locking were seen. A theoretical model for the ELM mitigation process in AUG is not yet available, therefore an extrapolation to ITER conditions is not yet possible. An important question relates to the density threshold for the occurrence of ELM mitigation. Empirically, this threshold is best characterized by a constant Greenwald fraction of the pedestal density. However, a collisionality dependence cannot be ruled out so far, which would lead to unfavourable scaling towards ITER. A very positive effect of the ELM mitigation scenario in AUG is the endurance of the ELM mitigation during pellet fuelling. The absence of immediate particle losses due to a type-I ELM triggered by the pellet ablation has enhanced the fuelling efficiency and H-mode densities well above the Greenwald density could be obtained. More refined studies with n=4 perturbations in the 2012 campaign are expected to shed further light on the physics mechanism of error field penetration and ELM mitigation. A second high priority topic were transport studies using the upgraded ECRH 2 system to study effects of pure electron heating and heating scenarios with no external momentum input, also in combination with ICRF heating. Despite some technical problems with new gyrotrons, important results were obtained and ECRH-only heated H-modes with almost 4 MW deposited ECRH power could be achieved. These allowed further studies of the interplay of density peaking, dominant turbulence mechanism and intrinsic plasma rotation. Typically, application of central ECR heating causes a change in the dominant core turbulence regime from ITG to TEM due to the ECRH induced changes in electron and ion temperature profiles. In the TEM dominated cases, a core localized, counter-current directed, residual stress momentum flux has been observed of the same order of the NBI torque. Intrinsic rotation studies using NBI beam blips revealed a correlation between the gradient of the toroidal rotation and the normalized density gradient. Fast ion physics studies profited in particular from new or upgraded diagnostics like FIDA (fast ion D_α) and ECE-imaging.

A strong ICRF-induced tungsten source and its concomitant radiative losses still hampers the application of high power ICRF in AUG. Tungsten sputtering by ICRF operation was further investigated employing the newly installed ICRF antenna with broad limiters. About 30 % reduction of the ICRF-induced rise in the core plasma tungsten concentration was observed with the new antenna. Further improvement of antenna performance regarding the tungsten sputtering is expected from the new 3-strap antenna design, which will be further developed in 2012.
The current discussion about a possible ITER operation starting with a tungsten divertor has enhanced the emphasis on studies of the effects of damaged tungsten components on operation. In addition to the W pin melt experiments already started in the previous campaign, a leading edge was exposed to a high power divertor plasma using the divertor manipulator. Ongoing modeling of the induced tungsten source, the transport of molten material and tungsten droplets and the divertor tungsten retention with various codes like DIVIMP, EMC3-Eirene and others will improve the predictive capability of these codes for ITER.

1.3 Technical Enhancements Installed in 2011 and Future Planning

The major item of the 2011 vent was the installation of another set of 8 magnetic perturbation coils, completing the coil sets above and below the mid-plane to in total 16 coils. These will allow studies with magnetic perturbations up to n=4. In addition, a second DC power supply has been installed to allow for more flexible coil configurations. Two ICRF antennas have received boron coated limiters to reduce their tungsten source. In addition to enhanced tokamak performance, further insight is expected concerning the role of near antenna W sources in comparison to remote W sources from locations connected to the antenna via field lines.
New diagnostics include an upgraded Doppler reflectometer with steerable k-value, a poloidal FIDA system, a poloidal CXRS system on the high field side, an ITER prototype CXRS spectrometer, beam emission spectroscopy for density fluctuations using the Lithium beam, a permanent retarding field analyser, new bolometer lines of sight, a FADIS switch for in-line ECE and 2 disruption mitigation valves on the high field side.
The experimental program for the 2012 campaign was prepared during the autumn experimental break and has been discussed and iterated with the AUG team and finally endorsed by the AUG Programme Committee on Nov 29th. About 1200 priority 1 discharges are foreseen, with again almost 1/3 external contribution. The campaign is planned to last roughly till the end of 2012. Afterwards, another vent is scheduled for installation of a solid tungsten divertor III and possibly two new 3-strap ICRF antennas. Further planned mid-term upgrades comprise the exchange of the old ECRH 1 system by 2-frequency, long pulse gyrotrons (‘ECRH 3’, completion planned for 2016) and 8 midplane MP coils (‘A-coils’) with AC capability up to 3 kHz for improved ELM mitigation, rotating field studies and potentially resistive wall mode stabilization. While the design of the A-coils is almost complete, their installation has to be postponed for financial reasons. To proceed with the planned program on rotating fields, RF power supplies will be designed and installed in the next step allowing initial experiments with rotating fields using the existing B-coils for frequencies up to about 1 kHz.

2 ELM Mitigation with New In-vessel Saddle Coils

The first set of eight active saddle coils (‘B-coils’) has been operated during 2011. The coil arrangement is shown in figure 1. Most frequently, an n=2 configuration has been used, with either even or odd parity (polarity in upper vs lower ring). The figure also shows (in blue) another set of eight coils, which has been installed in 3Q and 4Q 2011 for up to n=4 operation from 2012 on. Early on, a mitigation effect on ELMs was found and subsequently, most experiments were aimed at characterizing its properties and access conditions.

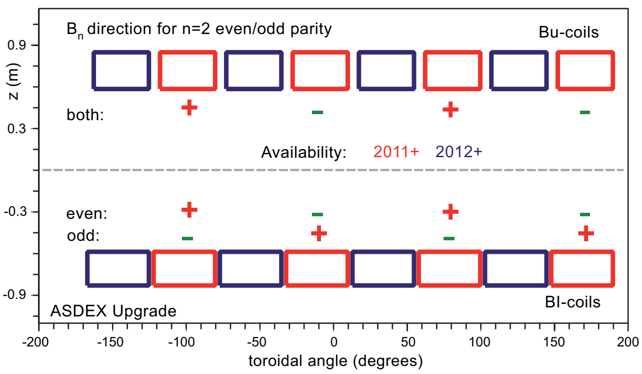

Figure 1: B-coils projected onto the outer torus surface and unfolded into a plane view. Available coils are marked in red.

ELM mitigation is demonstrated in figure 2, a side by side comparison of two phases with B-coils off and on, respectively, in the H-mode flat top of the same discharge, conducted with identical machine parameters. With B-coils off, type-I ELMs lead to significant losses of stored energy, particle and edge temperature (top three traces). There is a significant peak power load in both inner and outer divertor (shown are area-integrated thermography measurements). With B-coils on (n=2 configuration, odd parity, I_B=925 A), excursions of all of these quantities are much reduced. Magnetic measurements reveal that there is still ELM activity, however with benign particle and energy losses. The additional power load associated with these ‘mitigated’ ELMs is smaller than the inter-ELM power load in the outer divertor. The inner divertor remains detached at all times. In all cases encountered so far, a clear transition from type-I to mitigated ELMs is observed as the B-coil current is ramped up; there is no continuous evolution of the ELM losses.

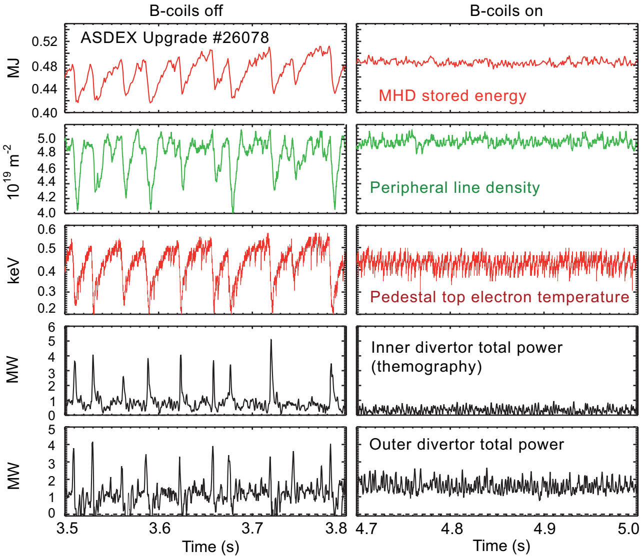

Figure 2: Time traces for typical B-coil on and off phases.

There seems to be no significant plasma performance reduction associated with ELM mitigation: Stored energy, plasma density and pedestal pressure in the mitigated phase remain close to pre type-I ELM values with B-coils off. Figure 3 shows edge density profiles, determined by Integrated Data Analysis from mm-wave interferometry and lithium beam data. The edge density gradient in the H-mode edge barrier region (R=2.07-2.10 m) does not change significantly as ELMs become mitigated, however the H-mode pedestal top density increases slightly. This is accompanied with an approximately 10 % pedestal top temperature reduction compared to pre type-I ELM values (figure 2, middle trace) such that the edge pedestal top electron pressure remains virtually the same. Effective ion charge, Z_{eff}, and tungsten concentration typically drop as ELMs become mitigated.

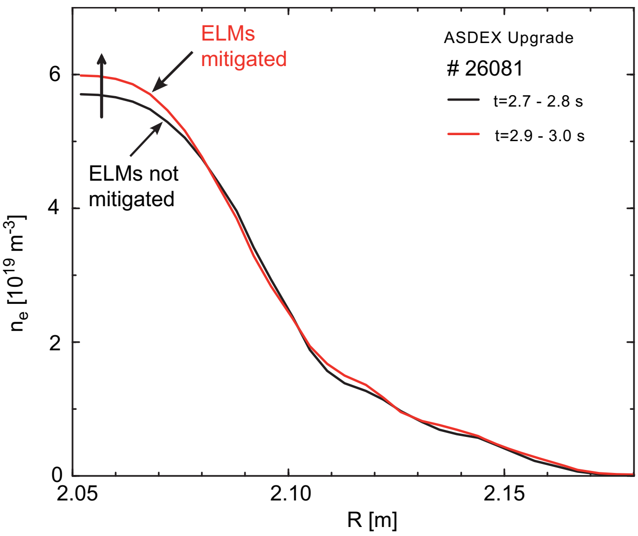

Figure 3: Edge n_e profiles with mitigated und not mitigated ELMs.

Further analysis is needed to determine whether this is solely an effect of reduced impurity influx caused by ELM-induced wall erosion or whether impurity transport in the main plasma changes as well.

Apart from presence of the magnetic perturbation, a main requirement for this ELM mitigation scenario is the plasma density exceeding a threshold. This is exemplified in figure 4, which shows time traces of a discharge with B-coils continuously on, where the transition from type-I ELMs to ELM mitigation is initiated by a small step of gas puff (third trace, t=3-3.2 s). As the plasma density (top trace) begins to rise very slightly, the frequency of type-I ELMs drops. During the longer inter-ELM times, the plasma density increases notably while the neutral density (second trace shows divertor neutral density) drops. This indicates improved particle confinement in the absence of large ELMs. After t=4.2 s, no type-I ELMs occur anymore, and the density levels off at a new, higher stationary level. So far, no 'density pump-out' has been observed together with ELM mitigation. At densities significantly below the threshold, and in particular in combination with nitrogen seeding, a reduction of plasma density can occur when switching on B-coils, in-line with observations in other tokamak experiments.

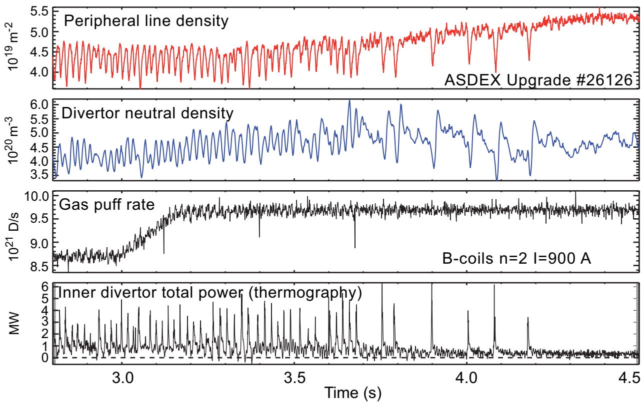

Figure 4: Time traces showing the n_e threshold of ELM mitigation.

A range of experiments have been made to determine the nature and scaling of the threshold density for ELM mitigation. Comparison of pre- and post-boronization pulses helps to disentangle neutral gas flux from plasma density and reveal that the threshold is one in plasma density. Its strongest dependence is on plasma current, and consequently the threshold is well described as the pedestal plasma density being a fixed fraction of the Greenwald density, f_{GW}=0.65. The presently available data set is not sufficient to rule out an edge pedestal collisionality threshold; however the safety factor (q_{95}) dependence, expected if the mean free path is normalized to the parallel connection length, is not observed. It should be noted that the pedestal temperature at the density threshold is typically well above the critical temperature for type-III ELM occurrence, so the mitigation effect is not simply a back-transition to type-III ELMs.

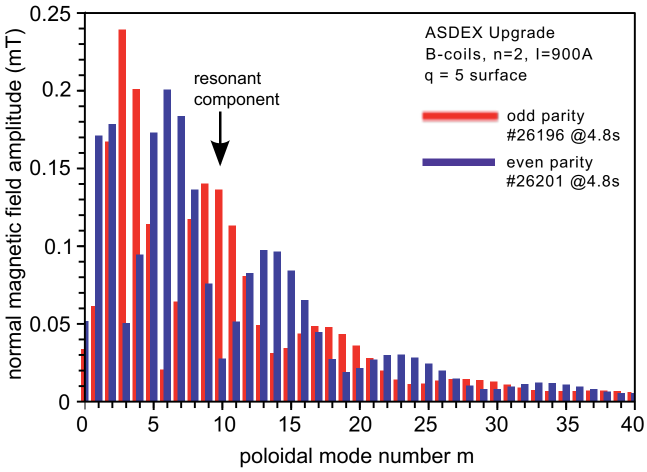

Figure 5: Poloidal mode number spectra for odd and even parities.

Access to ELM mitigation, as a surprise, does not seem to depend on whether the applied perturbation field is aligned with the equilibrium magnetic field ('resonant') or not. This can be tested with two poloidally separated rows of coils as they are presently available. For a few distinct values of the edge safety factor, the resonant perturbation amplitude is maximized for one parity and minimized for the other. For the low triangular plasma shape at safety factor q_{95}=5.5, odd parity corresponds to maximum resonant and even parity to minimum resonant field. Figure 5 shows the poloidal mode number (m) spectra for both cases (for the n=2 main toroidal component) on the q=5 surface. The resonant field amplitude at m=10 differs by about a factor of 5 for odd and even parity. It is important to note that because of the low magnetic shear at outboard mid-plane, between the two rows of coils, the resonance condition for odd parity is met simultaneously at all (q=half integer) surfaces in a large radial range between about 50 % and 97 % normalized flux. For odd and even parity, the B-coil current threshold for ELM mitigation has been measured in a pair of otherwise identical discharges (figure 6) and is found to be identical despite the

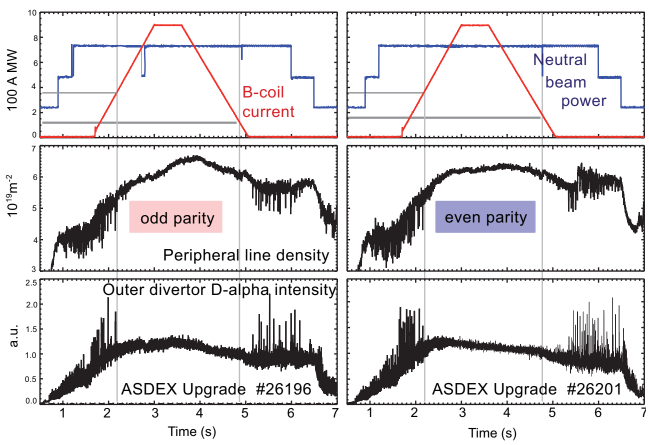

Figure 6: Comparison of B-coil current threshold for odd and even parities.

difference of resonant perturbation field amplitude. Larger ELMs re-occur only at a lower coil current and type-I ELMs comparable to those before onset of ELM mitigation come back only as the coils are completely switched off. It is a topic for further study whether or not this apparent hysteresis is a result of the higher plasma density when coils are ramped down. Cryogenic deuterium pellet injection into ELM-mitigated plasmas is characterized by high fuelling efficiency and favourable confinement at high density. Figure 7 shows a discharge with ELM mitigation from t=2.3 s on, in which the divertor neutral density is feedback-controlled by means of gas valves. Fuelling-size pellets are injected after t=3.3 s with two different repetition rates, with fuelling rates up to 1.5×10^{22} D/s. Due to feedback action, the gas puff rate is reduced by 5×10^{22} D/s, demonstrating the much better fuelling efficiency of the pellets. The plasma density increased from f_{GW}=0.76 to f_{GW}=0.9, while the MHD stored energy remains the same.

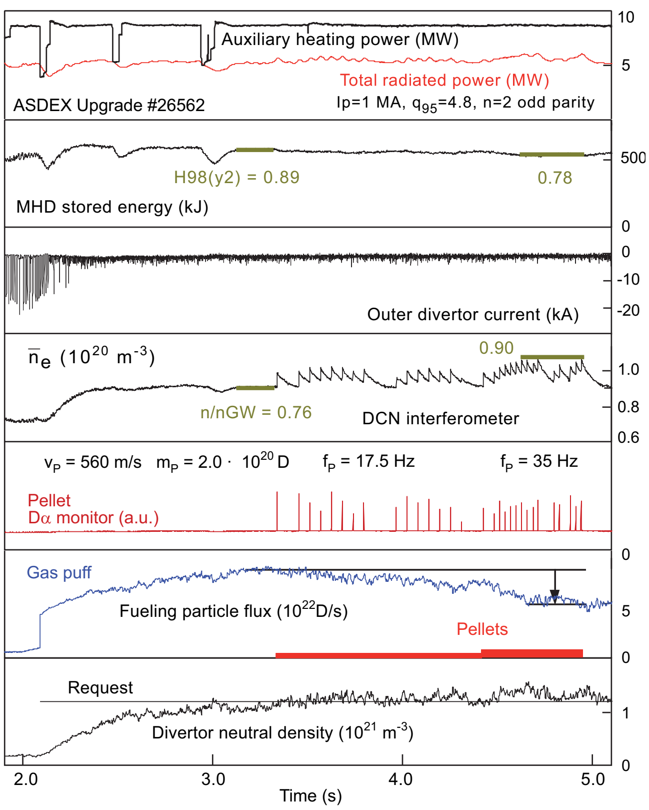

Figure 7: The traces show, that pellet injection during excited B-coils do not trigger ELMs.

A data base of all pellet-fuelled ELM mitigated plasmas shows that up to highest plasma densities the confinement follows the ITER H98y(2) scaling, if its positive density dependence ($\sim n^{0.41}$) is removed. A maximum line averaged density of f_{GW}=1.5 was obtained with pellet fuelling, with peaked density profiles and pedestal density somewhat below the Greenwald limit. Most interestingly, pellet injection into ELM-mitigated phases does not lead to triggering of large type-I ELMs, in contrast to injection into similar ELMing plasmas with B-coils off. Obviously, the mechanism that suppresses large ELMs is strong enough to withstand the large edge perturbation produced by pellet ablation.

3 Scenario Improvements

The improved H-mode scenario with I_p overshoot has been extended up to a normalised β_N of 4 and confinement up to an H-factor of 2.5. Up to now this could only be reached transiently and the high performance phase is terminated by strong MHD activity. The scenario uses a fast plasma current ramp up to 1.2 MA with NBI heating starting at the X-point formation and ending at maximum I_p. Then an ohmic phase with a current ramp down to 1 MA is introduced to modify the edge part of the q-profile. In the heating power ramp to about 10 MW many parameters, e.g. stored energy and electron density, but also the radiation, increase strongly.

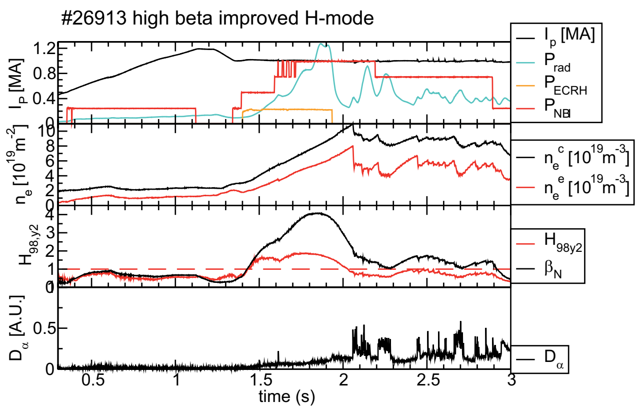

Figure 8: Time traces of an improved H-mode with I_p overshoot reaching β_n up to 4 with H98y(2) close to 2.

The most stable pulses so far utilise also on-axis ECRH for impurity control and off-axis ECCD to stabilise an occurring (2,1) mode in the periphery of the plasma. Unfortunately, the density increase is often connected to an ELM free H-mode phase and, therefore, not controlled. This leads to an ECRH cut-off and to the re-occurrence of the (2,1) mode, which ends the high performance phase. The MHD modes are located in the outer part of the plasma indicating that the very flat q-profile from an ASTRA current diffusion calculation is not unrealistic. The strong radiation build-up is located poloidally asymmetrically on the low field side from the mid-plane up to the top of the machine. This is thought to be connected to a very fast toroidal rotation, which produces a centrifugal force for W ($M_W \approx 6$) that tries to prevent penetration and a modified neoclassical transport at high rotation.
In figure 9 the temperature profiles for two different time points together with GLF23 calculations for the same pulse are plotted. In the first phase with low density an ion ITB forms in the core. At t=1.5s (on the left hand side) the ITB is still developing and only a peaking in the ion temperature can be seen. The GLF23 model on the other hand underestimates the transport largely and produces a much higher temperature without a strong internal barrier. Later a relatively broad ion temperature develops experimentally, but GLF23 overestimates the ion heat transport. In both cases the electron temperature is reproduced relatively well even though the radial structure and hence the gradients are not reproduced well. The reason for the discrepancies is not clear yet, TGLF calculations are under way.

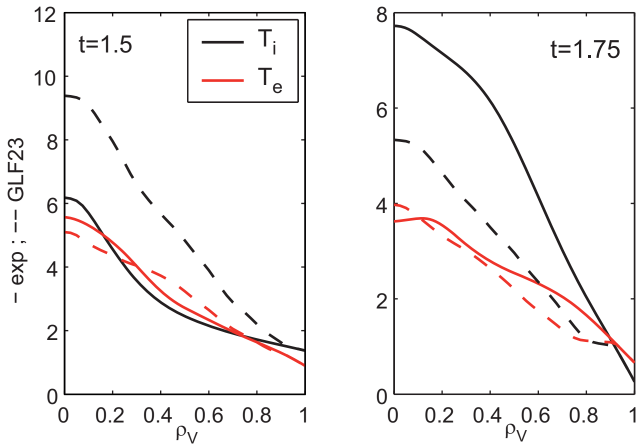

Figure 9: T_i and T_e profiles from experiment and GLF23 calculation from ASTRA.

The scenario for high power exhaust studies has been further extended up to 23 MW heating power using an optimized configuration of power supplies and a mix of NBI, ICRF and ECR heating. As shown in figure 10, the feedback controlled nitrogen seeding maintained the peak heat flux in the outer divertor below 5 MW/m², which is the current limit expected for DEMO. Despite the strong deuterium and nitrogen puffing, good H-mode confinement could be maintained.

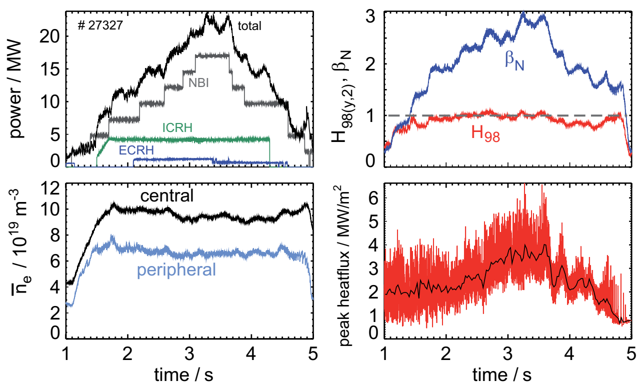

Figure 10: Time traces for a high power exhaust demonstration discharge with N_2 seeding (I_p = 1.2 MA).

The increase of available ECRH power in 2011, delivering now up to 4 MW, made an investigation into the influence of pure electron heating versus combined electron and ion heating on high collisionality H-mode plasmas possible. This was done by replacing both NBI and ICRF heating in small steps with ECRH while keeping the total heating power constant (time traces and kinetic profiles of replacing NBI, figure 11).

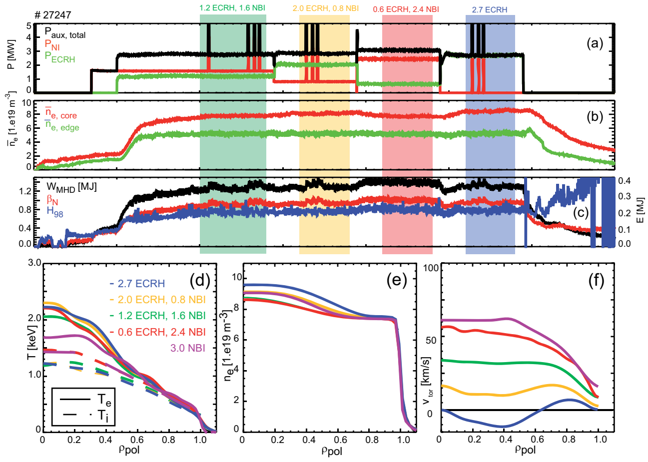

Figure 11: Plasma parameters of # 27247: (a) total auxiliary, NBI and central ECRH power; (b) line averaged density in the core, at the edge; (c) stored energy, and confinement H98y(2); averaged kinetic profiles during different heating phases: (d) T_e (solid) and T_i (dashed); (e) electron density; (f) toroidal rotation; purple traces taken from # 26457.

Thus the mixture of electron and ion heating was varied from around 50 % to 100 % of electron heating. The analysis of these experiments does not show any degradation in the basic plasma parameters and performance when replacing NBI and ICRF heating by ECRH. Furthermore, no difference between NBI and ICRF heating could be observed. The application of small amounts of ECRH power leads to a slight increase of the electron temperature and a slight decrease of the ion temperature. Both effects saturate when ECRH power amounts to one third of the total applied power. With increasing fraction of ECRH a slight increase in density peaking and a severe drop in rotation can be observed. When transitioning towards pure electron heating, the energy exchange term by Coulomb collisions increases so that the electron heat flux decreases over the entire plasma radius. On the other hand the heat flux in the ion channel is independent of the heating method and increases towards the pedestal top. The nature of the underlying micro-instability (ITG) does not change in this high collisionality domain when changing the heating mix. A thorough comparison with theory and a refined gradation of the replaced heating power will be addressed in further investigations.

4 L→H mode Transition and Pedestal Development

The L→H mode transition is caused by a reduction of turbulent transport in a narrow region at the plasma edge. It is widely accepted that the well of the edge radial electric field (E_r) plays a key role in turbulence suppression. However, the physics mechanism responsible for the L→H transition itself is still under investigation, as a trigger mechanism might be necessary. Recent measurements with Doppler reflectometry yield experimental evidence for the inter-play between Geodesic Acoustic Modes (GAM) and turbulence, in which the turbulence is suppressed by the GAM oscillation. This behaviour appears as limit cycle oscillations, labelled 'intermediate phase', and occurs prior to the L→H transition. Concomitant with the turbulence level, the transport oscillates between high and low values, while the E_r also displays strong modulation, convincingly suggesting that this mechanism may play a key role in the L→H transition triggering. The density dependence of the threshold power, P_{thr}, required to access the H-mode is non-monotonic and exhibits a minimum at a density named $n_{e,min}$. In AUG, this behaviour has been investigated over a wide density range, from $1\times10^{19}m^{-3}$ to 8×10^{19} m^{-3}, using ECRH. In particular, the increase of P_{thr} below $n_{e,min}$, which is not yet understood, has been studied in detail. The recent extension of the ECRH system allowed this region to be explored down to densities as low as 1×10^{19} m^{-3} while applying up to 3.2 MW of ECRH to reach the L→H transition. Under such conditions, the electron and ion heat channels are decoupled up to the plasma edge where T_e/T_i as high as 3.5 was recorded at the L→H transition. The clear separation of the two channels demonstrates the key role played by the ions in the L→H transition physics and explains the increase of P_{thr} towards low density through the electron/ion decoupling.

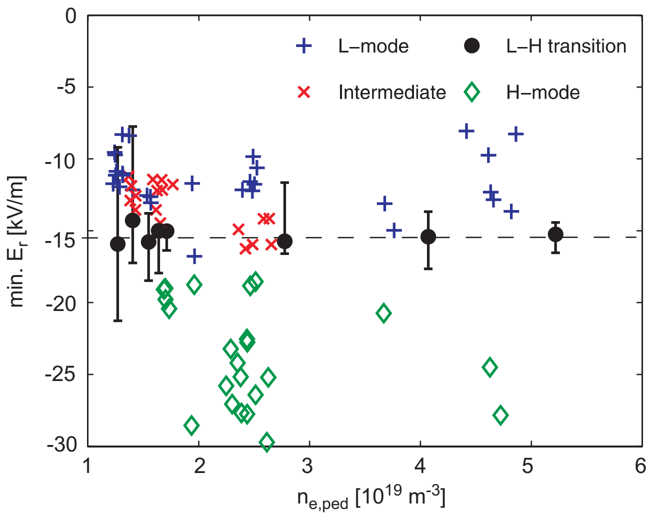

Figure 12: Minimum of the Er well at the plasma edge versus pedestal density for L-modes, intermediate phases, L→H transition points and H-modes.

In these experiments, the radial electric field profile can be estimated from the ion diamagnetic term. Its minimum is found to be constant at the L→H transition, independent of the density, which was varied over a wide range in this study, see figure 12. This strongly suggests that a minimum E_r shearing is required at the L→H transition. Thus, a possible picture of the L→H transition emerges: a minimum E_r shearing seems necessary prior to the L→H transition while the trigger might be provided by the turbulence suppression induced by the GAM and the transport reduction is further sustained by the increasing E_r well through the steeping of the ion pressure gradient as the H-mode develops.

In discharges with L-mode densities close to the threshold power minimum, $n_{e,min}$, the transition into the H-mode with its subsequent increase in density leads to an increase in P_{thr}. If the heating power is kept constant just above the threshold corresponding to the L-mode density, the heating power might be lower than P_{thr} for the developed H-mode density. Nevertheless, the discharges do not fall back into L-mode, but evolve to ELMy H-modes, demonstrating that the pedestal can develop at powers below the threshold.

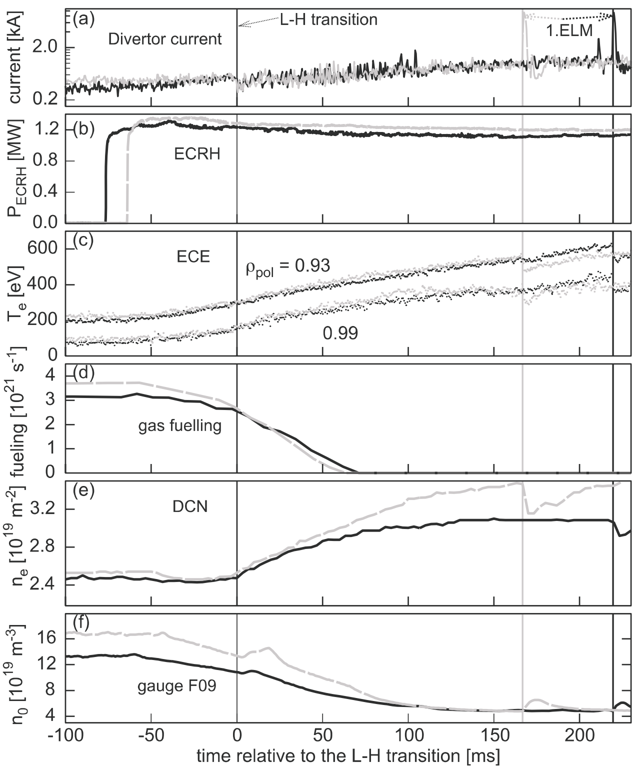

Figure 13: Time traces relative to the time of the L→H transition for 2 L→H transitions in black and grey (# 25438). Panel a) divertor current as L→H and ELM monitor, b) ECRH power, c) 2 edge T_e channels, d) D_2 fuelling rate, e) edge n_e, f) neutral density in the divertor. The transition with higher neutral gas density (grey) develops a higher density, and the first ELM appears earlier.

With the aim of distinguishing between transition induced changes in particle and energy transport, the development of the edge electron density and temperature profiles after the L→H transition was analysed in purely ECRH heated discharges, thus excluding a core particle source. A significant difference was found in the temporal development of electron density and temperature profiles in all phases across the L→H→L cycle. Selected time traces of two L→H transitions are shown in figure 13. The electron temperature increases from the start of the P_{ECRH} pulse and its rate of rise is not strongly affected by the L→H transition itself. When ECRH is turned on, no significant change in the edge electron density is seen until the L→H transition occurs. Then, the density increases sharply, even though the fuelling valves close. This implies a significant change in particle transport. In discharges with similar P_{ECRH} and L-mode density, the electron temperature develops virtually identically while the final H-mode pedestal top density depends on the neutral density in the divertor prior to the L→H transition. Consequently, the first ELM appears earlier for higher pedestal top densities. This is in line with the peeling ballooning theory, where a critical edge pressure gradient destabilizes an ELM.

After switching off the ECRH, the profile dynamics of the H→L back-transition were investigated. While the density at the pedestal top is higher and the temperature is lower at the H→L back transition, as compared to the L→H transition, the pedestal top pressure values are the same.

Large ELMs, including those occurring just after the L→H transition, are an issue for future devices. As presented in a previous section, above a given density, $n_{e,mitig}$, magnetic perturbations induced by external fields allowed the mitigation of the ELMs in fully developed H-modes. However, the magnetic perturbations also influence the L→H transition and subsequent ELMs, depending on the density. Below 0.5 $n_{e,mitig}$ the L→H transition is not affected and large ELMs generally occur. However, at higher density, P_{thr} exhibits a strong increase and exceeds its usual value by a factor of 2 for densities around 0.8 $n_{e,mitig}$. At intermediate densities of about 0.65 $n_{e,mitig}$ the L→H transition is followed by small type-III ELMs, which evolve to fully mitigated ELMs as density increases. This behaviour, for which the required heating power at the L→H transition is at most 20 % higher than the usual P_{thr} value, is a promising scenario for ITER.

5 Technical Systems

In 2011, the major focus of the experimental programme was on ELM mitigation through the application of an external magnetic perturbation field from the first set of B-coils (4 upper and 4 lower). The experiment was in operation for 86 days, performing 1320 pulses in total with 942 pulses useful for the physics program. 175 discharges were heated with more than 10 MW, and 6 of them with up to 23 MW.

During the operation period 2 unscheduled openings followed by vessel baking were necessary to fix problems. A broken vacuum window for ECE measurements had to be replaced in February and in May broken B-coil cover tiles had to be replaced inside the vessel. The second half of the year was used for enhancements: installation of the second set of the B-coils and diagnostic installations. In-vessel work started on August 1st and was finished with the closing of the entrance port on February 17th, 2012. The first plasma experiments are envisaged for February 28th, 2012. The in-vessel inspection immediately after the vessel opening in August revealed that the machine was in very good condition. Local surface modifications and melting were observed at leading edges of B-coil and inner column protection parts and 2 of the 128 tiles of the outer divertor. The large number of high power arc tracks in the vicinity of the PSL structure is one of the main causes for concern.

5.1 Machine Core

B-coil Installation and Diagnostics

During the 5 month of vessel opening two main tasks had to be fulfilled: (i) Installation of 2×4 B-coils at the upper and lower PSL including a modification of the pumping system to free space for the installation of current feed throughs for the lower B-coils and (ii) modification and installation of new diagnostics. The fixing points and flanges for the current feed throughs for all 2×8 B-coils were prepared during the 2010 opening. In September 2011 the remaining 2×4 B-coils were installed and the conditioning of the PEEK insulation, which separates the vessel potential of the current feed through from the PSL potential of the coil casing and acts as a CF gasket, was done by applying a short baking procedure in November 2011. By using anti-fatigue bolts and vacuum compatible lubrication the pre-tension across the PEEK gaskets could be increased. This way the actual conditioning could be limited to a single baking. The complete set of 2×8 B-coils are now installed. In addition to the coil installation, the lower B-coil protection tiles were hardened on the basis of FEM calculations to withstand a 3-fold load compared to the former tiles. The opening was used to modify existing and to install new diagnostics. A few diagnostic modifications were necessary because of conflicts with the B-coils. A main effort was the rewiring of the reflectometry antennas and the installation of a new re-entrance port for the vessel viewing system. Other diagnostic modifications can only be briefly mentioned. In total 3 valves for massive gas injection are now installed: one at the low field side and two at the high field side behind the protection tiles of the central column, toroidally separated by about 160°. For locked mode detection a set of 7 magnetic pick-up coils and 4 saddle coils were installed at the high filed side. The investigation of ion temperatures in front of the ICRH antennae is supported by a new retarding field analyzer mounted on a magnetic drive near the mid-plane connected along the magnetic field to the broad antenna limiter. The CXRS diagnostics were complemented by the addition of a poloidal high field side system. In addition, a new Li-beam observation head for fluctuation measurements and a test system for multiple pass Thomson scattering were installed.

Torus Pumping and Gas Inlet System

The modifications to the TPS caused by the B-coils are finished. All old turbo molecular pumps (TMP) are replaced by Pfeiffer TPU 2301 PN and contemporary S7 CPUs are installed. The 16 electrical feed throughs for the B-coils require a vacuum on the order of 10^{-3} Pa to prevent electrical breakdown during AC-operation. Calculations showed that due to the distance between the feedthroughs and the dedicated turbo pump the connecting tube must have a diameter of 100 mm to provide sufficient pumping speed. To achieve this, a completely new system was constructed consisting of four toroidal half-ring tubes, which encircle the torus to form two vertically displaced full-ring tubes close to the upper and lower B-coil feedthroughs, respectively. The ‘ring tubes’, each equipped with a full range pressure gauge, are connected to one common conduit, from which each half-ring tube can be separated by a gate valve. Each feedthrough can be separated from its ring tube by a pneumatic valve. The conduit will be pumped with a TMP (Pfeiffer TPU 2301 PN), which will be installed in a ferrous box for screening magnetic fields.
The gas inlet system allows the operation of 20 fast piezo valves in parallel. Up to now, each valve was firmly connected to a specific gas species. However, owing to a new gas matrix, the gas species fed to a valve can now be changed in between plasma pulses, which allows the reduction of the number of valves at equivalent positions. Gas feeding through the large A-Ports at the low field side should be minimized due to disturbances of optical diagnostics. For this reason the valves in sector 9 have been shifted to sector 3. The distribution of the valves was redesigned leading to 4 in A-ports, 8 in the lower and 4 in the upper divertor. For the upper inner divertor 8 additional tubes were built in. These tubes were fixed at sectors 2, 7, 10 and 14. Furthermore, they were connected with a valve assembly group at the corresponding Fo-ports. The valve assembly group consists of two compressed air controlled valves and is linked directly with the piezo valves. The final connection to the valve array will be done in 2012. Due to this upgrade a completely new concept of the gas injection control system is necessary. This control system will be implemented in 2012/13. A routine inspection of the inter-vacuum system revealed an intolerable leakage for the A-ports in sectors 11 and 13. An insufficient fastening torque of the bolts was identified as the reason. Fixing of the bolts reduced the leakage in sector 11 to a tolerable level but not in sector 13. Here, the vacuum sealing was recovered by a welded stainless steal shield inside the port. The bolts of the remaining 5 A-ports were preventively tightened to 120 Nm.

5.2 Experimental Power Supply

Over the last few years a lot of modifications and innovations have been implemented at the power supply facilities. Therefore, an IPP wide power failure test was performed in October 2011. The last test was in 2006. The aim was to check the protection systems that are important for the safety of people and facilities (e.g. emergency shut-down, emergency lights, alarm and detection systems). It included tests of the emergency mains and UPS units under almost real conditions. Furthermore, during the outage some important repair work was carried out. Regarding the generators, the effort to improve the plant safety has been continued. The mechanical braking system of generator EZ4 has been completed by the re-installation and commissioning of the modified clutch and disk brake that will brake the generator down from 200 rpm to zero. At the 10 kV side, the switchboard Group E has been extended by additional circuit breakers and current transformers to allow for redundant switching possibilities in case of emergency. The 400 V auxiliary power supply distribution board of EZ3, including the emergency power supply network, has been completely rebuilt to become state-of-the-art. On the measurement and control side, the focus was on the data acquisition of EZ2. A new recorder for fast analog transient data logging has been purchased and the former analog line recorder has been substituted by a digital WinCC display. At the high current converters, the intermediate power supply for the second set of B-coils has been prepared. The new coils have been connected and commissioned. To improve fault finding possibilities the old and fault-prone transient recorder has been replaced by a modern distributed data acquisition system. The former W7-AS high voltage power supply has been commissioned and is ready for operation on a dedicated load. The integration into the high voltage power supply network will take place in summer 2012. According to modules 3 and 4, the high voltage modules 1 and 2 have been modified to allow for negative voltages. Now it is possible to supply two independent test facilities (Batman and Elise) with negative voltage from a single high voltage converter (modules 1-4). The forces at the OH2u coil are a critical item. Therefore, stringent current limits depending on the main OH current are applicable. To identify potentially dangerous scenarios and to investigate possible corrective measures, the complete OH circuit has been simulated in 'Simplorer' and various anticipated fault scenarios have been analyzed.

5.3 Neutral Beam Heating

In the 2010/11 campaign neutral beam injection was used in 854 pulses and provided up to 17.5 MW heating power. All eight sources were operational most of the time, with few exceptions. In March 2011 the operation of injector II had to be interrupted for 21 days due to a leak at a bellows of the calorimeter. In the end of June a brief intermediate maintenance of the titanium sublimation pumps on injector II was carried out to ensure the availability of full NBI until the end of the campaign. Dedicated studies were conducted to characterise the behaviour of the neutral beam sources in pulsed operation. Pulsing is frequently used to provide power ramps and heating powers less than a full NBI source. It was found that the power during modulation is somewhat lower than expected, but the difference decreases with increasing modulation frequency. In addition, short (8-20 ms) beam blips for charge exchange spectroscopy are being requested increasingly often. A difference was found between the temporal evolution of the power of the extracted ion beam and the charge spectroscopy signal. The difference could be qualitatively attributed to an oscillation of the beam divergence during the first ~20 ms of the beam, which in turn appears to be a consequence of a minor initial oscillation of the beams perveance. In addition, short beam pulses of injector I into the neutral-gas-filled torus were provided for a first attempt at cross-calibrating various spectroscopy systems and determining the beam geometry with higher precision. The following experiment break was used for routine maintenance of the in-vacuum components. Because time permitted, two spare neutral beam sources that had been stored in vacuum for several years were mounted on injector I in exchange for the ones that were in use until then. The aim was to (re-)condition both in order to have ready-to-use spares at hand whenever needed and, furthermore, to gain experience for the upcoming conditioning of NBI sources for W7-X. Conditioning of the first spare source, de-conditioned due to a water leak in 2006, was mostly achieved after 750 pulses. Conditioning of the second source, which was well-conditioned at the time of storage, took less than 100 pulses.

5.4 Ion Cyclotron Resonance Heating

Experiments with the broad limiter antenna indicated that the design approach used to reduce the W impurity production from the ICRF antenna in a W machine is valid. The broad limiter antenna was a partial design optimization in order to test the design approach without too much additional cost (figure 14). Pushing the optimization further leads to the design of new, broader antennas with 3 straps. Following the conceptual design, which was optimized using HFSS and checked with TOPICA, a 3-D CAD model has been drawn and it is planned to have two antennas built in international cooperation, to be installed during the next long vessel opening.

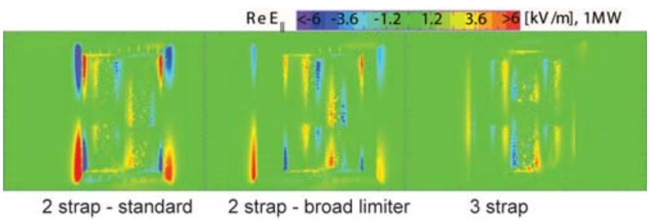

Figure 14: Comparison of the parallel electric fields for the 3 types of antennas.

During the present opening, the limiters of two of the regular antennas were coated with boron, so as to reduce directly the tungsten impurity production. This will allow ICRF to be used again on a more routine basis in a larger parameter space even before the installation of the new optimized antennas. One of the ASDEX/W7-generators was modified to operate with a commercially available EIMAC tetrode. The generator has been tested up to 1.5 MW. Following an upgrade of the cooling system, to adapt it to the different cooling requirements of this tetrode, the power of the generator will be increased with the aim of reaching 2 MW.

5.5 Electron Cyclotron Resonance Heating (ECRH)

In 2011 the ECRH 2 system operated with 2 more units (3 out of 4 planned units), bringing into operation 2 new beam lines. Except for the last missing gyrotron and the corresponding phase-correcting mirror-surfaces, the ECRH 2 system has been completed. The maximum power injected into the plasma by the ECRH 2 system was 2.4 MW for several seconds. Together with the old system (ECRH 1) 3.9 MW for 2 s (max. pulse length of the old system) have been reached. As expected, arcing in the new beam lines hampered operation, but is expected to reduce as the beam lines condition. There were several unforeseen problems with the ECRH systems such as the failure of a double-disk torus window in one of the new beam lines, several quenches of one of the new gyrotron magnets and a failure of the body insulator of the other new gyrotron. The latter two issues were settled by the manufacturer as part of the product guarantee. The window fault, which brings into question the concept of the multi-frequency torus-window, is being analysed by KIT (Karlsruhe). The ECRH systems have been used in the majority of the discharges in the 2011 campaign. Most applications used X2 or X3 heating with 140 GHz. In July an optimization of the O2-scheme has been successfully demonstrated using thermocouples integrated into the reflectors on the high-field side within a new real-time system. Differences between the temperature at the upper and the lower edge of the tile were used to adjust the vertical launcher angle within a few 10 ms. Also O1 heating at 105 GHz and B_t=3.2 T has been tested in order to test the sensitivity of the sniffer probes to a small amount of wrong polarization with respect to O1 operation in ITER. A multi-frequency system is still hampered by the window problem. If the disk thickness (here 1.8 mm) is a multiple of $\lambda/2$, the disk acts as a Fabry-Perot-Resonator, yielding the required low reflection for 105 GHz ($3\times\lambda/2$) and 140 GHz ($4\times\lambda/2$), but no solution has been found yet for intermediate frequencies. The concept of grooves on both sides of the disk, which would act as additional anti-reflective surface coating was abandoned in 2011, because calculations at KIT showed that the grooves reduced the tolerable pressure difference across the disk by a factor of 3 to just above one atmosphere, an unacceptable risk for disk and gyrotron. The final concept is a demountable ring-resonator. The beam leaves the gyrotron horizontally inclined via a 2-f window allowing 2-f operation to begin in July 2012. For intermediate frequencies, the ring resonator has to be mounted. It contains a second disk with identical reflection properties. With the help of an additional fast-adjustable mirror the reflection from this second disk is brought to destructive interference with the reflection from the first disk, such that all the power can leave the gyrotron. This concept will be demonstrated during the factory acceptance test in spring 2012. IPP is considering replacing the old ECRH 1 system (4×0.5 MW, 2 s) by a new system similar to ECRH 2 (4×1 MW, 10 s, 2-f), using the ECRH 1 ports. Planning for this project (ECRH 3) has started and additional funding from HGF has been granted.

5.6 CODAC

With the recently implemented concept of real-time diagnostic integration it was possible to achieve major progress in active plasma control. In collaboration with IST Lisbon it was possible to demonstrate that plasma position control can also be accomplished using reflectometry instead of magnetic measurements, a result that is also of interest for ITER. In particular, the outer plasma radius R_{aus} was reconstructed and controlled in L- and ELMy H-modes based on reflectometry data. Another application of the real-time diagnostic integration was ECRH heating in X3-mode using a holographic mirror tile. The gyrotron beam strike point on the mirror deflection caused by plasma density variation is compensated by a feedback controller using eight thermocouple probes from the DTR diagnostic. A number of new feedback controllers have been tested in preparation of the active NTM stabilization. The location of the NTM island is calculated by the ECE diagnostic, which was enhanced by integrating in an SIO data acquisition system. The diagnostic now features 64 channels with 1MHz sampling rate and 14 bit data resolution resulting in a data stream of 144 MB/s, which can be directly stored into a shared computer memory. This enables the localization of NTM islands with latencies below 2 ms. Simultaneously, the present ECCD deposition location is determined by the real-time TORBEAM algorithm using real-time measurements of the magnetic flux and density profile. The control system then moves the mirrors, until the locations reported by ECE and TORBEAM converge. Additional options like lazy tracking have been developed for the ECRH mirror control in order to reduce fatigue of the drive mechanics. For ECCD power a relay controller has been designed, which turns on the gyrotron only while the deposition is close to the NTM island location. Thus, all necessary components to close the NTM stabilization loop are available. Demonstration of the complete system will be attempted in the early phase of the next experimental campaign. The heavy use of integrated real-time diagnostics has proven to be a pillar for the development of advanced plasma control. In the future, the integration of even more diagnostics is expected. The CODAC group supports this trend by developing hardware and software infrastructure for these systems. The SIO system was further extended by dedicated ADC modules and digital I/Os. A series of 'normal' non-RT diagnostics such as lithium beam and the Doppler-reflectometry have been refurbished using the SIO concept. A successor of the current SIO solution, SIO II with data rates up to 1000 MB/s and higher channel numbers is already available in prototypes. In an ongoing effort the plasma control system is being ported from VxWorks to Linux and from a distributed single core to a centralized multi-core architecture. Thus, state of the art technologies can be used to further improve the performance of the control system.

6 Core Plasma Physics

6.1 Momentum Transport

Recently, significant progress in momentum transport studies has been achieved. Torque modulation experiments designed to quantify the diffusive and convective parts of the momentum transport were successfully carried out. These experiments confirm the presence of an inward momentum pinch and show that the Prandtl number is close to one, consistent with the strong coupling expected between ion heat and momentum transport in the presence of ITG turbulence. In addition, experiments in NBI heated H-modes have demonstrated definitively the presence of a counter-current intrinsic momentum flux when sufficient ECRH power is added. Lastly, an AUG intrinsic toroidal rotation database was created, which shows that counter-current rotation appears to be produced only when the logarithmic electron density gradient is sufficiently large and the turbulence is either in the TEM domain or close to the ITG-TEM transition. Local gyro-kinetic calculations suggest that these observations can be explained by the combination of residual stresses produced by E×B and profile shearing mechanisms. The interplay observed in these studies between the turbulent heat, particle, and momentum transport channels demonstrates the importance of a comprehensive approach to understanding core plasma transport.

6.2 Comparison of Different Sawtooth Crash Models for Transport

The sawtooth oscillation is one of the fundamental instabilities in tokamaks. It is associated with abrupt changes in central plasma confinement due to growth of an (1,1) mode. This growing mode leads to rapid crashes of the central electron temperature and proper modelling of such crashes is necessary for an accurate prediction of the plasma confinement. Transport code ASTRA was used to predict the plasma profile evolution using different models for the sawtooth instability: (i) Kadomtsev's full reconnection model; (ii) Porcelli's partial reconnection model; (iii) a new stochastic model where the safety factor is not affected and remains the same after the crash. The predicted changes of the measured angles for Motional Stark Effect (MSE) measurements calculated with ASTRA code were compared with MSE measurements. Analysis of the results from the measurements shows that Kadomtsev's and Porcelli's models overestimate real changes in the safety factor profile. Thus, the sawtooth crash does not affect strongly the safety factor profile i.e. I_p profile, but redistributes the temperature during the crash. This is in agreement with the new model.

6.3 Central Impurity Convection and Connection to MHD

The mitigation of central W accumulation through the use of central ECRH in H-mode discharges has been observed to correlate with non-standard sawtooth cycles where (1,1) modes saturate early in the sawtooth cycle. Such modes often relax in so-called 'inverse crashes', characterized by hollow SXR profiles before the crash and a rise of the central SXR emissivity at the crash time, despite still exhibiting a drop in the central electron temperature. The analysis of the T_e perturbation as detected from ECE has shown how such saturated modes can sometimes be clearly resistive. A combined analysis of the SXR and CXRS data has revealed that the hollowness in the SXR profiles is due to hollow W density profiles, while light impurities remain flat or slightly peaked. In such cases, the transport of W cannot be characterized through perturbative transport studies since the transport is changing during the sawtooth cycle itself. Moreover, the non-axisymmetric geometry of the system due to the presence of the mode has to be taken into consideration. Analysis tools are therefore being developed to simulate the SXR emissivity in 3D including the (1,1) magnetic perturbation, and to model the transport of W during (1,1) mode activity.

6.4 Transient Behavior of n_e vs T_e during Modulated Central ECRH

In recent experiments, the transient response of density and temperature to pulsed central ECRH was investigated. A density response to central heating is often observed in L-mode discharges, but also exists in some H-mode cases. It was found that in the presence of square wave ECRH power modulation, the temperature responds faster to changes in the applied heating power than the density. In the local density-temperature diagram, this results in the occurrence of a hysteresis loop, as illustrated in figure 15. This loop can be explained by today's transport models.

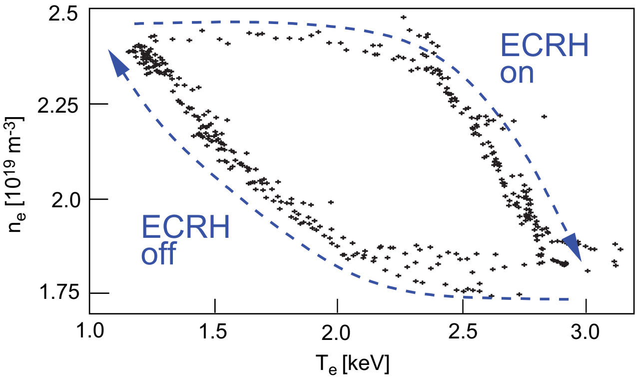

Figure 15: n_e vs. T_e scatter at $\rho = 0.5$ during modulated ECRH.

6.5 Fast Particle Physics

In H-mode discharges, the behavior of the fast-ions in the type-I ELM stabilization by externally applied resonant and non-resonant magnetic perturbations (MP) has been investigated using FILD detectors. The mitigation of type-I ELMs by (externally applied) n=2 non-resonant MP is accompanied by a rather large loss of fast-ions, steady in time, with a broad band frequency and whose amplitude is correlated with the current in the MP coils. The measured lost fast-ions are on banana orbits that explore the entire pedestal width. Fast-ion radial profiles have been studied using Fast-Ion D_α (FIDA) spectroscopy. The measured FIDA profiles are compared to theoretical fast-ion distribution functions from TRANSP using the forward modeling code FIDASIM. In the absence of MHD instabilities good agreement is found between the measured and predicted on- and off-axis NBI profiles when neoclassical transport is assumed. The fast-ion transport induced by sawtooth crashes has been studied. A clear drop of the central fast-ion density is observed together with an increase of the fast-ion population outside the q=1 surface.

6.6 ICRF Induced Intrinsic Rotation

The effect of RF heating on intrinsic plasma rotation is of particular interest. A series of shots were performed using pure ICRF D(H) minority heating scenario with a symmetric antenna spectrum. The purpose of these experiments was to investigate the effect of the ICRF resonance position on the plasma rotation by varying the central magnetic field, and investigate the omnigenity breaking mechanism contribution into plasma rotation. Figure 16 shows rotation profiles measured with CX spectroscopy for 3 different positions of the ICRF resonant layer. Numerical simulations are underway.

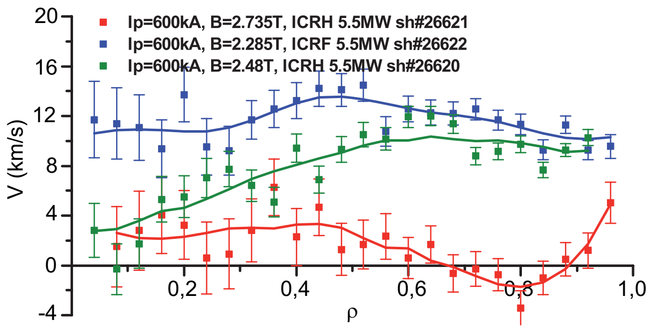

Figure 16: Rotation profiles at three different B_t.

6.7 Characteristics of Ion Cyclotron Emission

We have carried out 2011 the first experiments to trigger Ion Cyclotron Emission at the edge with NBI and ICRF heating. This instability occurs when fast ions born in the center (like fusion products or minority species accelerated by RF fields) have enough energy to graze the plasma edge, to resonate with the background ions at harmonics of the cyclotron frequency, and to excite the compressional Alfvén eigenmodes. The resulting emission can be measured with small cross-dipole antennas located on the sides of the vacuum vessel. It is thus a promising non-intrusive method to get information of the distribution function of fast ions. The difficulty is to find the range of plasma parameters, which sustain this phenomenon and to untangle the contributions from the density profile and from the fast ions velocities. The results showed that a power level above 8 MW NBI and an edge density lower than $4.5 \cdot 10^{19} m^{-3}$ are required to excite this emission. A short signature of ^3He and of protons was noticed, although the latter was hard to distinguish from the stationary cyclotron emission due to the edge-ionized deuterium from the neutral beam. With ICRH, we were not able to reach an edge density low enough (under $3 \cdot 10^{19} m^{-3}$) to excite the emission.

6.8 Massive Gas Injection from the Inner Wall

A new gas valve was developed and mounted on the high field side (HFS) in 2010. In terms of opening time, amount of gas injected and flow characteristics, the valve is similar to the one already mounted on the low field side (LFS) inside the torus. Nevertheless, it was dimensioned anew, in order to make it fit behind the HFS heat shield, where there is less space than on the LFS. The number of discharges shut-down with the HFS valve is presently limited to 5, due to a premature failure of the valve stem. However, these preliminary experiments already show that the new HFS valve has a significantly higher fuelling efficiency (F_{eff}) than the LFS one. F_{eff} is calculated as the ratio of the line integrated density measurements, averaged over the plasma during the I_p quench, and the total amount of gas injected by the valve. F_{eff} is found to be in the range of 35-55 % (compared to 20-30 % for the LFS), increasing with plasma energy and decreasing with the quantity of injected neon. Although it is reasonable to attribute the larger HFS F_{eff} to the $E \times B$ drift, there is no direct experimental observation of it at the moment. A large fraction of E_{th} is radiated during the cooling phase and the thermal quench, mostly in the sector of the valve. The AXUV diagnostic, which measures the spatial distribution of the radiated power, shows a very fast redistribution and penetration of the impurities into the plasma core during the thermal quench. The radiation emission during the I_p quench is toroidally symmetric. The improved performance of HFS compared to LFS injection motivated the installation of a 2nd HFS valve 2011 in the attempt to reach n_c.

6.9 Real-time Magnetic Equilibria for NTM Experiments

Real-time magnetic equilibria are required for the microwave ray tracing code calculation of the mirror angle necessary for driving current on the rational surface where a neoclassically tearing mode island (NTM) is located. The equilibria are calculated by a real-time Grad-Shafranov solver constrained to fit 40 magnetic probes and 18 flux loop differences. The solver was extended to include 10 further constraints on the plasma core I_p profile from the Motional Stark Effect (MSE) diagnostic, and a cycle time of 0.75 ms for 6 fitting coefficients was achieved. The q-profile is calculated from flux surface contour integrals at 5 values of normalised poloidal flux. Rational surfaces are located as a function of normalised radius by spline interpolation. These normalised radii and the 33×65 poloidal flux matrix are available on the reflective memory network with a 3 ms cycle time. From ECE T_e fluctuation measurements at the mode frequency of the NTM, it is inferred that the NTM is located at a normalised radius of 0.55 in the scenario used. In the absence of MSE measurements in the current campaign, it proved necessary to choose appropriate basis I_p profiles for the solver to predict this value of the normalised radius of the NTM rational surface.

6.10 Progress on Real-time NTM Control

Stabilization of NTM at AUG uses electron cyclotron current drive (ECCD) inside the magnetic island. Considerable progress now has all individual components (ECCD beam steering, mode detection and localization) tested and they are working as required. Using 1 MHz ECE measurements, we can reliably localize the island in real-time with a correlation technique. Between the n=2 magnetic signal and each ECE channel, a correlation amplitude and phase can be determined. This data identifies the island O-point in normalized magnetic flux coordinates r. Based on the island position r_{NTM}, the beam-steering mirror can be set appropriately. The required mirror angle (α_{set}) is determined by extrapolating from the current deposition location (r_{tbeam}) and the necessary change of the deposition ($dr=r_{NTM}-r_{tbeam}$) with respect to a small change of the mirror angle ($\Delta\alpha$) at the current setting of the launcher (α_{meas}):

$$\Delta\alpha = \alpha_{set} - \alpha_{meas} = \rho_{tbeam} \cdot \frac{\delta\alpha}{\delta\rho}(\alpha_{meas}) - \alpha_{meas}.$$

The inputs to this process come directly from the TORBEAM code, which is calculating r_{tbeam} and $\delta\rho/\delta\alpha(\alpha_{meas})$ using a numerical derivative. Having now all ingredients available, we will close the feed-back controlled loop for active NTM control in 2012.

6.11 Simultaneous Core and Edge n_e and T_e Profiles with the Upgraded Thomson Scattering System

In the past years a single Thomson scattering (TS) system with 16 spatial channels and 6 lasers as light sources was used to measure *alternatively* n_e and T_e profiles either in the plasma core or the edge. Thus for plasma edge pedestal studies two discharges with the same parameters were required with the TS system set first to the core and then edge position. A newly constructed TS system with 10 spatial channels and 6 lasers is now in operation, which measures the n_e and T_e profiles at the plasma edge in each discharge. For minimum light loss the scattering volumes are directly imaged through air onto the photo-detectors. The older TS system, now with 4 lasers, is used for the plasma core. Both the core and edge n_e and T_e profiles, measured by TS, are now available *simultaneously* for any discharge, thus saving experimental time.

6.12 Impurity Density Determination using CXRS and BE Spectroscopy

Charge exchange recombination spectroscopy (CXRS) on the neutral heating beam is a well established method to measure impurity density profiles. The impurity density can be determined from the measured radiance provided the densities of the neutral beam species are known. The beam observation optics of one beam line has been refurbished and equipped with 3 rows of 30 fibres. At the observed beam, the images of the 3 rows are vertically separated by only 1.6 cm, which is small compared to the beam height of about 30 cm. This offers the possibility to measure CX and D_α emission of the beam on virtually the same lines-of-sight to obtain a measure of the neutral beam densities. A spectrometer for beam emission (BE) spectroscopy has been operated during the last campaign. The spectra are fitted by a function that contains a model for the MSE spectrum of each energy component and the beam halo. This delivers the neutral D densities in the n=3 state, from which the densities in the n=1 and n=2 states are calculated with a collisional-radiative excitation model (ADAS). A first analysis yields a strong contribution of excited halo neutrals to the active CX-signal, which so far had not been taken into account.

6.13 First Neutron Measurements with a Compact Spectrometer

A compact neutron spectrometer installed at ~10 m distance from the torus measures the neutron energy distribution functions with a perpendicular view through the tokamak midplane. The 2011 campaign delivered useful measurements, with good statistics already at integration times of ~100 ms for NBI discharges. The digital pulse-shape discrimination is good (figure 17a)). Pulse Height Spectra (PHS) are broader for perpendicular NBI (figure 17b)), as expected. There is evidence of a synergy effect between NBI and ICRH. In disruptive discharges ~MeV γ are detected. PHS de-convolution will allow the inference of neutron energy distributions.

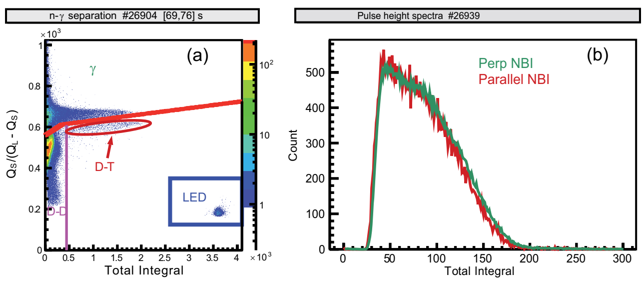

Figure 17: γ-n separation (a) and PHS with perp. (green) and parallel NBI (red) (b).

6.14 X-Ray Pulse Height Analysis (PHA)

A new silicon drift detector in combination with a digital signal analyzer allowed X-ray survey spectra to be recorded in the range 0.9-15 keV. In particular, W lines composed of n=2→3,4 transitions in ionization states W^{60+}-W^{65+} have been found for the first time in a fusion plasma during transient phases with T_e up to 18 keV (figure 18). In the lower T_e range the spectra are dominated by tungsten M lines from W^{38+}-W^{49+} ions. But frequently also pronounced lines from Ar, Fe, Cr and Ti impurities were observed. In particular cases impurity concentrations could be derived from line intensities and central T_e via the slope of the continuous spectra. In addition, the PHA measurements allowed for cross calibrations between different diagnostics.

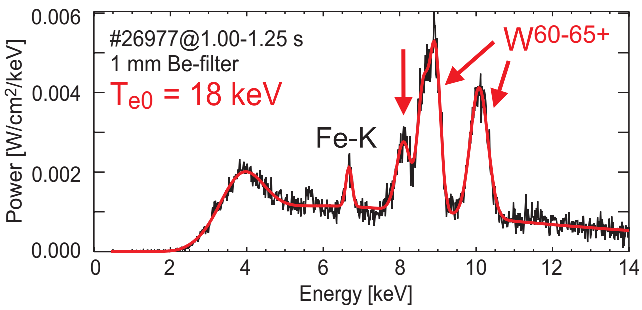

Figure 18: Typical PHA spectrum at high T_e.

7 Edge and Divertor Physics

7.1 Solitary Magnetic Perturbations at the ELM Onset

AUG is equipped with a set of fast sampling diagnostics well suited to investigate the chain of events during ELMs. In this process *solitary magnetic perturbations* (SMPs) are identified as a dominant feature of radial magnetic fluctuations. They are typically observed half a millisecond before the onset of pedestal erosion. SMPs are field aligned structures rotating commonly in the electron diamagnetic drift direction. Comparison of perpendicular rotation velocities yields that they are generated by current perturbations at or inside the separatrix. For very pronounced examples of SMPs a number of peaks per toroidal turn less than 3 has been found. A comparison to linear stability calculations suggests that SMPs are a signature of the non-linear ELM phase. In some discharges precursors of type-I ELMs were observed. They appear earlier and with different features compared to SMPs. Using gas puff imaging, ELM filaments have been observed. Considering 3D geometry their onset time is often well described by the passing of an SMP at their location. Owing to these properties, SMPs are regarded as signature of a central sub process in the ELM evolution.

7.2 Edge Snake in between Type-I ELMs

The Edge Snake is a MHD instability in AUG during type-I ELMy H-modes. It is best described and simulated as a magnetic island with a defect current inside the O-point of the island, which is located in the steep gradient zone in the outermost centimeters of the plasma inside the separatrix. This current wire is radially and poloidally strongly localized, and the temperature and density profiles flatten therein. This significant reduction of pressure gradient leads to a reduction of the neoclassical Bootstrap current and can plausibly explain the drive of the instability. The Edge Snake has a fundamental toroidal mode number of n=1, a poloidal mode number around m=6 and a mode frequency of around 2 kHz. It occurs only during type I ELMy H-modes, but is not clearly related to the ELM cycle. The Edge Snake can be clearly distinguished from similar instabilities at like EHO, Palm Tree, Picket Fence, Wash Board or Outer Mode.

7.3 Observations of ELM-induced Radiation with AXUV Bolometry

The recently installed AXUV diode bolometry system offers a high temporal (5 µs) and spatial resolution to study ELM induced radiation. Its temporal evolution can well be observed, e.g. the rise time at the beginning of the ELM with 50-100 µs. As seen in figure 19, radiation already appears before the ELM induced poloidal current is measured at the target plates. This indicates radiation buffering, i.e. part of the ELM resolved energy is already radiated before it reaches the wall. Also a time delay between the radiation at the outer and inner divertor of around 50 µs can be measured.

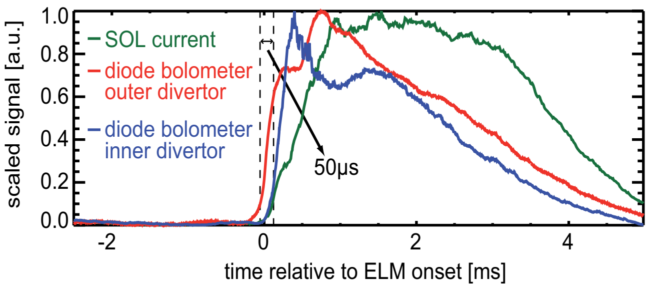

Figure 19: Coherent ELM-averaged signals of diode bolometry and poloidal current.

7.4 Edge Pedestal width Studies

A pedestal database was built for type-I ELMy H-modes of AUG, DIII-D and JET. The pedestal width, Δ, was determined directly before an ELM crash with the two-line method. Applying the same method to data from all machines reduces uncertainties, which might arise due to the use of different analysis codes. Therefore, it is possible to identify dependencies in the data set, which might otherwise be invisible. A strong shape dependence of the coordinate transformation between flux and real space coordinates was found. This also means, that although in flux space the pedestal width strongly depends on the plasma shape, this dependence is reduced significantly in real space. For theories based on MHD physics the pedestal width is set in the pressure. Therefore, the pedestal widths of temperature and density should be the same. However, in the database Δ_{Te} and Δ_{ne} show a different scaling. Both widths similarly depend on machine size, poloidal magnetic field, pedestal electron temperature and density. The difference arises with the ion temperature and the toroidal magnetic field. The electron temperature pedestal width depends on ion temperature and not on the toroidal field. The density pedestal width is influenced by the toroidal field but not by the ion temperature.

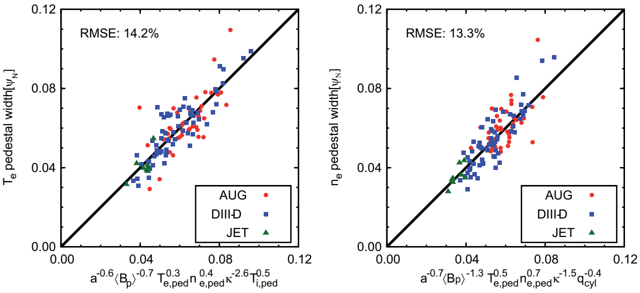

Figure 20: Best fits to the pedestal width database.

7.5 Edge E_r Profiles Derived from CXRS

The installation of a new poloidal CXRS diagnostic enabled the determination of the radial electric field, E_r, at the plasma edge. The system provides highly-resolved radial profiles (~5 mm) of impurity ion temperature T_i, density and poloidal rotation v_{pol}. In conjunction with the existing toroidal edge CXRS diagnostic E_r can be derived from the radial force balance. The new system has been validated using the T_i and intensity profiles of both edge CXRS diagnostics and good agreement has been found. For the impurity ions the E_r well is found to be dominated by the v_{pol}-term in the radial force balance. A consistency check of the E_r profile has been performed by determining E_r using the CX spectra of different impurities (He^{2+}, B^{5+}, C^{6+}, Ne^{10+}). It was found that the obtained E_r is reproducible within the uncertainties regardless of the impurity species used for the analysis. This good agreement provides confidence for detailed analysis of the position and shape of E_r. E_r was also studied in plasmas, in which the magnetic perturbation coils were applied. E_r profiles were compared in ELMy and ELM-mitigated phases. No obvious effect on E_r was observed due to magnetic perturbations.

7.6 Far SOL Intermittency with Non-axisymmetric Magnetic Perturbations

The influence of non-axisymmetric magnetic perturbations (MP) on the intermittency, using a reciprocating probe in the far SOL at the outer mid plane was studied. The applied MP was n=2 with odd parity. An H-mode scenario with I_p=0.8 MA, B_t=-2.5 T and 9.5 MW of additional heating power was investigated. The density was ramped from 6.5 to 7.3×10^{19} m^{-3}. Three reciprocations were performed: without and with MP at lower and with MP at higher n_e. ELMs are mitigated at higher n_e only. With the MP changes in the SOL transport occur already at low n_e. The ion saturation current (I_{sat}) profile increases and flattens in the far SOL. Also in the normalised PDF of I_{sat} the transport modification becomes visible when the MP is switched on – the intermittency is reduced. There is no further change of the PDF when ELM mitigation sets in while n_e is increased. Even when ELMs are mitigated strong but less frequent I_{sat} peaks occur in the far SOL with peak values as high as during type-I ELMs in the reference case. Related energy losses are low. These peaks have to be density blobs at rather low temperature. This is supported by T_i measurements.

7.7 T_i of ELM and Turbulence Filaments in the SOL

First systematic measurements of ion energies in ELMs and turbulence filaments were carried out in the scrape-off layer using a retarding field analyzer probe (RFA). Ion energies in type-I and, for the first time, mitigated ELMs were measured 35-60 mm outside the separatrix. The ion temperature averaged over an ELM, $T_{i,ELM}$ is in the range of 20-200 eV, which is 5-50 % of the ion temperature at the pedestal top. $T_{i,ELM}$ decreases with the separatrix distance and increases with the ELM energy. This suggests that the filaments in large ELMs propagate faster radially on average. Lowest $T_{i,ELM}$ was measured during mitigated ELMs. The ELM power fluxes estimated from the RFA data compare favorably with the ELM power loads to the probe head monitored by an infrared camera. First measurements of the ion temperature in L-mode turbulence filaments, $T_{i,turb}$ were obtained, providing useful information for turbulence modelling. At 2 cm outside the separatrix $T_{i,\,turb}$≈80-110 eV, which is 3-4 times that of the background ions and 50-70 % of the ion temperature at the separatrix. Gyrofluid turbulence code GEMR was employed to test the reliability of the method used to measure $T_{i,turb}$.

7.8 Poloidal Asymmetry of Toroidal Rotation

Beam-based CXRS provides the parallel and poloidal impurity flow velocities at the outboard midplane (LFS), while a deuterium-puff based CXRS measurement provides the parallel impurity flow velocities at the inboard midplane (HFS). The measurements from both locations are aligned according to T_i (figure 21a)). The flow measurements are depicted in figure 21b). The continuity equation applied to a flux surface requires the HFS flows to be described by the purple curve.

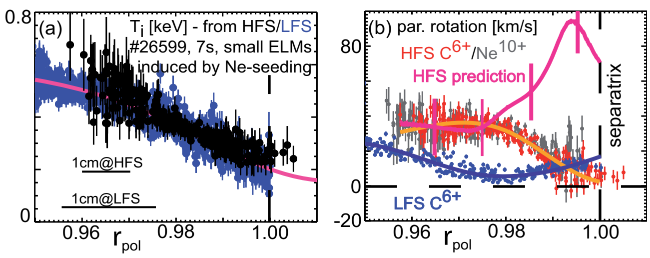

Figure 21: Edge profiles of T_i and v_{pol} at the HFS and LFS.

At the outermost region, the observation does not agree with the expected flow velocity. Thus, it is planned to refine the model, allowing for impurity density asymmetries on a flux surface and taking radial transport into account.

7.9 I-mode Studies

The I-mode, originally labelled 'improved L-mode' at AUG, emerges gradually from the L-mode when sufficient heating power can be applied without triggering an H-mode, as achieved in 'unfavourable' magnetic configurations with a high H-mode power threshold. The transition from L to I mode, which occurs indifferently with NBI, ECRH or ICRH, requires a minimum heating power, which is proportional to density and higher than the 'favourable' H-mode threshold. The I-mode exhibits good confinement, but, despite the absence of ELMs, seems not adequate for a reactor as it requires high heating power. The good I-mode confinement is provided by a temperature pedestal while density keeps L-mode characteristics. The pedestal develops slowly with a concomitant deepening of the edge radial electric field well, E_r. This evolution can happen at constant heating power, suggesting a feed-back between E_r and turbulent transport reduction, as supported by a gradual decrease of the measured turbulence level. Moreover, the I-mode pedestal evolution often leads to an H-mode transition, underlining the importance of E_r in this phenomenon. Understanding these observations would shed light on pedestal physics.

7.10 Inter-ELM Power Fall-off Length for JET and AUG and Extrapolation to ITER

The power decay length, λ_q, in the SOL region is a crucial quantity concerning the divertor peak heat load for current and future devices. Despite the importance of an accurate prediction of λ_q, a commonly accepted theoretical model or empirical extrapolations from current devices to ITER remains elusive. Such an attempt must include at least two devices with different linear dimensions to establish the major radius dependency. Data from AUG and JET are used to establish this dependency. In earlier attempts, the radial movements of the strike line on target, with amplitudes reaching up to the power decay length itself and modulated by ELMs were ignored. Here, this effect was carefully taken into account by making use of state-of-the-art thermography with about 10 kHz temporal resolution. The resulting scaling shows linear dependency on q_{95}, inversely linear to poloidal magnetic field and notably no major radius dependency. Extrapolation to ITER (for I_p=15 MA and Q=10) gives λ_q=1 mm. It is yet unclear if the corresponding integral λ, defining the actual peak heat loads, can also be scaled to ITER from the current data base, or if the different divertor geometries of JET and AUG need to be taken into account.

7.11 Modifications to ICRF Antenna Design to Reduce W Release during Operation

Guidelines have been developed with the help of EM finite-elements calculations to reduce parasitic parallel RF electric fields in front of the ICRF antenna and reduce the tungsten release during ICRF operation. One of the ICRF antennas has been modified prior to the 2011 experimental campaign in accordance to the guidelines. The modifications included broader antenna limiters, modified antenna straps and additional RF current carrying surfaces. It has been observed that the new antenna has a better balance between ICRF heating and the W source. This allows ICRF operation at lower gas injection rates without W accumulation inside plasma. A quantified comparison of limiter spectroscopy measurements is difficult because of the different geometry of the new antenna limiters. Nevertheless, there are indications of lower W source at the new antenna. The question remains whether the improvement in operation is due to the reduction of parallel RF electrical fields or due to the changed geometry of the magnetic field line connection lengths because of the modified antenna limiters.

7.12 Evolution of Surface Melt Damage and its Influence on Plasma Performance

The study of melt behaviour of castellated structures in a tokamak is crucial for the operation and design of full metal divertor concepts in future devices. Here castellated tungsten structures with a dedicated leading edge were exposed in the divertor manipulator to study the influence of melt events on plasma exposed surfaces and the plasma discharge itself. Structures similar to the design of respective ITER PFCs were used to study material re-distribution as well as re-solidification and subsequent power handling. At a total heating power of 10.6 MW with 0.6 MW ECRH, a plasma current of 0.8 MA and toroidal field of 2.4 T, the strike point position was moved from an area next to the divertor manipulator on top of the castellated structure to induce melting. Roughly 80 MW/m^2 impinged onto the leading edge. Moving the strike point onto the target lead to melting with a clear loss of tungsten droplets into the divertor – the plasma did not disrupt despite the obvious tungsten emission. A repetition of the same pulse was not possible owing to a strong event related to the loss of larger amounts of tungsten from the pre-damaged structures and re-solidified melt. Post-mortem analysis revealed that the leading edge prevailed despite clear melting.

7.13 EMC3-Eirene Simulations of Spatial Dependence of the W Divertor Retention

The Edge Monte Carlo 3D (EMC3) Eirene code package is applied to simulate the deuterium plasma and neutral particle as well as the W impurity transport. Good agreement is found for the deuterium bulk plasma for an L-mode discharge, both in the upstream and downstream profiles. The tungsten concentration in the core is computed for a point source placed at different positions around the outer strike point. Comparing the mean impurity residence time for divertor and main chamber sources yields the divertor retention factor R, which shows a very strong dependence on the location of the source relative to the strike point and also on the discharge parameters. While the tungsten transport is strongly suppressed directly at the strike point, it becomes much more efficient in the region 20-100 mm above it. The dominant physical mechanism to explain this effect can be understood by a simple model for the impurity force balance along the field lines in front of the divertor target plates.

7.14 Electron Density Measurements in Detached Divertor Plasmas via Stark Broadening of the Balmer Lines

In the detached regime, the region of high recycling electron density is retracted from the target and Langmuir probes do not provide information of the plasma in the divertor volume. Based on the Model Microfield Method an electrical field is determined in a statistical manner and applied to calculate the Stark broadening of the D_ε line of the deuterium Balmer series. A least square fit to the measured spectra enables n_e for values larger than 3×10^{19} m^{-3} to be determined. Lines of sight ending in a viewing dump for minimizing stray radiation have been installed. Their geometric alignment allows a volumetric reconstruction of the line weighted n_e. With this new diagnostic the movement of the front of the electron density to the X-point and the formation of a zone with high neutral density situated between the front and the target has been measured during the evolution of the plasma towards complete detachment. Measurements have been taken in forward and reversed B_t-field direction. Large n_e and ion flux densities are measured in the far SOL in L- and H-mode discharges, consistent with interferometric and neutral flux measurements. Nitrogen seeding reduces the extension into the far SOL of the high n_e and ion flux density region.

7.15 Study of Dust Particle Populations

To collect dust, a box containing a Si wafer was mounted. This technique allows capture of dust particles, which are mobilized during plasma operation. A defined substrate as Si wafers enables automatic SEM analysis. Typically, 10.000 EDX spectra and geometrical properties of dust particles were gathered for each Si wafer. This number of particles allows for statistical analysis and classification of the particles. It turned out that 6 classes of dust particles (W-spheres, W-flakes, C, B, Fe and Cu) are sufficient to describe 90 % of the particles found. The average flux is 10 part/cm^2/s. The W-spheres and W-flakes are presumably produced by arcing at the PFCs. Dust collectors were also exposed in LHD and DIII-D. Evaluation of fast camera measurements enables to identify plasma phases, which produce or mobilize dust. In contrast to video observations, the high frame rate allows to separate dust events: events, which are observed for more than 20 frames (i.e. 2 ms) are classified as dust particles. Analysis of 1.500 plasma discharges shows that significant dust is only observed in 5 % of the discharges. Unstable plasma phases and disruptions are prone to produce dust.

8 Stuttgart

8.1 SOL Properties in L and H-mode

Langmuir probes have been used to investigate SOL turbulence in L-mode and ELM-free H-mode phases. The SOL density and the fluctuation level are reduced in H-mode despite higher heating power and plasma edge density. Power spectra, fluctuation amplitudes and correlation times remain almost unchanged. Turbulent structures propagate in the outer SOL poloidally with several hundred m/s in the ion-diamagnetic direction. An abrupt reversal of this flow in L-mode 1.5 cm outside the separatrix could be related to the $E_r\times B$ velocity from emissive probe measurements. In H-mode, the reversal must be located close to the separatrix or even inside. Other than the shear flow location, only small differences have been observed in the SOL fluctuation properties between L- and H-mode.

8.2 Temperature Fluctuation Impact on Probe Investigations

Intermittent electron temperature fluctuations have been identified in-phase with density and plasma potential fluctuations close to the separatrix. The electron dynamics could be resolved using self-emitting Langmuir probe measurements as well as conditionally sampled I-V characteristics. The independent experimental approaches are in agreement and consistent with GEMR gyro-fluid simulations. It was shown that floating potential fluctuations are strongly influenced by temperature fluctuations and, hence, are strongly distorted compared to the actual plasma potential. Interpreting floating as plasma-potential fluctuations while disregarding temperature effects is not justified near the separatrix. This has far-reaching consequences concerning plasma turbulence investigations with Langmuir probes.

8.3 Real-time Control of the Injection Angles in Discharges with O2-mode Heating

In the O2-heating scenario with incomplete absorption, two holographic mirrors at the inner wall localization are used for a second pass of the beam through the plasma centre. Thermocouples in these mirrors act as a beam localization system and provide real time signals for the adjustment of the poloidal injection angle during density changes or mismatched injection angles. In collaboration with CODAC, a real-time code based on the rtDiag framework and a controller were developed. The real-time code filters the measured data with a median filter and transmits the signals to the discharge control system. Here, a proportional controller with an included hysteresis calculates the new poloidal injection angles out of the temperatures of the top and bottom thermocouples and adjusts the ECRH launcher. In high-density discharges, the feedback control was successfully used, and the beam was focused in the center of one mirror within a few 10 ms. On the other hand, the angles were not modified with an already centred beam.

9 International & European Cooperations

9.1 IEA Implementing Agreement

The IEA Implementing Agreement on '*Cooperation of Tokamak Programs (IA-CTP)*' welcomed India as a new member in April 2011. China and Russia have been invited to join. Since a framework for collaboration between ITER and other Tokamaks is needed, the ITER participation in the CTP-IA is in discussion, but legal aspects on both sides have to be clarified first. In 2011 personnel exchanges involving IPP in the frame of IA-CTP took place with US labs. Joint experiments were conducted both on DIII-D and AUG devoted to the suppression of ELMs by RMP (section 2). Other topics covered during visits of IPP scientists of US labs concerned the physics of fast particle driven MHD modes and reconnection studies on the Magnetic Reconnection Experiment. In addition, joint experiments on the localisation of off-axis NBCD were continued.

9.2 EURATOM Associations

In 2011 the participation of EU Associations stayed on the high level of previous years. In the following, short reports are given for the 2011 contributions of a selection of EU Associates. Due to limitation in space such reports were not possible for all EU Associates involved in the 2011 AUG Programme. Their contributions are documented in the staff list below and the section 'Publications'.

CCFE & CEA

Experiments have been conducted at AUG in the frame of an ITPA study on ρ^* dependence of transport and stability in hybrid scenarios. As a first step an identity match to existing JET hybrid plasmas has been achieved. The same JET reference plasma (δ~0.36, single-null configuration) was chosen as for the DIII-D/JET joint experiment. This shape is compatible with both devices and approaches the shaping envisaged for ITER. The experiments were performed with dominant heating from co-injected neutral beams on both devices, but a small amount of ECRH power was added to the AUG plasmas to mitigate impurity accumulation. AUG data was obtained at 0.93 MA/2.24 T with the aim to provide the identity match with previous JET experiments at 0.81 MA/1.06 T. The plasmas were designed to match as closely as possible a range of dimensionless parameters with respect to the reference JET plasmas: plasma aspect ratio, plasma shape, q_{cyl}, ρ^*, β, ν^*, and M_{th} (Mach number with respect to the ion sound speed). The first indications are that similar plasma shapes were achieved and the ion temperature and density profile were matched despite differences in hybrid operational techniques (e.g. early NBI heating on AUG compared with Ohmic current ramp-up on JET) and first wall materials (i.e. tungsten on AUG compared with carbon on JET). Work has begun to analyse these experiments using interpretive TRANSP simulations.

DCU – University College Cork

Further progress was made in the adaptation of the CLISTE free boundary equilibrium reconstruction code to ITM standards, whose goal is the complete extraction of machine specific information from the code. Difficulties that arose in fitting discharges with 'long' type-I ELMs, where more vigorous control system responses generated larger vessel currents, were resolved by allowing CLISTE to fit the two fast control coil currents as free parameters, thereby strongly reducing the fit error to magnetic signals during 'long' ELMs. Experimental observations of low frequency Alfvénic modes on AUG have been compared with results obtained by solving numerically the low-frequency kinetic mode dispersion relation. Various factors, such as plasma elongation, realistic background plasma temperature and density profiles as well as realistic safety factor profiles, obtained via equilibrium reconstructions using the CLISTE code, have been included in the analysis. This has been used to further demonstrate that the kinetic dispersion relation is capable of recovering accurately the frequency continua of modes with purely Alfvénic (BAE) and mixed acoustic/Alfvénic polarizations. That the frequency evolution of these modes is highly dependent on the diamagnetic frequency ω^*_p through background temperature gradients in the plasma has also been demonstrated both experimentally and numerically. Finally, it has been shown that the on-axis safety factor value could play an important role in determining the evolution of low frequency core-localized chirping modes, which appear to differ in nature from the BAEs. Further work on the topic of inter-ELM pedestal current density evolution has resulted in substantial progress. Detailed ELM-synchronised equilibrium reconstructions covering the full ELM cycle, from crash to full recovery, have been made at 0.1 ms time resolution. An important finding is the reliability of neoclassical theory in determining the edge current density. It is hoped that the breakdown of the bootstrap current into its constituent parts could shed light on varying ELM frequencies and also differences between ELM regimes. In order to test this, a database of equilibrium reconstructions is currently being established based on kinetic fits. In addition, preliminary stability analysis has also been conducted on some discharges, showing promising results.

ENEA

First measurements of γ-ray emission due to fast ions in AUG were performed. The plasma scenarios developed for the experiments involved deuteron or proton acceleration. No evidence of γ-ray emission was found in the deuteron acceleration scenario. In the proton acceleration scenario, emission from capture reactions on boron and deuterium was observed in two (H)D discharges with radio-frequency heating in the minority acceleration scheme. The observed count rate was used to infer the values of the fast proton tail temperature. TAE fluctuations were observed with Mirnov coils and associated proton losses were detected with the FILD diagnostic. The observed emission rate assessed the confinement of protons at energies E_p<400 keV and in particular revealed that particle-mode resonances involving negative multiples of the bounce harmonics did not significantly affect fast ion confinement. Future γ-ray spectroscopy measurements of confined protons should be aimed at raising the proton tail temperature up to 150 keV and above, where improved statistics would allow for even better comparison with diagnostic information on lost protons from FILD. Experiments on the avoidance of NTM-driven disruptions at high β by means of ECRH (P_{ECRH}=1.7 MW) in NBI-heated plasmas (P_{NBI}~7.5 MW, I_p=1 MA, B_t=2.1 T, q_{95}~3.6) were extended to the case of ECCD. The localized perpendicular injection of ECRH/ECCD onto a resonant surface (triggered in real-time by a combination of U_{loop} and locked mode precursor signals) leads to a delay and/or complete avoidance of disruptions. ECRH discharges were found to last longer than the ECCD ones. Simulations of the MHD mode evolution by means of the generalized Rutherford equation indicate that the ECRH term (Δ'_H) is generally larger than the ECCD one (Δ'_{CD}) in the initial phase of EC application when the discharge is 'saved'. Experiments on extension of density limit with ECRH/ECCD localized injection were designed in order to study the condition for stable operation above the density limit. Thereby ECRH is used to stabilize MHD activity accompanying the density limit disruption. In the 2011 experiments the high density led to a deflection of the EC beam with consequent loss of the crucial alignment between power deposition and MHD island (q=2 surface), for this reason new experiments were designed to compensate the RF beam refraction by a trajectory of mirror steering, keeping the alignment between power and the q=2 surface during the density growth. The related experiments have not been completed due to technical difficulties in the control system of the EC mirrors movement. The 2011 results have confirmed previous ones proving that disruption can be avoided, until the refraction moves the RF beams away from the proper deposition region. The aim of other experiments was to investigate the possibility of reducing the outer divertor power load in H-mode plasmas by decreasing the incidence angle of the separatrix on the target. Starting from a reference H-mode discharge # 25374 modified equilibria have been defined by using CREATE XSC Tools. The plasma internal parameters (l_i, β_{pol}, I_p) were kept fixed. The upper part of the plasma was kept frozen and the currents flowing in the PF coils were within the actuators limit. A few dedicated shots were run to verify the effective feasibility of this heat load control tool. Data analysis is still to be completed.

FOM

In 2011 the multi-pass Thomson scattering (TS) project was initiated. The aim of the project is to design and build an intracavity, multi-pass TS system for the AUG pedestal, and to demonstrate the potential of this technique to measure not only temperature and density profiles with high spatial and temporal resolution, but also electron drift velocity profiles, an important parameter when studying the effect of edge current on the pedestal stability. Following the original conceptual design, a feasibility study was completed, which concluded that the proposed system has the potential to measure current density profiles in the pedestal region with a ~15 % accuracy, ~1.5-3 mm spatial resolution and 1 kHz sampling rate, sufficient for fast ELM studies. Design, manufacture and installation of a number of in-vessel test components took place during the 2011 shutdown. Initial testing will follow in early 2012 and the full system will be installed during the 2012 shutdown. The 2D ECE imaging diagnostic has been used in 2011 for the investigation of a variety of plasma instabilities, most notably the type-II ELM regime. During type-II ELMs, a broadband temperature fluctuation is continuously observed at the plasma edge. Surprisingly, the time averaged amplitude of this mode shows a strong poloidal asymmetry, with a strong minimum at the low field side mid-plane. A more detailed investigation of this mode shows beat-wave-like behaviour, indicating that it actually consists of multiple simultaneous modes. Destructive interference between these modes might provide an explanation for the observed poloidal amplitude asymmetry. A very similar fluctuation is also sometimes observed just before type-I ELM crashes, where its occurrence seems to delay the next ELM crash. In the type-II regime, where this mode is continuously present, the crashes disappear altogether, indicating that the broadband mode plays an important role in the dynamics of the plasma edge.

FZ-Jülich

The erosion of W as a wall material in future tokamaks is determined by impurity seeding used for controlled radiation cooling in the divertor. The aim of this experiment is to spectroscopically investigate this interaction with regard to optimizing the relation between impurities (N_2) and hydrogen and by this minimizing the W erosion. A setup of WI/WII lines absolutely calibrated with WF_6 injections at TEXTOR allows to quantify the W erosion in the UV and VIS range and has been applied to erosion measurements in the AUG divertor. The experiments were performed with two distinct scenarios either utilizing a feedback on the divertor temperature to regulate the deuterium fuelling or the N_2 influx. Divertor temperatures down to 5-10 eV have been reached. For the deuterium regulated cases clearly a steady decrease in tungsten sputtering was observed, while for the N_2 regulated cases firstly an increase in sputtering was observed due to sputtering of W by nitrogen, followed by a turn over to conditions of less erosion in a cool divertor.
Intrinsic error fields on tokamak machines originate from unavoidable inaccuracies in coil manufacture and coil alignment. These error fields have normally low toroidal mode numbers n and are known to lower the thresholds for the excitation of locked modes. Of special interest are n=1 fields, which may contribute to the seeding of locked (2,1) modes, which can grow to large size and cause a plasma disruption.

At higher β error fields can contribute to the seeding of NTMs and deteriorate the plasma confinement. The set of 2×4 B-coils allowed to determine the n=1 component of the intrinsic error field. The standard procedure for this measurement is to apply n=1 fields with different phasing (orientation of the magnetic field direction with respect to the vacuum vessel) and to determine the coil current, which excites a locked mode. From the differences in coil current at mode excitation the amplitude and direction of the intrinsic error field has been derived. The error field in AUG amounts a few 10^{-5} T, which is very small. It is planned for the next campaign to refine the measurement using the complete set of B-coils. A tungsten melt experiment was performed as well (see section 7.12). FZ-Jülich also contributed to the organisation of the AUG programme by taking over the management of the AUG Task Force IV 'MHD instabilities and their active control'.

HAS – KFKI RMKI, Budapest

The NTI Wavelet Tools package was integrated into the AUG data analysis system MTR. With its convenient GUI and feedback interface it supports the wavelet based time-frequency analysis of the measured data. This new tool was utilized in physics studies involving MHD activity and fast ion losses. A possible interaction mechanism of the two sawtooth precursor modes and its role in the sawtooth crash was published, and the interaction of fast ions and ELM-related MHD activity was studied in detail. A new in-vessel optical head with tangential view at the lithium beam was finished in 2011. The new system has much more channels and a much larger field of view than the old system, thus enables the observation of plasma fluctuations with better signal/noise ratio and improved spatial resolution. The exploitation of the system starts early 2012. The replacement of the existing photomultiplier based detection array with an avalanche photo diode camera was also started. The AUG pellet camera system was upgraded with a Photron SA5 camera, capable to run as fast as 1 million fps. Using this camera, the pellet cloud was observed with a frame rate exceeding 300.000 fps. The first analysis of these recordings suggests that the pellet cloud is continuously moving together with the pellet. In some cases the pellet itself can also be observed in the middle of the cloud, supporting the above findings. The shape of the cloud is changing even faster than 3 µs, and therefore it could not be resolved in all details. Pellet cloud detachment and the subsequent cloud movement could be observed showing a dominant drift towards the LFS. The pellet ablation was also investigated in both ELMing and ELM mitigated H-mode phases and up to now no differences were recognized in the penetration depth and pellet cloud behaviour.

IST – Centro de Fusão Nuclear

Plasma position control using microwave reflectometry (as foreseen for ITER) was successfully demonstrated on AUG (an EFDA priority support task). The FM-CW reflectometer channels were equipped with a Real Time data acquisition connected to the AUG control system. The outer plasma position could be successfully controlled with the ITER required accuracy (~1 cm) during both L and ELMy H-mode phases. Simultaneously control of the inner and outer plasma radius is planned for 2012. The HFS channels were operated during 2011 with modified front-ends to be compatible with stray ECRH radiation. Results will be evaluated after new calibrations are obtained. The installation of additional MP coil current feeds forced a major renovation of the FM-CW in-vessel waveguides during the summer break. Due to delays in component delivery only the K, Ka and Q (LFS/HFS) channels could be completed. The frequency hopping channels were upgraded with a SIO based data acquisition system provided by IPP and new control software; resulting in extended frequency turbulence measurements. Physics studies included: (i) Fast particle/MHD modes – Alfvén Cascades (ACs) were studied in different heating scenarios (NBI only or NBI with ECRH). For the 60 keV NBI case ACs show a bursting upward chirping frequency behaviour that can be explained by the existence of an 'explosive' regime due to strong non-linearity. The HFS/LFS radial structure of the AC to TAE transition is asymmetric at the edge suggesting different fast ion transport. (ii) No significant change has been observed in either the density profile or fluctuations when ELM suppression occurs with the use of MP coils. Signatures of plasma filaments in reflectometry signals have been observed and their study is ongoing. (iii) Reflectometer measurements have also contributed to several studies: L-H transition, improved H-mode confinement, type-II ELM discharges and improved L-mode regimes. A key reflectometer simulation tool was developed by coupling plasma turbulence simulations from the GEMR gyrofluid code with the REFMUL/REFMULX 2D full-wave codes. Comparing plasma fluctuations from GEMR with synthetic reflectometer signals allows a better understanding of the diagnostic capability to give quantitative data on edge turbulence parameters.

RISØ

Designed and constructed in 2011 by RISØ-DTU, RF-switches directly couples the CTS to the ECRH waveguides. One of the RF-switches has been installed on an ECRH waveguide in a section of the NBI control room where all CTS diagnostic hardware is planned to be located. This upgrade will have the added flexibility to easily change the receiver transmission line allowing different scattering geometries. An additional CTS receiver (formally located at TEXTOR) has been modified and installed at AUG, thus allowing two simultaneous CTS measurements. Tested during the 2011 experiments, a new high bandwidth acquisition card (12 GSamples/s) has been adapted to the CTS receiver allowing (in addition to the conventional CTS measurements) high frequency resolution measurements of certain portions of the CTS spectra. Improvements of the CTS diagnostic techniques in 2011 have increased the CTS's ability to resolve the observed secondary emissions (SE), which hamper the diagnostic's capability to measure the fast ions. Some SEs were identified and their reproducibility under certain operating regimes is also known. However, some SEs still need to be understood, which may have more than one physics explanation. The hardware upgrades mentioned above not only will make the CTS more flexible, it can shed light on the physics of the SE in future experiments and possibly provide a solution in its mitigation. The experience gained will directly impact the design of the CTS system proposed on ITER.

ÖAW – IAP, TU Vienna & University of Innsbruck

The evolution of the electron density profile and its dependencies after ECRH induced L→H transitions have been investigated. This is one of the main AUG topics and is described in the L→H transition (see section 4). The lithium beam diagnostic has been extended to provide also density fluctuation measurements. For this purpose a new optical head has been installed. It has been developed and constructed in collaboration with HAS (see above). Beside fluctuation measurements, first poloidal flow velocity measurements and edge current density measurements using the lithium beam with its new observation head will be attempted. Poloidal flow velocity measurements require a vertical deflection of the Li-beam. Therefore, deflection plates, placed above and below the beam were added prior to the neutralizer. An electrical circuit to hop the lithium beam a few cm at frequencies of several hundred kHz, using a MOSFET switch from Behlke GmbH was developed. For fast data acquisition a new SIO system has been successfully installed and tested during the 2011 campaign. In 2011, measurements of electric and magnetic fluctuations in the SOL have been continued. A probe head with 6 Langmuir probes was inserted during L-mode discharges almost up to the separatrix. After exposure to the plasma the probe pins were inspected visually and were found to be unspoiled. The evaluation of the data is not yet completed, especially concerning the radial transport parameters. One of the objectives was to find the edge shear layer. The transition of a shear layer by the probe is accompanied by a reversal of the rotation in poloidal direction. With two ion-biased probes time series were taken and the cross correlation was derived. On the shear layer the maxima of the cross-correlation jump from a positive time lag to a negative time lag or vice versa. During several L-mode discharges the method was tested successfully. Also the plasma density profile was determined almost up to the separatrix and the results were compared to the Li-beam diagnostic.

TEKES

In 2011, TEKES contributed to the AUG programme on 3 frontiers: transport, fast ion physics and PWI. In dedicated shots the momentum transport coefficients as a function of q-profile and collisionality were examined using the upgraded CXRS diagnostic. An optimisation routine to find the Prandtl and pinch numbers was developed, and a procedure to extract the non-NBI torque from the NBI modulation data was created. The results indicate a Prandtl number close to 1 and the presence of an inward directed convection. Erosion and re-deposition of different materials were studied using both campaign-integrated data obtained with marker tiles and discharge-resolved data using marker probes. Net erosion was found to depend exponentially on the charge number of material: Ni and Cr (representing steel) eroded some 4-5 times faster than W. ERO simulations of a marker probe indicate that the effect of C, O, N, and Ar impurities on the erosion patterns is noticeable. 22 new marker tiles were manufactured by DIARC-Technology Inc. Migration of materials was studied using a combined $^{13}C/^{15}N$ injection experiment at the end of the 2011 campaign. First results show strong deposition peaks on ICRH antenna structures and on tiles next to the injection valve as well as clear toroidal asymmetry of the deposition at the outer midplane. Both observations agree remarkably well with the ASCOT-PWI predictions. The effect of cross-field drifts on the divertor conditions was investigated experimentally by reversing B_t/I_p in L-mode discharges and modelled with SOLPS5.0 and ERO. The cross-field drifts were found to affect both the divertor plasma regime and local deposition pattern of injected carbon. A new method, based on spectroscopy and fast camera imaging of injected carbon, for measuring SOL flow profiles on the high-field side was devised and tested on AUG. The measured flow profiles were compared with results from ERO simulations and a very good agreement was found particularly near the separatrix. The ASCOT code now includes a realistic description of the B-coils, and NBI simulations indicate that tangential beams are affected more strongly (a factor of 4) than the normal ones (a factor of 1.5). With TF ripple only, the wall load is dominated by the normal beams, but the B-coils bring the power from tangential beams up to the same level (almost 10 % of the injected power). Since also MHD events affect the fast ion confinement, ASCOT was enhanced with a numerical model for NTM-type islands that is applicable even for non-axisymmetric configurations. This work was carried out in collaboration with IPP's TOK department. Redistribution of fast ions at the location of a NTM island was studied, and resulting changes in electron heating were compared to T_e measurements. Both indicate flattening of the T_e profile. Work on building a numerical model for the effect of Alfvén eigenmode type of MHD activity on energetic particles was started, again in close collaboration with TOK.

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JET Cooperation

Head: Dr. Josef Schweinzer

The initial months of JET operation with the ITER-like wall have been very rewarding. The routine of interspersing commissioning sessions with experimental work was typical for JET operation in 2011. IPP scientists have been involved – often in a leading role – in many key experiments of JET campaigns C28 & C29. One of the most important results, is the confirmation that hydrogen retention with the metallic wall is greatly reduced compared to the carbon era.

Introduction

The EP2 shutdown for installation of the ITER-like wall (ILW) with a Be main chamber wall and a tungsten (W) divertor was completed in 2011. The first pulse on August 24th after this shutdown of 22 months was successful on the first attempt. After only a few days of restart, JET campaign C28 started with the assessment of fuel retention in the conditions of a pristine metal wall by conducting ohmic discharges and ICRF-heated L-modes at low power (~3 MW). The gas balances of these experiments clearly show that retention with the ILW is an order of magnitude lower than with the carbon wall.

Power supplies and beam sources of the JET NBI system have been considerably enhanced. Bringing the system back into operation has taken longer than planned. Neutral Beam heating was available from part of the Octant 8 box in the last few weeks of the 2011 campaign with power building up to 10 MW. In first H-modes, accumulation of high Z impurities has been found to be a problem unless the type I ELM frequency is kept sufficiently high. This experience is very similar to that in AUG. Such H-modes could only be achieved with the available heating power by operating at reduced magentic field (1.85 T) and plasma current (1.7 MA).

Seventeen IPP scientists were seconded to the 2011 JET campaigns, leading in total to ~3 ppy of JET participation in campaigns C28 – C29 from September to December 2011. In many cases IPP personnel took a leading role in the preparation, execution and analysis of experiments. A senior IPP scientist has been leading the JET Task Force E1. In addition, seven long-term secondments of IPP staff to the Close Support Unit (2), the JET CODAS group (1) and to the JET Operator (JOC, 4) were active in 2011. IPP staff seconded to JOC has been responsible for diagnostics (thermocouples, infrared cameras and pyrometers) to monitor the temperature of PFCs, ECE diagnostics, Langmuir probe measurements, spectroscopic measurements of impurity influx and maintenance and development of codes for data analysis.

A study on inter-ELM power fall-off lengths based on IR thermography data of JET and AUG from previous campaigns was finalized in 2011 (see chapter 'ASDEX Upgrade', section 7.10) and has impressively demonstrated how important the step-ladder approach AUG – JET is for the extrapolation to future devices like ITER.

The following is a summary of the main results obtained with significant IPP involvement during the 2011 JET campaigns. The analysis of these results is still in progress and should be considered as preliminary. At the end, the last two reports concern activities in support of JET performed at IPP Garching.

Spectroscopic Diagnostics for the ILW

Two new visible spectroscopic diagnostics for the ILW (KS8 and KT1-visible) were commissioned.

KS8 is a survey diagnostic (a series of compact survey spectrometers and one Echelle spectrometer) with 8 chords viewing the W-coated neutral beam shine through areas and one divertor view of tile 5 (outer divertor, solid W), routinely providing influxes from low ionization stages of all main plasma impurities and deuterium.

KT1-visible is an upgrade of the two existing poloidally scanning VUV spectrometers (a vertical system viewing the divertor area and a horizontal system viewing the upper dump plate). The new, tritium-compatible, system collects the visible light from the plasma using an oscillating mirror via a telescope and splits it into photomultiplier assemblies. Each KT1 system is equipped with 8 photomultipliers, providing poloidal distributions of C, Be, W and D influxes with a typical time resolution of 5 kHz for 40 s.

Tungsten Spectroscopy

A method to determine tungsten (W) concentrations in JET plasmas was implemented by transferring the W-spectroscopy experience and knowledge from AUG along with atomic data calculated with ADAS codes and improved at IPP.The diagnostic makes use of the VUV spectrum of W at 5 nm (cf. figure 1), which is dominated by the emissions of W^{27+} to W^{35+} (T_e~1-2 keV). Their emissions form a broad spectral feature, as each of the contributing ionization stages emits many small spectral lines. These form a quasicontinuum in the spectrum.

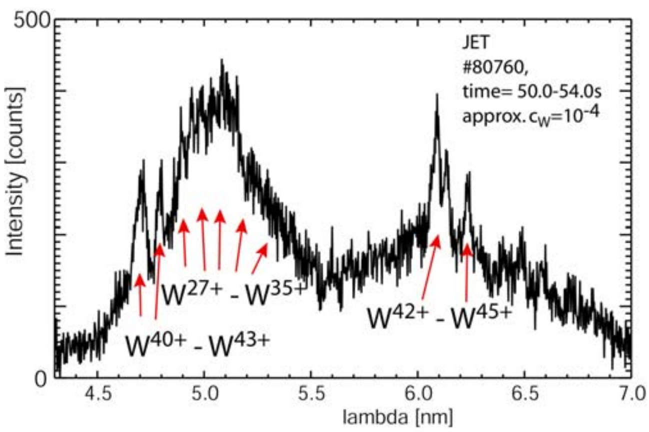

Figure 1: Measured VUV spectrum with indication of emission lines resulting from various charge states of tungsten.

The intensity of this spectral feature is interpreted by taking the electron profiles (T_e, n_e) and the spectrometer's line of sight into account. In the plasma core, the ionization stages W^{40+} to W^{45+} (T_e>2 keV), may additionally emit resolvable spectral lines. These lines are separated by a multi-line fit and then used to obtain an independent evaluation of the W-concentration, in regions with higher T_e.

Infra Red Thermography

The divertor thermography system consists of three IR cameras. Two identical systems observing the horizontal divertor target plates (KL9A/B, target resolution: 1.7 mm) and one system for the inner and outer horizontal targets (KL3B). All systems have been calibrated and the in-vessel measurement has been cross checked with pyrometers. The JET divertor has two types of target plates, tungsten coated carbon fibre composite (CFC) tiles and bulk tungsten tiles. The latter are segmented into four poloidal stacks with 24 separate lamellae each. Between the lamellae, which have a width of 5.5-6 mm, there is a gap of 1 mm. This gap acts as a cavity radiator, with an emissivity higher than that of tungsten. Thus, when the bulk temperature of the lamellae is sufficiently high, the cavities appear brighter than the actual tile. The spatial resolution is not adequate to resolve these toroidal gaps, which complicates evaluation of the surface temperature (see figure 2).

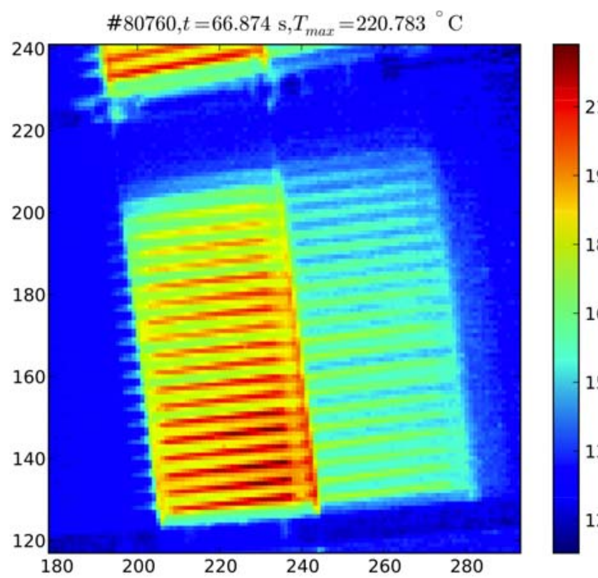

Figure 2: IR measurement of the bulk tungsten target. Gaps between the lamellae appear hotter than the lamellae themselves.

In order to overcome this problem, one of the cameras (KL9A) will be equipped with a new lens in order to double the spatial resolution (0.85 mm). Already without this foreseen improvement, the divertor IR systems have registered peak surface temperatures. Only with these valuable measurements could machine protection be assured during the development of H-mode scenarios.

Be Migration

The start of the JET ILW campaign provided a unique opportunity to study both material migration and the resulting evolution of plasma facing surfaces with well defined initial conditions of clean Be and W wall areas. In a discharge series the evolution of gross erosion flux, impurity plasma concentration and divertor surface composition were investigated by spectroscopic measurements in the visual and ultraviolet spectral range. Local impurity sources of both the plasma facing materials (Be, W) and of residual impurities (C, O) were measured at the main chamber guard limiters and at the divertor target plates. Subsequent monitoring discharges using the same standard plasma cross-section and plasma parameters were used to follow the long term wall evolution after the initial experiment. In addition, impurity deposition in the divertor was measured by quartz microbalances (QMB). The experimental results confirm the generally observed migration pattern in devices operating with bottom single null divertor configuration, which is characterised by the main chamber wall and outer divertor as areas subject to net erosion of plasma exposed surfaces and migration of eroded material predominantly to the inner divertor where the material is finally deposited at the target plates. The characteristic time scale for the main wall Be source reaching steady state was found to be ≈100 s, compared to typical values >400 s for previous experiments with heavy Be evaporation. Furthermore, the QMB data showed that material transport to remote divertor locations became much lower in the ILW wall configuration, reaching a stationary deposition rate after the first 10 discharges. This correlates to the expected and measured smaller abundance of carbon as a residual impurity, which also continuously decreased in the first discharges and reached steady state conditions after approximately 1000 s plasma time. The measured temporal evolution of wall material gross erosion sources provides a new data set to benchmark WALLDYN simulations of the dynamic change of wall composition using a redistribution matrix obtained by DIVIMP simulations on a computational grid covering the entire poloidal cross-section of the vessel up to the first wall.

Interactions of ICRF Antennas with ILW

Studies of interactions between the ICRF antennas (the so called 'A2' antennas) and the ILW have been started. Three main issues arising during ICRF operation are being addressed: (1) W release; (2) Be sputtering; (3) heat load deposition at plasma facing components. Of particular interest is (1), in connection with the AUG all-W wall experience and planned W divertor for ITER.

By using the multi-view JET divertor spectroscopy diagnostics to estimate W influx, an additional W source during ICRH exists in the areas of the outer divertor baffles and vertical plate. However this increase is relatively small and cannot always be made responsible for the significantly higher W content in ICRF heated L-mode plasmas compared to NBI. This statement rests on the assumptions that the effect of ICRF induced SOL modification on W ionization and transport is small and that the divertor W diagnostics cover the relevant divertor locations and are not strongly disturbed by multiple light reflections and background radiation. Another possible explanation of the systematic difference of W content in the plasma depending on the used heating method is an additional W source in the main chamber. It remains to be shown if such an additional W source is a consequence of W re-deposition from the divertor or of wall components such as several W-coated CFC tiles mounted in the main chamber to protect the wall from NBI shine-through.

L/H Power Threshold

After initial ICRH experiments suggested that the L-H transition threshold power may be lower than with the carbon wall, L-H transition studies in pure ICRH plasmas were conducted. The goal was to investigate the effect of shape dependence and divertor configuration on the threshold power P_{L-H}. Five different magnetic configurations were compared in order to decouple 'main chamber' from 'divertor' effects.

The experiments consisted of power ramps at low density, with up to 5 MW ICRH heating only at 42 MHz, resulting in slightly off-axis heating with the resonance at R=2.7 m for the 2.4 T toroidal field. The H-modes obtained were of moderate quality, with low temperature and density pedestals. Consequently, the confinement factor H_{98}~0.8 was also low. No ELMs were observed, instead these plasmas exhibited a continuous low frequency n=0 MHD mode after the L-H transition. Core radiation was high, with W and Ni as main radiators.

At constant edge line averaged density the threshold power P_{L-H} decreases as the lower triangularity (δ_l) increases. P_{L-H} increases with increasing upper triangularity (δ_u) at fixed δ_l. The lowest threshold power (P_{sep}≅1.5 MW, with bulk radiation subtracted) was obtained for δ_u≅0.19 and δ_l≅0.3 at a line average density of $2 \cdot 10^{19} m^{-3}$, while the highest (P_{sep}≅2.8 MW) at the same density was obtained for δ_u≅0.38 and δ_l≅0.33. Density scans performed in the two low δ configurations show the occurrence of a minimum in P_{L-H} at edge $n_e \sim 2 \cdot 10^{19}$ m^{-3}. Below this density P_{L-H} increases strongly, related to a strong increase in core radiated power. Such a minimum in P_{L-H}, first observed in JET in the late 1990's with the MkII-GB divertor, was not found in L-H experiments with the current MkII-HD divertor in its configuration with carbon tiles, although a similar density range was explored as with the ILW.

First N_2 Seeding Experiments with the ILW

The reduction of power and energy loads on metallic divertor targets using seeding of impurities such as nitrogen (N_2) or neon into the plasma is mandatory for the operation of relevant heated scenarios. In December 2011 the first N_2 seeding experiments since installation of the ILW were performed. Nitrogen atoms were first introduced into the plasma as a tracer and spectroscopically observed at various positions. The scrape-off layer properties for the trace-seeded discharges (ohmic heating, 2.0 MA plasma current, 2.2 T toroidal field, low triangularity) were extensively characterized by the reciprocating Langmuir probe as well as other diagnostics. These tracer discharges are to be compared to scrape-off layer transport simulations with SOLPS/DIVIMP. In subsequent discharges N_2 was seeded in the divertor at increasing rates to load the surface of plasma facing components with nitrogen. The formation of ND molecules at the strike point was observed spectroscopically and deuterated ammonia was detected in the exhaust gas by mass spectrometry. After this series of N_2-seeded discharges the liquid helium divertor cryo pump was regenerated to allow a gas balance. The overall amount of gas (N_2+D_2) not recovered by this regeneration amounted to 6.4 % of the total injected gas. In interpreting this number one has to take into account that some of the ammonia formed during the discharges can still be trapped on the liquid nitrogen panels, which were not regenerated. Following the loading of the wall, a series of 'cleaning' discharges (limiter plasmas as well as ohmic and ICRH- or NBI-heated divertor discharges) was performed to study the removal of nitrogen from the plasma facing surfaces. The presence of nitrogen did not affect the stability of the first monitoring divertor discharge after the loading. The decrease of both the nitrogen line emission and the mass-spectrometry signals of nitrogen-containing species was monitored together with the surface temperature (infra-red camera) at the W divertor target. Removal of N was more effective during the heated discharges. A final gas balance resulted in an overall difference between injected and recovered gas of 1.6 % in these discharges.

Langmuir Probe Measurements & Divertor Detachment

The Langmuir probe diagnostics were upgraded for the ILW. The reciprocating probe was equipped with a 7-pin probe head, which was designed for turbulent transport and fluctuation measurements. It has been widely used during the 2011 campaigns e.g. for detachment studies or to characterize the SOL width in limiter plasmas. The main chamber wall has been equipped with 36 probes distributed poloidally on the inner and outer wall tiles.

In the divertor a set of 36 fixed probes has been installed in order to obtain profiles of local parameters. Their data acquisition system has been upgraded from 10 kHz to 200 kHz with the capability to sample a complete JET pulse at full sampling rate. Thus, this diagnostic is now a routine diagnostic delivering data for basically every JET pulse. An important feature is the production of reliable processed data on an intershot basis. Target particle flux profiles are at hand shortly after each pulse. This permits a quick reaction time, enabling improvement of the experimental program by optimizing discharge settings on the fly.

Divertor detachment is a prerequisite for operating large burning plasma fusion devices such as ITER. The devices AUG and JET are fully covered by metallic plasma facing components. Work at JET has focused on comparing the detachment behaviour in Ohmic and L-mode discharges for these two devices for lower single null vertical target configuration. In AUG with increasing line-averaged density the inner divertor is strongly detached early on and the outer target exhibits a roll-over of the ion flux density, I_{sat}. In JET ohmic density ramp discharges with the ILW, the values of I_{sat} at the inner and outer target roll over, with the inner I_{sat} slightly preceding the outer target (see figure 3). This observation is new for JET where, with carbon PFCs, the inner divertor was strongly detached independent of the chosen divertor configuration during most of the density ramp.

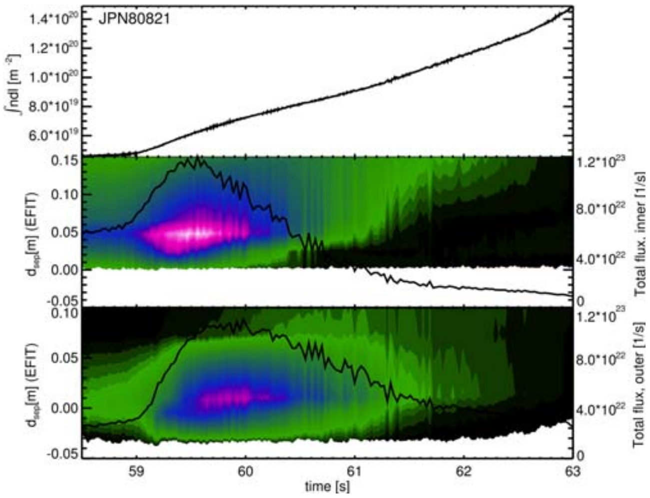

Figure 3: Profiles of I_{sat} versus time are shown together with the line integrated density for an ohmic density ramp discharge.

As the dimension of AUG and JET differs, the influence of the ratio of the neutral mean free path to the inner target plate to X-point distance on the detachment threshold is being analysed using the SOLPS5.0 code. The volumetric plasma temperature and density profiles in the inner divertor are strongly influenced by the radiation of impurities and of the recycling main ion species. The way, in which the intrinsic impurity levels affect these volumetric divertor plasma profiles and how this impacts the neutral mean free path and therefore the divertor regime is subject of on-going work.

Lifetime of W-coatings

IPP's work on the tungsten coated ILW divertor tiles has moved from quality assurance and production issues to the assessment of their lifetime. When in use in the JET divertor such coatings experience high temperatures, which will lead to diffusion of carbon from the substrate into the coating and subsequently to the formation of tungsten carbide. Subsequent high heat flux pulses can cause delamination of the coatings. This was already demonstrated in GLADIS tests. To have a predictive estimate of the lifetime in terms of JET campaigns the kinetics of this carbide formation process was investigated as a function of temperature.

A question not yet addressed in GLADIS high heat flux tests is the coatings' capability to withstand heat shock pulses similar to ELMs. For this purpose tests with high pulse numbers were run in 2011.

Erosion and Deposition Studies

Erosion of several elements and deposition of carbon was measured at the inner wall, in the outer divertor, at inner wall guard limiters (IWGL) and in recessed areas between IWGLs during the campaigns 2001-2004 and 2004-2009. The total amount of carbon sputtered from the inner wall between the IWGLs during the 2004-2009 campaign was estimated to be 220 g. SEM analysis of the eroded samples did not show any directional effects, indicating that erosion by ions is negligible and mostly due to neutral particles. Energy spectra of charge-exchange neutral particles were obtained at the inner midplane from the observed erosion of C, Be, Ni, W. The spectra are characterized by a large fraction of low energy neutrals, which erode mainly carbon by chemical erosion. A complicated distribution of erosion/deposition areas is observed on the IWGL tiles, and about 109 g carbon has been redeposited here.

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Stellarator Research

Wendelstein 7-X

Head: Prof. Dr. Thomas Klinger

In 2011, considerable progress was achieved in the construction of Wendelstein 7-X. Fabrication of all major components has been finished and they are ready for assembly or have already been assembled. Assembly of the device progressed very well and by the end of 2011 all five magnet modules have been installed in their final position in the cryostat module, in three modules the ports have been installed and two modules have been connected already.

1 Introduction

In 2011 the organisation of the project Wendelstein 7-X (see figure 1) underwent a few changes. In January 2011 the Technical Director of W7-X left the project to become the Technical Director of ITER. To fill the gap, in fall 2011 a new, experienced Chief Engineer was hired, first in part time, with the beginning of 2012 in full-time. The tasks were accordingly redistributed between the Scientific Director, the associated Director Coordination and the Chief Engineer. Due to the retirement of the sub-division head “KiP” in fall 2011, the position has been taken over by an experienced engineer working already since many years in the sub-division. In the summer 2011 Prof. T. Sunn Pedersen joined the project in addition to his appointment as a new scientific member of the Max-Planck society. He took over the responsibility for the diagnostics systems and an additional sub-division “Diagnostics” was created with four different departments. The former sub-division “Physics” now concentrates on “Heating and CoDaC”. The sub-division “Design and Configuration” changed its department structure in the beginning of 2011 in response to the near completion of the design activities in the cryostat and the necessity to focus on the design of peripheral components and diagnostics. Design and manufacturing of the different components of the basic device have significantly progressed, as described in chapters 2 to 4. The assembly of the stellarator device and the development of the related technologies have made great progress, as described in chapter 5. The accompanying efforts of the engineering sub-division (chapter 6) and the design and configuration control (chapter 7) are still indispensable. Heating systems (chapter 8) and diagnostics developments (chapter 9) as well as the development of control systems (chapter 10) 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. Assembly started with module 5; the assembly sequence is M5-M1-M4-M2-M3.

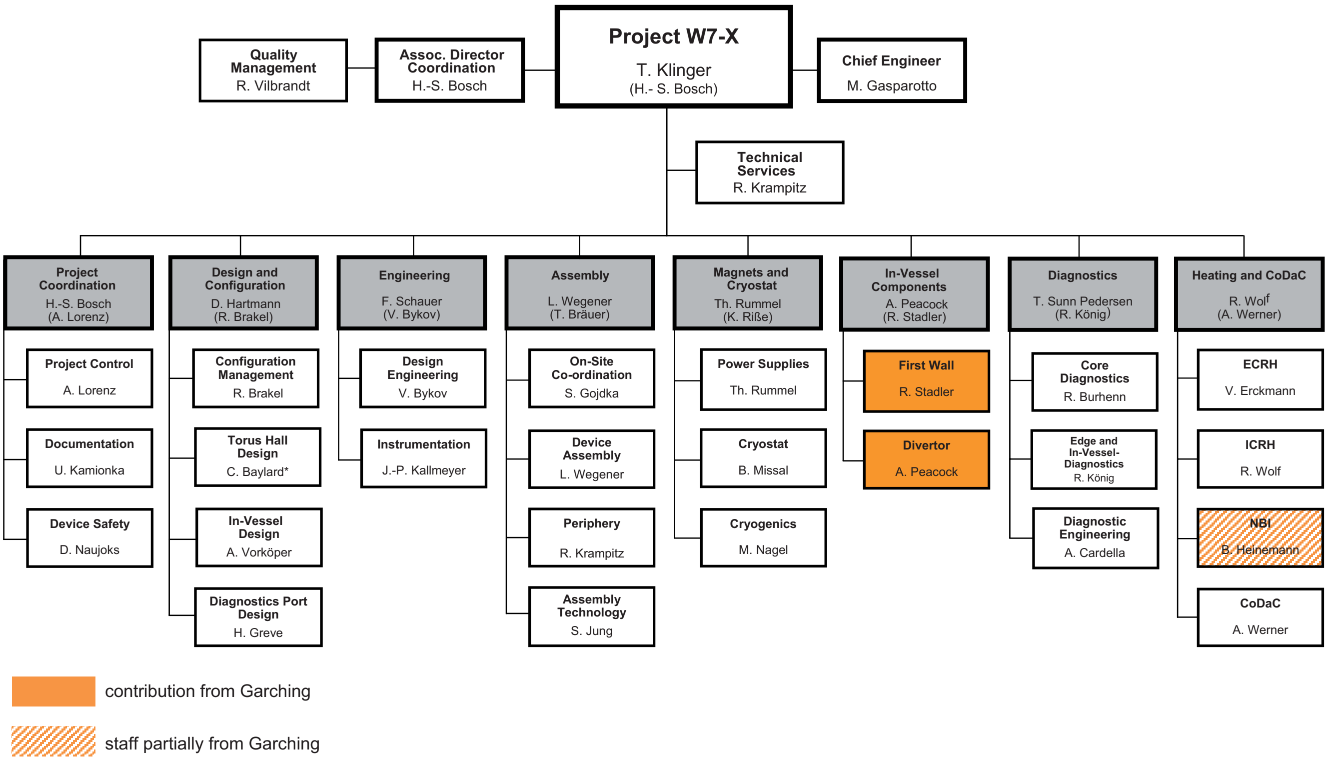

Figure 1: Organigramme of Wendelstein 7-X project as of 31 December, 2011. Names in brackets indicate the respective deputy.

Quality Management

The Quality Management (QM) department reports directly to the project director via the associate director coordination. The department organises 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. In fall 2011 another routine supervision of the QM system of Wendelstein 7-X by the TÜV NORD CERT according to the DIN EN ISO 9001 has been performed. TÜV NORD CERT certified a further improvement of the system, no obligations were given.

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 monitors and co-ordinates component delivery and assembly schedules, supports the component responsible officers in the handling of industry contracts; it deals with organisational 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). In 2011 the use of the Integrated Planning Tool (IPT), developed up to the end of 2009, has been enforced. As of now the IPT is the routine tool for the responsible officers, their supervisors, but also for the financial reporting to both the management and the supervising bodies. The concept of establishing links between all sub-projects in a stable and reliable way has been extended. Interlinked processes within the project are monitored in a control WBS, which compares the delivery milestones of components with the dates when these components are required for assembly preparation or for other work processes in a different department/sub-division. Also design work in the central design office has been included in the monitoring and control process. (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. An electronic documentation system (now ORACLE-PLM) is used for archiving documents and CAD models (in CADDS5 – as well as in CATIA v5-format). All the models in the archive are imaged into a working directory of all W7-X models, the so-called “W7-X assembly”. Since the completion of the implementation of the CATIA-PLM interfaces in November 2010 the “CATIA assembly” has replaced the former “CADDS5 assembly”. (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, in particular, further progress has been achieved in the definition of the supervision systems of W7-X and in the assessment with respect to their device safety relevance as well as in the analyses of the global hazard events possible during W7-X operation. Probabilistic safety assessment (PSA) methods, which were developed for nuclear power plants have also been applied to W7-X. As an example, a reliability model for one of the W7-X systems – the divertor target cooling circuit – was developed in order to demonstrate the capability of different measures, e.g. the realization of redundancy of important system functions and preventive actions (spare part policy, preventive maintenance), to improve the availability and to identify weak places (both hardware and human actions) in the complex environment of the different W7-X systems. This activity was performed by the Lithuanian Energy Institute and continued the successful and fruitful collaboration of IPP and LEI in the last years.

Schedule

The time schedule of the co-called “scenario 3” (developed in fall of 2007) was followed in 2010 as the years before. All four milestones scheduled in 2011 have been achieved, three of them ahead of time, one with a delay of four weeks. Also in the second module the port assembly turned out to require more time than foreseen. However, this does not result in any delay to the assembly end date. The end of assembly and start of commissioning of W7-X is still scheduled for August 2014. By the end of 2011, all five magnet modules are installed in their respective cryostat vessel modules. In the first four module, nearly all ports have been insulated and inserted, in the first three modules all ports have been welded. At the first module separation plane welding of plasma and outer vessel has been performed with the quality required, at two more separations the central support ring modules have been connected, closing of the respective vessel modules is under way. The detailed planning of assembly packages for the peripheral installations such as supply systems, diagnostics and heating systems is being continued.

2 Magnets and Cryostat

2.1 Magnet System

2.1.1 Coils

W7-X has a superconducting magnet system consisting of 50 non-planar coils and 20 planar coils, which provides the main magnetic stellarator field. All superconducting coils are finally assembled and in their final position in the machine. In addition to the superconducting coils, normally conducting coils were developed to fine tune the magnetic field and to increase the flexibility of the magnetic field configuration. The five trim coils will be located at the outer side of the cryostat and have a relative small cross section but a size of 3.6 m × 3.3 m and 2.8 m × 2 m, respectively.

In the frame of an international cooperation the US laboratories Princeton Plasma Physics Laboratory (PPPL), Oak Ridge Laboratories (ORNL) and Los Alamos National Laboratories (LANL) received a three years grant from DOE to support the stellarator research at IPP. Within the frame of this support program, PPPL will contribute the five trim coils. PPPL has accomplished several tasks to finish the final design, e.g. the detailed manufacturing design for the winding and for the coil connection area. The design work was accompanied by a detailed analysis of resulting forces and moments to prove the design. As a consequence of these analyses the originally planned temperature difference between the cooling water inlet and outlet was reduced to 30 degrees in order to reduce the forces in the winding pack. Successful design reviews at PPPL have confirmed the coil design. A call for tender was placed and the manufacturing contract was awarded to a US company received. At the moment the manufacturer is procuring the manufacturing tools and materials. PPPL has procured the copper conductor and plans to provide the components for the electrical connection, the hydraulic inlet and outlet and the instrumentation components. The delivery of the first two coils is scheduled for mid of 2012. IPP took over the responsibility for the design and procurement of the coil supports. The support design is divided into two parts. The part one will be welded onto the outer vessel and these parts are already available for assembly in the first modules. The second part clamps the coils with a kind of a bracket; the related call for tender has been prepared.

2.1.2 Coil Support Structure and Cryo Legs

The support of the magnet system is composed of the central support ring, the inter coil supports and the cryo legs. The central support ring consists of ten identical sectors (half-modules) with a total weight of 72 t. It is made from steel plates, cast flanges and cast extensions, which are welded to a half module. During assembly of the five magnet modules, in each case two half-modules have been connected (bolted) to a module. For the assembly of the modules to a ring connection elements at the module flange are necessary. These connection elements are composed of several 3-D shims, diamond foils and special bolts. They adjust the assembly tolerances and avoid a movement during the operation. Special measurement tools were developed for the fabrication of the shims and three out of the five connections where measured in 2011. The associated shims are pre-machined and the manufacturing process is running according to the schedule. Three module connections were finally completed in 2011. 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. Meanwhile all NSE were produced and assembled. The lateral support elements (LSE) join the non-planar coils in the outer side of the torus by welding. The semi products of most of the LSE's have been manufactured. The final measurement, custom-machining and assembly were successfully completed. For the LSE-D06, which is situated at the module separation plan, a new design was created. A mock-up was successfully tested and the semi-finished parts and all connection elements (bolts, super nuts and diamond foils) were specified and delivered. The final machining and assembly of the LSE-D06 of two magnet module connections has been finished in 2011. The planar support elements (PSE) connect the planar coils to the non-planar coils. Two types of the PSE had to be pre machined and afterwards E-beam welded. After the welding the final shape had to be realized after a special measurement of the real geometry. All PSE were fabricated and assembled in 2011. Two sorts of contact elements (CE) support the non-planar coils at the half-module separation plane and at the module separation plane. They take up pressure loads while simultaneously allowing sliding and tilting. Each contact elements consists of two machined steel blocks, padframes, pads and sliding plates. All smaller contact elements (CE 330) were machined, assembled and installed at the half module separation plane. Also the steel blocks for the module connection (CE 540) have been machined and assembled. The padframes, pads and sliding plates have been assembled, too. Depending on the measurement after installation of the magnet modules into the torus, they have to be finally adjusted. For two module connections this final adjustment has been performed in 2011. The coil support structure is vertically supported by 10 cryo legs. After delivery of all ten cryo legs IPP reworked the base-plates and installed the instrumentation for measurement of vertical forces. The cryo legs of all modules have meanwhile been installed. Also the associated bellows were welded according to the schedule in 2011.

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 situated in the space between the plasma pessel and the outer vessel. Together with the ports, these two vessels create a cryostat keeping the magnet system at cryogenic temperature and constitute the boundary between the W7-X main device and the external environment. The 254 ports give access to the plasma vessel for diagnostics, plasma heating and supply lines. The vessels and the ports are equipped with a thermal insulation to protect the cryogenic components from the heat load of the warm environment. MAN Diesel&Turbo (MAN-DT), Germany, is responsible for the manufacturing and partly also for the assembly of the plasma vessel, the outer vessel and the thermal insulation.

2.2.1 Plasma Vessel

The maximum outer diameter of the helically twisted plasma vessel is approximately 12 m; the minimum inner diameter is 8 m. The plasma vessel is made of the austenitic steel 1.4429 and has a wall thickness of 17 mm. The shape of the plasma vessel cross-section changes within each module from a triangular to a bean form and back again to a triangular form. The plasma vessel is composed of ten half-modules. Manufacture of all ten half-modules was completed in 2005 and installation of the superconductiong coils and the thermal insulation has been completed. In 2011 the first two plasma vessel modules were welded together. The installation of the thermal insulation at the module separation plane is running. All 15 vertical supports of the plasma vessel have been delivered. The last vertical supports were welded successfully to the lower shell of the outer vessel by IPP in 2011. For the horizontal support/centring system the design activities were finished, the components have been delivered or manufactured and the preparation of the first assembly trial is running.

2.2.2 Outer Vessel

The outer vessel is designed as a torus with an outer diameter of approximately 16 m. The internal diameter of the cross section is 4.4 m. It is made of austenitic steel 1.4429, the same material as the plasma vessel. The nominal wall thickness of the shell is 25 mm. Also the outer vessel is made of five modules; each module, however, is divided into an upper and a lower shell. The outer vessel has 524 domes for ports, supply lines, access ports, instrumentation feed through and magnetic diagnostics. All modules passed the works acceptance check and were delivered to IPP. The upper and lower shells of four modules have been welded already. The upper shell of the last module was placed in its final position in December 2011.

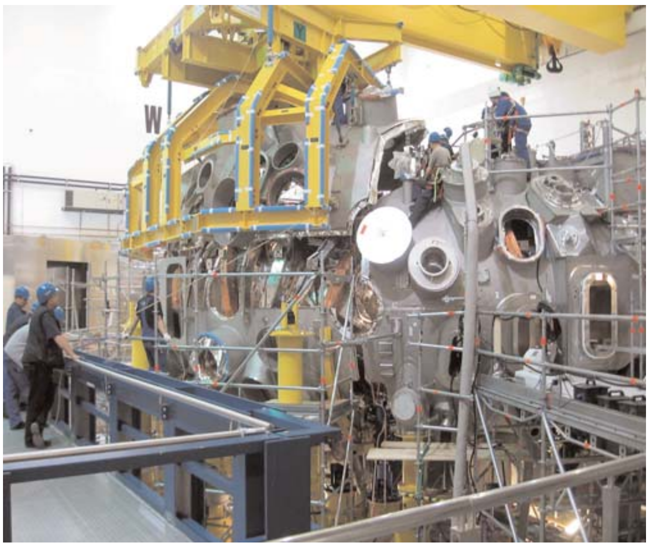

Figure 2: Assembly of last upper shell of the Outer Vessel.

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 square; the ports are equipped with bellows to compensate deformations and displacements of the plasma vessel with respect to the outer vessel. All ports are surrounded by water pipes in the bellow-area to control their temperature. All the ports and their fixing tools were delivered already until 2007. Circular water cooling channels have been installed at all supply ports in 2011. At some special ports additional copper stripes between cooling pipes and ports where installed for a better heat transfer. The routing of water pipes in the bellow area has been corrected in all modules.

Figure 3: Diagnostic Port AEK-V2.

Because of a misalignment of some ports an enlargement of dome plates was necessary in a few cases. Additional sickle plates were designed and tested. For three modules all plates have been delivered and assembled in 2011. For the remaining modules the manufacturing runs according to schedule. Several damaged bellows were found during the assembly preparation of the ports. After an in-depth analysis it was decided to change the bellows with severe scratches because of safety reasons. Smaller scratches are repaired by laser welding. The associated repair procedure was developed and qualified. The very difficult space situation required changes in the assembly procedure of the two NBI ports AEK-v2 and consequently several reworks of the ports. Special effort from IPP had to be made to motivate the manufacturer to deliver the ports in the required accuracy and quality. One port was completely assembled in W7-X in 2011; the second will be assembled in the beginning of 2012.

2.2.4 Exhaust Gas System

To avoid overpressure in the plasma vessel and the outer vessel, overpressure safety valves (rupture disc flanges) where developed. A special feature is the combination of the exhaust systems of both vessels in one common exhaust gas system in the torus hall. In 2011 the basic design of the exhaust gas tubes and supports was done. Calculations of pressure losses where finished and showed acceptable values. The preparation of the technical specifications of several components has been started.

2.2.5 Cryo-pipes

The cryo-pipes of W7-X distribute the cold helium within the cryostat with pipe diameters ranging from Ø13×1.1 to Ø50×3. They start at the Helium port in the cryostat and end at the individual feeders of the cold components like the coils, the central support structure, the thermal shields, etc. The very restricted space inside the cryostat resulted in a complex, three dimensional pipe routing. A new assembly concept for the current leads (CL) was developed requiring temporary supports that hit the He-supply pipes for the current leads. As a consequence the pipe design had to be adjusted to the new requirements. The design for all modules was completed. The manufacturing drawings for the pipes and the corresponding supports will be made by IPP. Also the new pipes will be bent by IPP workers. Helium being expulsed by the cryo pipes in case of a malfunction is led outside the cryostat via the quench pipes (e.g. in case of a quench of a superconducting coil or loss of vacuum). Outside the cryostat the He is collected in a ring manifold and then transported to the gas storage tanks. In the unlikely event of a very huge mass flow rate the He cannot be transported to the gas storage tanks any more. Then the expulsed He will be directly released into the torus hall. The mass flow rates and quench gas pipe diameters were determined. The boundary conditions required for the correct definition of the safety valves were discussed with the manufactures. Conceptual design activities for the quench relief system have been started.

2.2.6 Thermal Insulation

The thermal insulation of the W 7-X cryostat is fixed at the warm cryostat surfaces (plasma and outer vessel and ports) and protects the cold components against heat loads from the warm surfaces. The thermal insulation consists of a multi-layer insulation (MLI) and a thermal shield. The shield is cooled by helium gas flowing in pipes attached to the shields via copper strips or braids. The manufacturing of the outer vessel shield of the last W7-X module was finished including all panels, cooling pipes and dome shields and the assembly was completed, too. The engineering of the CAD-models for the port shields made further progress. All CAD- models of the fourth and fifth module were sent to the manufacturer MAN-DT. The manufacturing models were created by MAN-DT and finally approved by IPP. All port shields of the fourth module were fabricated. Sixty percent of the port shields for the last module were also manufactured. In 2011 the port shield installation was finished for the second module. Additionally the shield installation was continued for the third and fourth module. Special effort was required for the design of the port shield for the two AEK-V2 ports, which will host the neutral beam injection. This was caused by the very restricted space available for the thermal insulation in combination with a complex 3-D contour that requires additional manufacturing tolerances. The undercuts at the port and at the port shield geometry required that the port was divided in two pieces, the “main body” and the “pocket”, located towards the plasma vessel. Several collision controls were necessary to generate a design fitting to the available space. Parting of the port in combination with the very limited accessibility of the cooling design of the port shield required a redesign. Isolated copper plates were installed on the port shield that helped to increase the heat flux inside the shield. Additionally the material thickness of the shield plates was increased from 2 mm to 3 mm wherever possible. The fabrication of the new port shields was released in autumn 2011 and the first shield arrived at IPP end of 2011. The access to the work space will be restricted by the mounted current leads at the time the dome shield of the current lead domes will be installed at the lower shell of the OV. So an assembly sequence for current lead installation and dome shield installation was developed and tested at a mock-up. The shield design and the assembly sequence could be confirmed.

2.3 Current Leads

The current leads (CL) are the electrical connection between the cold, superconducting magnet system inside 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, i.e. the cold end is on top and the warm end is on bottom. In total 14 current leads are necessary for W7-X. The production and the tests are being performed by the Karlsruhe Institute of Technology (KIT). In 2011 significant progress has been achieved in the production as well as in the field of testing. A stable production process has been established, accompanied by a sufficient quality management system. In 2011 eight current leads have been fabricated. Main components like high temperature superconductors, heat exchangers, vacuum tubes, electrical insulation are available on stock for further five current leads. By the end of 2011 six current leads have been tested under cryogenic conditions. In one test campaign, always two current leads are connected to form an electrical circuit. After a thorough check under room temperature the whole test arrangement was cooled down to cryogenic temperature with a speed of 10 Kelvin per hour.

After the hydraulic and thermal stabilization the CLs were successfully loaded up to the maximum current of 18.2 kA several times. Also a test of a loss-of-Helium-flow accident showed sufficient time to de-energize the W7-X magnet system slowly, before a quench would occur. The safety margin of the superconducting parts was tested by induced quenches, too. The margin between the operating conditions and the achieved quench temperature meets the requirements. The necessary helium mass flow rates to operate the current leads fit to the expectations. After the test campaigns under cryogenic conditions a high voltage test under different environmental pressures were performed successfully at all current leads. This demonstrates the proper behavior of the electrical insulation. The test reports were prepared and checked by IPP. The documentation has been prepared and was sent to IPP. The delivery of the two prototypes and of the first two series current leads is scheduled for January 2012.

2.3.1 Current Leads mechanical support

Mechanical supports of Current Leads are needed to support the current leads at the section between warm and cold side with all the allowable movements coming from the operation. Simultaneously they will be needed to support the bus system up to the central support ring. They consist of two main parts, which will be manufactured in different steps. Firstly the bearing at the central support ring with the connected horizontal rods to join the coil support structure with the fixing box. In the second step the fixing box itself with the bearings for the current leads and the bellows is built. Because later there is no access possible, the supports and rods have to be installed first. The manufacturing for all bearings and rods was finished in 2010 and in 2011 the assembly of the components was finished. Because of a reduced access during the assembly of the fixing box, a mock-up was manufactured to test and to optimize the assembly procedure.

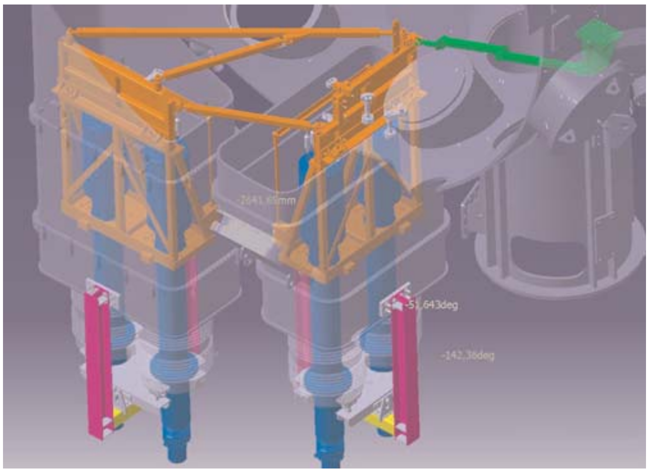

Figure 4: Two current leads (blue) with: fixing box (orange), lower supports (magenta), domes, rectangular pipes (green).

With the first results the design was partial reworked and finally finished for the fixing box, the bellows, the bearings for the current leads and the connected bus supports. The first rectangular pipes for the fixing box have been manufactured. A tender action for the series production of the fixing box has been completed and the manufacturing documents have been prepared. The 14 bellows were produced and tested. The first two bellows have been delivered in 2011. The current lead assembly requires additional flanges in the domes of the outer vessel to temporarily support the current leads in several steps of the assembly sequence. The rework of the domes has been started in 2011.

3 Supply Systems

3.1 Helium Refrigerator

The helium refrigerator produces and distributes the cold helium required to cool the cold components of W7-X. The cryo plant has been installed and the commissioning of the refrigerator is in progress. The integral leak testing of all the warm piping was finished. Incorrectly working components were repaired or exchanged, such as shaft seals of the high pressure oil pump, a compressor brake wheel of turbine 2, nozzle wheels for turbines 6&7. The Helium gas inventory was replenished to be able to continue with the commissioning activities.

Figure 5: Electrical drive with oil separator, oil cooler and filter of the screw compressor unit.

The daily archiving of the refrigerator data to an IPP server was established. While carrying out the cold operations, thermo acoustic oscillations have been observed in pressure and mass flow values at the cold end. Linde Kryotechnik AG (LKT) has been attempting to solve the problem by implementing various changes. LKT already changed the piping routes, incorporated thermal intercepts and introduced additional mechanical supports. Some of the cryo valves were changed to larger elements. Dampers were inserted on instrumentation tubes and non-return valves etc. have been installed. LKT is still working on the topic. The refrigerator was operated in short standby mode and close to standard mode operating conditions as required for W7-X cooling applications. These operations indicated a good performance of the refrigerator. Control adjustments on cold circulators and on the first cold compressor were introduced for the normal functioning of these components. The acceptance test procedure for the compressor system together with the oil removal and the cooling water system was finalized. The acceptance tests of these systems were performed for all the four operating modes. The required mass flow rates were achieved. The data evaluation and finalization of report is in progress.

3.2 Magnet Power Supply

The superconducting magnet system is divided into seven electrical circuits, five circuits with ten non-planar coils of one type each and two circuits with ten planar of one type 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 realised by fast circuit switches, which short-circuit the coils and dump the magnetic energy into resistors. The whole system was installed and finally tested in 2005. Over the time the failure rate of the power supplies tends to increase. Intensive negotiations with the main contractor ABB were performed to find a common solution in terms of repair, warranty, payment and spare parts. ABB started the repair mid of 2010, but also in 2011 ABB performed several repair measures. In December 2011 a final test was performed to demonstrate the proper operation of the system. All power supplies were operated in a way, which simulates the W7-X operation at the maximum field of 3 Tesla for eight hours. The test was successful, but small inaccuracies in two current measurement devices still have to be corrected.

3.3. 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 also 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 quench detection units will be put into 10 so called subsystems. One subsystem contains up to 64 quench detection units and is equipped with an internal AC/DC power supply combined with an uninterruptible power supply to secure the independent operation of the subsystem. For control and data acquisition an internal controller is installed to evaluate and to transmit the quench signals to the magnet safety system and to allow a fully remote control. The fabrication of a prototype subsystem has been finished, and in a steady state test over several weeks the faultless operation was demonstrated. Due to the good results the prototype subsystem will be used as the first series subsystem. The production of the remaining nine subsystems has been started and completed in IPP in 2011. All subsystems have been running in the steady-state test set-up since summer 2011. So far all systems are working as expected.

Figure 6: QD-subsystems during the steady-state test.

4 In-vessel Components

The in-vessel components (IVCs) consisting of: the divertor components (target, baffles, and toroidal closure plates), plasma vessel protection (panels and heat shields), control coils, cryo-pumps, port protection and special port liners for the different heating systems together with the complex system of cooling water supply lines continued their detailed design and fabrication in 2010. In particular, the detailed design of the high heat flux divertor continued concentrating on the target modules of the high iota tail. 2010 saw the delivery of the control coils to Greifswald and 2011 saw the first major delivery of the remaining IVC components to Greifswald consisting of 40 plug-ins and 80 baffle modules.

4.1 Target Elements

The main building blocks of the high heat flux (HHF) divertor are the 890 target elements being manufactured by Plansee SE. These HHF divertor elements consist of 8 mm thick carbon fibre composite (CFC) tiles joined to a water-cooled CuCrZr heat sink and are designed to withstand power fluxes of 10 MW/m^2. The contract with Plansee SE plans delivery of the elements in two main phases. All of the 282 first phase elements were delivered to IPP in 2011. The elements had been fully tested at Plansee SE, and subsequent helium pressure tests and pressure drop measurements have been conducted by IPP. All the tests showed that the elements were well within the specification. The first 20 elements (figure 7) were delivered ahead of time in order that the series elements could be tested in the GLADIS high heat flux facility at Garching. These 20 elements and subsequently 20 more were successfully tested giving no indication of any problems between the CuCrZr heat sink and the CFC tiles. The helium pressure test and pressure drop measurements were repeated after GLADIS testing, and again showed no problems. As the bond between the CFC tiles and the CuCrZr heat sink is crucial to the performance of the elements special visual inspection equipment has been developed as part of a BMBF funded development programme. This equipment was used to visually inspect the 6000 tile edges of the delivered elements, no significant cracks or defects were found, neither before nor after the GLADIS tests.

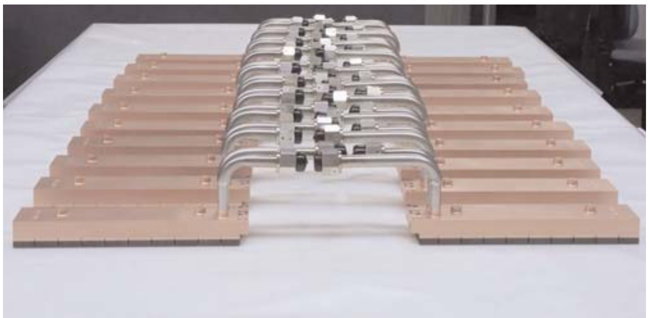

Figure 7: First delivery of 20 elements (January 2011).

The remaining target elements will be delivered in the second phase of the Plansee SE contract. These second phase elements are longer and in some cases wider than the first phase elements and also have additional tiles on one end of the element, which means that they are more complicated to manufacture and to test. As part of the BMBF funded development programme mentioned above a number of open issues concerning these elements were addressed and solutions developed. Part of the outcome of the development programme was a pre-series of elements (figure 8) with all of the features of the second phase elements. These pre-series elements were also delivered to IPP, found to meet the specified values for heat flux and underwent, without problem, all of the standard tests and on this basis the release was given in 2011 for the manufacture of the second phase series elements. These are now in production in Plansee SE and will be delivered in batches in 2012, 2013 and 2014.

Figure 8: Prototype second phase elements.

4.2 Target Modules

Sets of target elements (varying from 6 to 12) are mechanically and hydraulically connected together to form target modules, the physical entities, which are installed in the W7-X machine. For each divertor unit there are 10 such modules. In parallel to the design of the modules, a prototype module was produced to demonstrate that the designed modules could be manufactured with the required accuracy and performance. Lessons learnt from the manufacturing process were then fed into the design to reduce costs and manufacturing time. The prototype module was also planned to be tested under similar conditions to those experienced in operation, i.e. the prototype module was conceived to be tested in GLADIS. The prototype module was made from prototype elements used for the development of the CuCrZr/CFC joining technology. The use of the prototype elements meant that only the horizontal target module TMh9 (with 12 elements) could be produced since other modules require other types of elements. The complex 3D plasma facing surface of the target modules was also replicated in the prototype module. This was done by two methods; the first involved machining the 3D surface on six of the individual elements, the second by machining the 3D surface directly onto six elements of the completed module. This exercise compared the advantages and disadvantages of the two methods. In the end the machining of individual elements was chosen as it met the dimensional requirements and greatly reduced the risk of the elements being damaged.

The prototype module (figure 9) relied heavily on the experience gained during the manufacture of the in-vessel pipe work for the manufacture of the water manifolds and the pipe welding. The prototype module was also successfully tested in GLADIS during 2012.

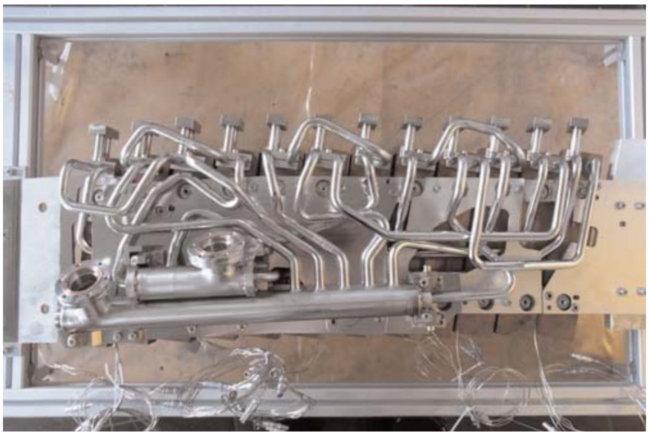

Figure 9: Backside of the test module prototype TM9h showing the complex piping arrangement.

In parallel to the prototype module production finite elements calculations with a complete model of the module were performed to ensure that there would be no systematic problems with this geometry under the geometric load conditions expected in the W7-X machine.

4.3 Test Divertor Unit (TDU)

The interim solution for the Divertor during the first phase of machine operation is the TDU. This has the same geometry as the HHF divertor, which will be installed later but uses inertially cooled graphite tiles instead of water cooled HHF elements. During 2011 the horizontal modules TMh1-TMh4 and TMv1-TMv3 together with their support frames were completed. The assembly process for the remaining parts for the modules TMh7-TMh9 was started at the end of 2011. The TDU has been built in cooperation with Garching, Greifswald and by external companies.

4.4 Baffle Modules

The design and manufacture of the remaining baffle modules continued in 2011 and by November the whole set of horizontal baffle modules had been completed and were sent to Greifswald. The last vertical baffle modules to be designed were geometrically more complex than the earlier modules; nevertheless the baffle design was completed in 2010. In total there are 170 Baffle modules, 120 of which have been manufactured by the IPP workshop in Garching. The graphite tiles and the associated TZM screws, which cover the baffle modules are procured externally and the contracts for graphite tile procurement run in parallel to the manufacture of the modules.

4.5 Wall Protection

Apart from the divertor the IVCs consist of double walled stainless steel panels (covering approx 70 m^2 of the inside of the plasma vessel) and heat shields (covering approx 50 m^2) consisting of water cooled copper plates coated with graphite tiles (similar to the baffles). In 2011 the delivery of the panels was completed by MAN-DT including six modified panels for the Neutral Beam (NBI) shine-through area. In this region the panels were reduced in size as there was a concern that the beam could damage the previously designed stainless steel panels. In this region the heat shields were extended. The design of the heat shields also integrates several plasma diagnostic components as well as mirrors for ECRH heating. By the end of 2011 a total of 150 of the 162 heat shields cooling structures had 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 inner surfaces of the plasma vessel.

Figure 10: AEAv3 port protection panel prototype during testing at IPP Garching.

For resource reasons, the manufacture of the port protection panels has been postponed to a later date. Nevertheless, a limited amount of design effort of these protection elements was continued to fix their interfaces and define the routing of the cooling water lines. Since the space behind the wall protection is very restricted, all port protection panels will be later supplied with water from outside. In addition a few port protection panels have been manufactured especially for those regions that will be relatively highly loaded during the first phase. A prototype of the AEAv3 port protection (figure 10) has also been built in order to demonstrate the technology for this large component.

The ports, through which the NB beams will shine as well as the port for the diagnostic injector need to be protected against energetic particles by CFC and graphite tiles from the beginning of operation. The design work for these port protections is completed, the manufacturing drawings have been prepared and a number of components are in manufacture.

4.6 Cryo-pumps

The in-vessel cryo-pumps, located behind the target plates of the HHF divertor, have been designed and partly manufactured. Since the cryo-pumps will not be installed until the HHF phase the on-going manufacture has only been performed when spare capacity has been available. The water baffle of one cryo-pump has been completed and coated with an ECRH absorbing coating. The aim of this is to reduce the ECRH stray radiation in the vicinity of the cold areas of the cryopump in order to stop them overheating. Results from the Mistral ECRH test facility showed that the coated water baffle was very effective at absorbing ECRH radiation. This indicates that coating of the water baffles could be a partial protection of the cryopump against ECRH stray radiation. Further tests are to be performed on the water baffle to clarify this point.

4.7 Control Coils

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. In 2011 the test operation of ten power supplies were continued by using dummy loads. The power supplies were operated up to the maximum direct and alternating current several times to check the electrical and thermal performance. Also the quality of the closed loop controller was checked an adjusted.

4.8 Plug-in

The in-vessel plug-ins are used to deliver water and in some cases diagnostic cabling from the outside of the machine to the inside of the vessel through the ports. These plug-ins consist of a flange with welded tubes for water supply and outlet (figure 11). There are eight different types of plug-ins depending on the port they are going through and the components they are supplying. Some plug-ins carry water for components that will take part in the “hot liner” experiments and calculations have shown that in one case, i.e. for the AER port plug-in, additional thermal shielding is necessary to avoid overheating of the port wall by radiation from the hot tubes. 60 of the 80 plug-ins had been completed by the end of 2011.

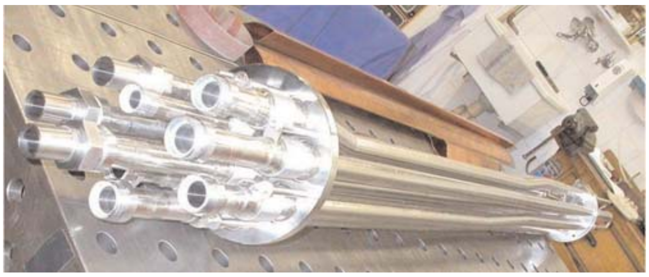

Figure 11: Fabrication of a plug-in in ITZ-Garching.

4.9 Water Supply Lines inside the Plasma Vessel

The cooling supply lines of the in-vessel components run from the plug-ins to a complicated system of manifolds and pipes, which deliver water to the various components via flanges. Significant progress was made in the final manufacture of the pipe work in 2011. The remaining water manifolds have been delivered by Dockweiler in 2011 and the final assembly of many of the cooling circuits has been completed. The IVC are cooled partly in parallel and partly in series. Adequate water flow has to be guaranteed to all of the components and to check this new software has been purchased from Flowmaster, which allows the flow in the different cooling circuits to be calculated based on the measured pressure drop in the individual components, also taking into account the pipework pressure drop. These calculations were also necessary due to the large number of different geometries, which occur as a consequence of local geometry variations. Through the use of this and other calculation methods it was found necessary at a number of locations to build into the cooling system restrictions to balance the water flow.

4.10 Glow Discharge System

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, delivered to IPP and finally tested. In 2011 the test campaigns under different operating conditions were continued.

5 Assembly

In 2011 the preparations of assembly equipment and extensive assembly trials have been continued. All magnet modules have been put into their outer vessel modules in the final positions in the experimental hall. The alignment accuracy achieved is much better than originally expected and lies at about 1×10^{-4}. All magnet modules are completed with the helium pipe system and the bus-bar system. Further complex assembly devices for the final assembly (current leads, in-vessel components) were put into operation and optimised. All pre-assembly work was accomplished. The preparation of outer-vessel (OV) shells was finished and the associated assembly equipment dismantled. As in the year before the main focus in 2011 was the optimisation of the port assembly, particularly the welding procedures and the installation of special ports. With large effort and additional resources this challenging task could be coped with. Again the process time needed for the port installation had to be extended noticeably. The schedule, however, could be kept constant through further increased work density, optimisation of the technology and restructuring of work packages. Both assembly and welding procedures for special ports were further optimised to minimise the welding-shrinkage. The assembly sequence and technology for current leads were completely tested and ran smoothly. A 1:1 mock-up was upgraded to qualify the associated welding technologies for CL-domes in detail. The challenging assembly process-planning, process documentation and work safety system run reliably.

5.1 BUS System

The work on all five individual magnet modules was completed without major problems. Compared to the first magnet module the process time was shortened from 60 weeks to 37 weeks because of optimisations and learning effects. These figures include process times for the helium pipework and the instrumentation. In the main focus now is the assembly of joint connections at the module separation planes, which means that bus-bars of neighbouring modules are being connected. Since each module is aligned individually the already prepared bus-bar ends need a special adaptation to make them fit precisely into the joint-base. The cooperation at the bus-bar work with IFJ in Krakow was fruitful and has been continued as in the years before. Development-works for the electrical connection of bus-bars and current leads (CLs) were intensively continued (see also 5.3.3 Final Assembly). Special attention was paid to the electrical connections between the strands of the bus-bars and the cold-end of the CL, the so-called CL-joint. Though the base-principles of this connection were defined in 2009 already, comprehensive test results of qualification specimens became available only in 2011 in conjunction with the CL acceptance tests. Geometrical accuracies of some 10 microns at contact surfaces must be achieved despite unavoidable welding works at these joints. Additional machining and coating of these surfaces on site seems hardly to be possible. 1:1 specimens of these joints were and are made and tested. The qualification still continues. Precise bending and customizing of the ends of the bus-bars and helium pipes, the reliable welding at these components despite a very limited access and a reliable making of the electrical insulation were other challenging development tasks, which have been successfully accomplished.

5.2 Vacuum Technology

The work packages of the vacuum technology group were continued in 2011 as in the years before. Main tasks were again the accompanying leak tests on site, which include the procurement of many specially designed test-chambers. More and more assistance to other groups and departments is provided to keep the vacuum compatibility in the designs and at the components. The design work on the three vacuum systems was continued as well as the work on gas supply and gas monitor systems. First sections of the vacuum pipe system were specified and will be ordered. The procurement contract for fast piezo-valves for the gas-inlet was done. A special task was the qualification of a multi-stage cleaning process, which is needed before the in-vessel work starts. The combination of sucking, wiping and CO_2 ice-blasting provides the necessary cleanliness at the inner surfaces of vessels and ports.

5.3 W7-X Assembly

5.3.1 Component Preparation

The work at the outer vessel shells has been accomplished. Works at the ports are continued routinely as planned. Only the preparation of ports for the later NBI-use required immense efforts since their geometrical accuracy had to be improved after the delivery. Consequences onto the project schedule could be minimised by increasing the work density at the later port-assembly in the torus hall. The set-up of the preparation for in-vessel components is being continued as planned.

5.3.2 Pre-Assembly

The last magnet module was made ready, it was transported onto its final position in the torus hall and hence the entire pre-assembly of W7-X is accomplished. The whole pre-assembly equipment has been removed. The associated hall space is available for the installation of ICRH components.

5.3.3 Final Assembly

In the final assembly the construction work at the first three modules of W7-X has been accomplished. All ports have been installed in four out of the five modules. At the fourth module the final port-welding has started. The port installation in the fifth module is starting in March. The assembly accuracy at the ports has been stabilised. The accuracy limits were specified using the lessons learned from the first modules. An additional laser tracker was procured to ensure sufficient metrology resources for the port assembly. The port assembly work ran routinely, except for the both very complex NBI ports. These did not only cause a lot of effort in the preparation but also the installation and the welding caused several interruptions and process modifications. Meanwhile the first one was successfully installed and the installation of the second is underway. Still missing are the ports at the module separation planes (MSP; see below).

At the first plane between the first two modules the ports will be installed soon. With the present knowledge no particular difficulties are expected here.

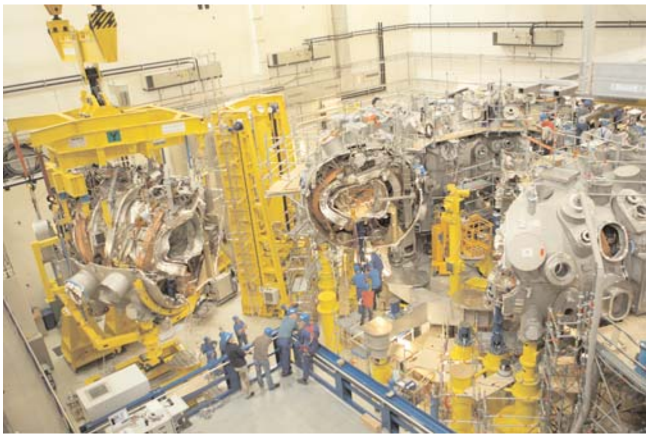

Figure 12: The last module before it is taken to its final position.

The cooperation with MAN-DT in the final assembly was running very smoothly in 2011. The working times at both IPP and MAN-DT were harmonized and that ensured a high efficiency in the ongoing assembly. At the MSP the technology for the mechanical connection of the neighbouring magnet modules was fully implemented. The technology worked as qualified in 2010. The shimming between the central support rings runs routinely. The same applies to the manufacturing and installation of the extreme precise lateral supports (LSE D06). The completion of the bus-bar system, the helium piping and the instrumentation went without severe problems. A special highlight was the connection of the first two cryostat modules, which started earlier than originally planned. For this one module (outer vessel and plasma vessel) had to be moved apart simultaneously to compensate for the expected welding shrinkage at the double-seamed splice plates between both vessel-modules. IPP developed the tools and processes to move the modules. It worked as expected. The shrinkage uncertainty however was slightly higher than the estimated 2 mm but still tolerable. At the next MSP a modified offset of the module's initial position shall improve the accuracy further. Unexpected high were local sags in the vicinity of welded domes at the outer vessel. Fortunately these could be accepted after thorough inspection. MAN-DT plans to improve the welding procedures to minimise the sagging in the future. The mechanical assembly procedure for the current leads (CL) was a main development task in the assembly technology. A detailed work procedure and comprehensive assembly sequence was tested using a 1:1 mock-up (figure 14). A new assembly tool (ramp no. 3) was developed and procured from Fantini SA (Italy), which enables the complex and precise manoeuvring of the heavy current leads in a poorly accessible installation space. It could be shown that the save handling of Cls fastened at the specially developed assembly ramp is accurate within 1.5 mm. The same applies to the handling of the three heavy dome sections. These are stacked one upon the other and surround every pair of CLs. The technological base-concepts for this mechanical assembly, which were developed by the ORNL in Oak Ridge and the PPPL in Princeton have been confirmed successfully. A second smaller mock-up was built to qualify the welding procedure at the first dome section in a relevant way. First results are very promising. This development program benefits from the experiences made at the port-assembly at the cryostat.

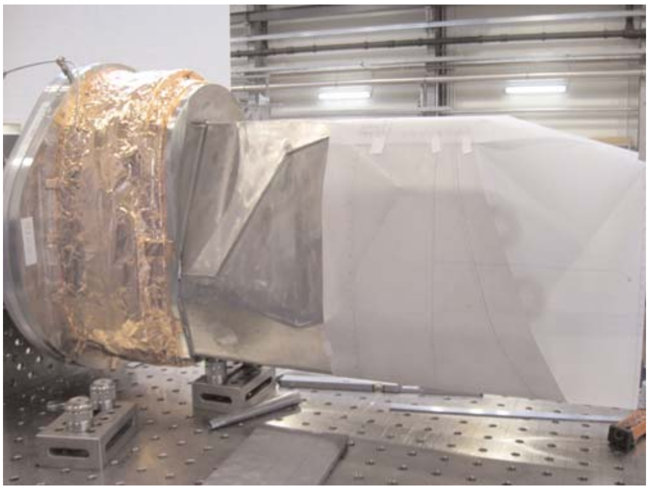

Figure 13: A NBI port prior to the contour cutting.

The cooperation with the KiP division in Garching with respect to the conceptual planning of the assembly of the in-vessel components has been continued in 2011. Trial assemblies with wall panels, heat shields and sweep coils have been performed successfully. Assembly accuracies of bolts, brackets and components were investigated systematically to identify and realise potential for improvements. A set of tools for the save and precise manoeuvring of measurement devices and manipulators were provided and tested. Further tooling for the stiffening and the handling of in-vessel components was specified and ordered. Under development is a welding tool, which shall combine the precise bolt-positioning with a percussion welding process. In case of success that tool would prevent inadmissible distortions, which occur due to the manual bolt-welding. About 1000 bolts per module have to be welded. Welding procedures at the water manifolds were further optimised. Because of the extremely poor access a certain amount of tempering colours had to be accepted here. A practical solution for the customized assembly of closures for residual gaps at components was successfully qualified. Several assembly-tests with magnetic diagnostics were performed. The assembly sequence for components and diagnostics in the plasma vessel was optimised accompanying the development of the technology. Once again the needed process time increased noticeably. An extended shift system might become necessary to comply with the project schedule. The technology development in terms of logistics, tooling and procedures is continued as planned. A powerful ventilation system was conceptually specified. It serves the maintenance of save working conditions inside of the hermetically closed plasma-vessel module. On the other hand it provides permanently a slight overpressure inside the vessel to prevent external pollutions. The first device will be tested in March 2012.

Figure 14: Assembly trial with CL-dummies and dome sections.

In the periphery, the work on cryo instrumentation in conjunction with the work at the bus-bar systems is nearly accomplished. Main focus is now the assembly of large feedthroughs in the outer vessel for the instrumentation of sensors and QD voltage taps. Two of those have already been installed and tested. The construction of cable systems in the torus hall is continued as planned. At the moment the main task here is the definition of collision-free available space for the needed cable trays. In terms of the cooling circuits, the industry has started with the production of the second stage of construction. That comprises the entire pipe work in the torus hall. Design work for the central platform in the torus hall continued as planned. The platform will be divided into four independent sections. The collision-free design of the first section was finished and the associated supply contract is being specified presently. The central platform serves also as support structure for cable trays and pipe work. The assembly control and the planning work are running routinely as before. That includes the weekly and the 4-weekly planning, the assembly documentation (QAAP, work and test instructions) and a refined resource planning. Quality deviations are reliably handled as in the years before. The assembly schedule was completely updated. Again the estimates for process times were extended. That concerns mainly the ports, the current leads, the in-vessel components and the periphery. The assembly sequence was optimised and the work density increased to minimise the influence onto the project schedule. The commissioning starting date was shifted by two weeks but it lies still in the middle of 2014. Altogether, assembly has reached the planned progress in 2011. Further new assembly technologies were qualified and successfully tested. The device assembly ran continuously and speedily as planned. Resources for engineering tasks and technicians for assembly works were adapted to cope with the changing work packages and required work capacities. The cooperation with external partners who provide skilled and well-trained technicians and engineers for the realisation of the assembly work on W7-X works soundly and smoothly.

6 Engineering

The sub-division Engineering (EN) provides engineering support to the Wendelstein 7-X project. EN is organized in two departments: Design Engineering (EN-DE) and Instrumentation (EN-IN).

6.1 Design Engineering

Design of the "basic machine", i.e. without in-vessel components, diagnostics and periphery, is largely completed. Structural parameters such as bolt preloads, initial conditions for contact elements, etc., are defined and implemented. Therefore, the focus is shifting towards fast analyses of non-conformities, deformations as input for collision checks, and changes in the assembly procedure. This assembly-related work is expected to continue until commissioning of the machine, however, with decreasing intensity. In parallel the analyses for in-vessel components, diagnostics and periphery, as well as the exploration of operational limits of the as-built machine and the expected instrumentation signals are increasing. In addition, some design work on the mechanical structure of the magnet system, vacuum vessel and cryostat for a HELIAS stellarator reactor has been continued, and collaboration with ITER has been started up.

6.1.1 Superconducting Magnet System

6.1.1.1 Mechanical Analysis

The magnet system comprising 70 superconducting coils and their support structure is analysed using a finite element (FE) model tree. The starting points are finite element (FE) global models (GMs) of a half module and of a complete module including the cryo-legs. Two FE models created with ANSYS and ABAQUS codes, respectively, have been continuously used to predict deformations of the winding pack for collision analyses and magnetic field error estimations, and to deliver input for refined local models (LMs) of support structures, cracked regions, of regions with serrated yielding at cryogenic temperature, etc. Parametric studies including all main uncertainties have been ongoing including the variation of the friction factor at bolted contacts and as-built gap variations at the narrow support elements (NSEs) of the coils.

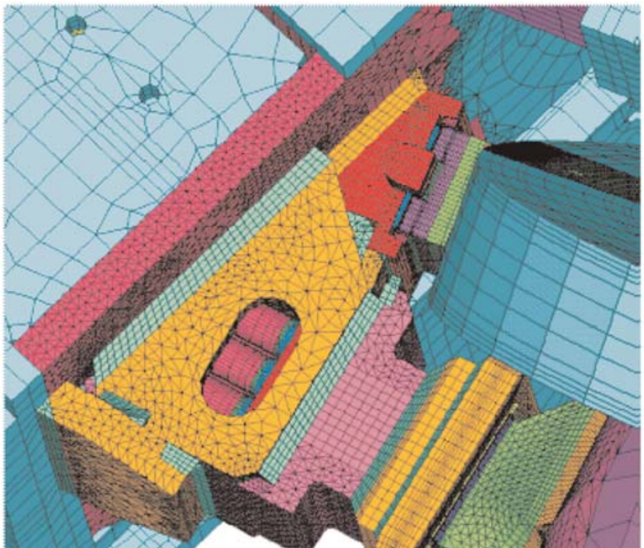

Figure 15: Refined local model of a critical CSE connection, introduced into the global magnet system FE model.

For loads not complying with the five-fold torus symmetry like forces from auxiliary supports during assembly, module misalignments, or trim coil fields, even larger but slightly simplified FE models of multiple modules up to the closed torus were created. The documentation of the GMs was completed. Local models of critical support structures have been further developed and used for parametric studies in collaboration with Warsaw University of Technology (Poland) and LTCalcoli (Italy). The behaviour and limit load of the bolted central support elements (CSEs) of the coils was checked. For each of the complex welds between the coils and the CSEs new detailed 3D LMs were developed and analysed with the conclusion that there is no critical situation under design loads. For the most critical connections, the detailed LMs were implemented in the ANSYS GM (figure 15) in order to determine the limit load with consideration of load redistribution due to yielding. LMs were developed using the sub-modelling technique to assess cracks in the welded lateral support elements (LSEs) between the non-planar coils (NPCs). The prediction of the envelopes of load cycle combinations from 0 to 2.5 T, from 2.5 T to 3 T, and switching from one electromagnetic load to another, respectively, is ongoing based on the most critical cracks that were observed after welding of the LSEs. The sub-modelling technique was also applied to the highly loaded narrow support elements (NSEs) between the NPCs to evaluate the temperature rise due to conversion of plastic work into heat and its consequences on the plastic limit load (in collaboration with LTCalcoli). The specification for measurement and machining of the LSE DO6 (connection between modules), to be prepared and fit with tens of micrometer accuracy, were completed on the basis of FE analyses and in collaboration with the Assembly division. The manufacturing and installation procedure is being closely supervised.

6.1.1.2 Magnetic Field Perturbation

The target position of the modules was optimised to compensate for manufacturing and assembly deviations of the individual coils and modules with view to minimise the magnetic field perturbation. For this purpose the asymmetry of the winding pack positions was considered based on geometric measurements over the entire process of manufacturing and assembly of the coils and modules to the final torus. The very positive final result is a relative magnetic field error for the standard operation case of 0.34×10^{-4}, which is several times smaller than the corresponding value estimated without the optimization. Calculations performed for other operation cases showed the remaining magnetic field perturbations being of the same order of magnitude. Analyses are ongoing to assess the effect of non-symmetric deformations of the as-built magnet system during operation based on deformation predictions generated with the FE GMs.

6.1.2 Trim Coils

Calculations of fields and forces for all electromagnetic configurations and two directions of current (19 load cases in total) were performed. The magnetic coupling between the trim coils and the W7-X magnet system as well as current and force changes during fast discharge was analyzed. The results of electromagnetic and thermo-mechanical simulations of the Princeton Plasma Physics Laboratory (PPPL) were benchmarked. Further activities concerned the analysis and design optimization of the trim coil supports taking into account the deformations of the outer vessel, as well as calculation and optimization of the assembly handling tool.

The trim coils will be brought into position at the outer vessel with this tool whereby the coil deformations have to be kept below allowable limits. Another contribution was the thermo-mechanical local analysis of the winding pack in order to check delamination and local stresses of the turn, pancake and ground insulations. EN assisted in specifying material tests on the rubber pads that are intended to be used in the clamping supports, and partly executed such tests.

6.1.3 Cryo-piping

FE-models of the magnet system cooling pipes are continuously updated for all five modules. The analyses are performed iteratively hand in hand with the design and installation of the pipes and their supports, and with further modifications due to non-conformities, re-design of components, re-routing, etc.

6.1.4 Cryostat

Main application of the ANSYS cryostat global model (GMCS) is to provide input for collision checks, for local analyses particularly of forces and moments in port welds, plasma vessel and outer vessel supports, for local deformations under trim coil loads, diagnostic port movements and deformations, etc. The current outer vessel FE model is based on a CAD design, which is outdated by now due to many modifications during manufacture and assembly. Therefore an updated GMCS with approximately 400 modifications is being created in collaboration with IGN company (Greifswald). All changes are collected and assessed in view of implementation in the updated outer vessel FE model. Further activities in the reporting period are listed in the following: Load cases and allowables were defined as well as the procedure to determine the thicknesses of the port welds to the plasma vessel and of the domes to the OV. All ports could be released for welding. For special ports, and in cases of doubt, laborious 3D FE models were created and analysed, including limit analysis. The work was performed in collaboration with the Lithuanian Energy Institute, Kaunas, Lithuania, and showed that also these welds are adequate with sufficient safety factors. Mainly due to tolerance deviations, some ports required machining, several outer vessel dome plates had to be split into two or more parts, and some plate welds had to be changed during assembly. Based on global and local FE analyses, design changes were accepted, or adequate weld configurations were recommended. The analysis of the planned outer vessel leg fixation on the machine base revealed an overload of the bolts due to thermal expansion during plasma vessel and port baking and the consequential heating of the outer vessel. An appropriate re-design was developed and implemented in collaboration with the Assembly division. The closure of the ports, which were skipped in scenario 3 was checked thermally and mechanically. The thermal loads on the plasma vessel, thermal insulation and magnet system are acceptable. However, the plasma vessel closure plate weld seam overstress requires additional protection measures under high heat loads during operation phase 2. Removal and/or modification of cooling and heating pipes on ports was followed up with corresponding thermal analyses, and in some cases copper stripes were proposed to improve the thermal connections between the pipes and ports. Based on FE analysis, a combination of electrical heating and thermal insulation on port flanges and contiguous tube parts protruding outside the cryostat was proposed in order to improve the temperature distribution during plasma vessel baking, and to limit the heat loss to the torus hall. For the AEKv2 ports additional copper plates were found to be necessary to improve the thermal connection to the outer vessel shield. Eddy currents and the subsequently induced electromagnetic forces had to be considered and kept below allowable levels (figure 16).

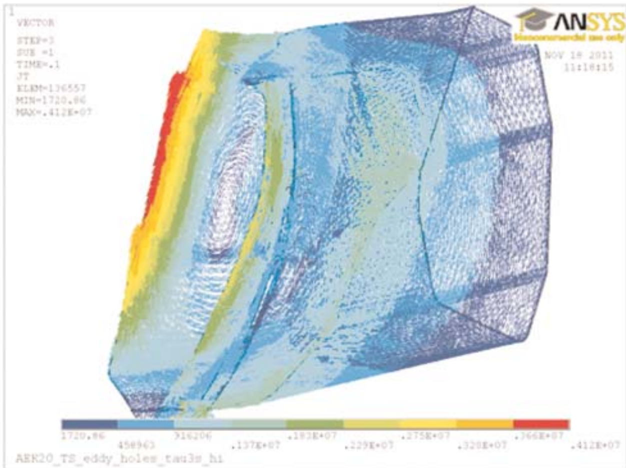

Figure 16: Eddy current densities (A/m^2) in the AEKv2 port shield.

Allowable thermal radiation loads on port bellows were specified. The instrumentation feed-throughs on dome plates were analyzed and modified in order to be compatible with the hot environment during plasma vessel and port baking. Port shutters for diagnostic ports were thermally analysed.

6.1.5 In-vessel Components

Analysis activities supporting the design of in-vessel components grew considerably; major examples are listed in the following:

EN participated in determining the heat loads inside the plasma vessel for all planned plasma scenarios. Not only the heat load on the in-vessel components was considered but also the heat load behind them and in ports due to thermal and ECRH radiation from the in-vessel component backsides and through gaps between them. An approach for ECRH stray radiation estimation with ANSYS has been developed, and benchmarking with experiments is ongoing.

Temperatures, thermal stresses and deformations of a high heat flux (HHF) divertor module were evaluated for overloads and realistic tolerances as achieved in production (figure 17).

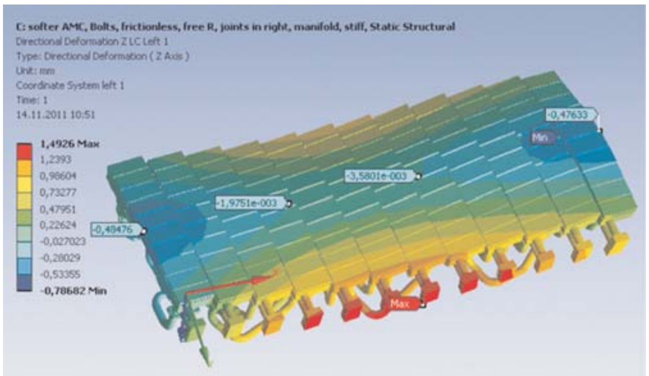

Figure 17: Deflection of an HHF target module under 10 MW/m^2 load applied onto the middle part of the top surface.

Temperatures, thermal stresses and deformations of the baffle modules were checked with the result that a temperature limit has to be observed to prevent overloading of the cooling pipe and/or the solder connection between the pipe and heat sink. Analysis of loads on the divertor and scraper elements as a function of magnetic field errors is ongoing.

6.1.6 Diagnostics

Typically, diagnostics are exposed to heat and ECRH stray radiation, which could cause overheating or critical thermal stresses and thus need to be analysed. Below a list of tasks that was carried out on various diagnostics is given: Thermal-mechanical simulation and dynamic analyses of retro-reflectors is ongoing. Thermal analysis of diamagnetic loops was carried out and benchmarked against experiments. Default ECRH absorption coefficients for steel and copper were found to be far below the experimentally derived values. Several other thermal analyses were carried out on diagnostics that are directly or indirectly exposed to the plasma like the Rogowski and Mirnov coils, TDU Langmuir probe, and the X-ray multi-camera tomography system (XMCTS). Mechanical analysis of the NPA (Neutral particle analyzer) support structure was performed. The structure design was approved from a stress point of view but remains under review to limit deformations. Also the HEXOS (high efficiency XUV overview spectrometer) frame was assessed mechanically. Deformation of the helium beam diagnostics was analysed and the design confirmed. Both the passively cooled ECRH bolometer camera behind the TDU and the water cooled one in the AEV21 port were analysed with regard to thermal gradients, the latter also with respect to mechanical loads due to water pressure. As a recurrent task, calculations of fields, vector potentials, eddy currents and consequential mechanical loads were performed on request as design bases for diagnostics components. As an example, one such task was the complex analysis of the response function for Mirnov coils under a graphite cover. Further development and improvement of software for calculation of magnetic fields, electromagnetic forces and inductivities (ELMA code) is on-going.

6.1.7 Reactor Studies

The structure concept of a HSR5 reactor with ≈12 T at the coil was further developed using a 72° FE model. The analyses show that most of the stress intensity in the double shell inter-coil structure is far below the allowable limits for steel, and that in the next step the structural mass can be greatly reduced. No central support structure as in W7-X is required (figure 18).

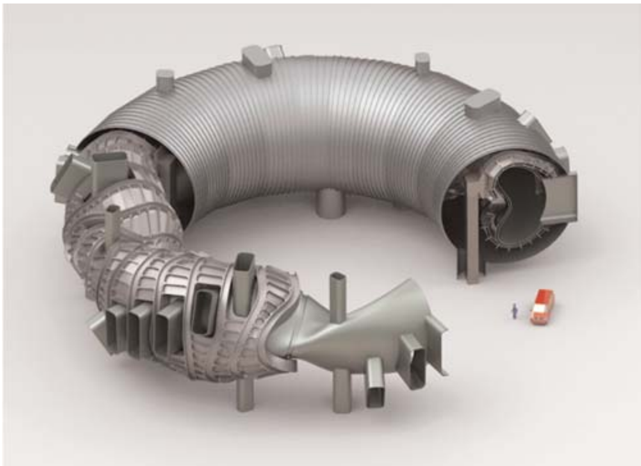

Figure 18: CAD model of the magnet system, cryostat and plasma vessel of a 5-periodic Helias reactor.

It was also shown that stress and deformation levels in winding pack components (cable jacket and insulation) are comparable to the ones of ITER. Moreover, a structural concept for the cryostat and plasma vessel was developed including simple welded connections at the module separation planes allowing the option to separate the torus for easy maintenance access.

6.1.8 ITER Collaboration

A collaboration with the ITER design team has been set up. As a first task the thermal and dynamic behaviour of the cryo-pump housing of the ITER cryostat was analysed (figure 19) based on thermal and seismic loads defined by the ITER team. In addition, magnetic shielding of ITER instrumentation cubicles was calculated for different arrangements of shield panels. A master thesis on thermal-mechanical investigations of the highly loaded ECRH-mirrors in ITER was supervised.

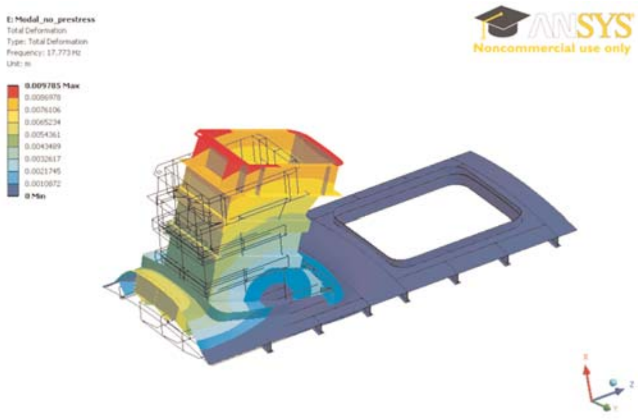

Figure 19: First deformation eigenmode of the ITER lower cryo-pump housing.

6.2 Instrumentation

The main activities in 2011 were the development of hard- and software for signal transfer and processing. In particular, the instrumentation cubicle development was finished. Some applied sensors were already used during assembly steps and assembly qualification procedures. The meetings of the Extended Instrumentation Group were discontinued. Its tasks, mainly interface issues, were shifted to the weekly instrumentation meetings of EN-IN and to common work with the respective groups.

6.2.1 Sensors

All remaining sensors measuring strains and stresses, coil deformations, gap opening and collision contacts were successfully applied on the magnet system. In-depth investigations on displacement sensors were performed in the framework of two diploma theses where the nonlinear behaviour and temperature dependence was studied. As a result, the absolute error of the displacement measurements could be reduced to 0.1 mm for the 20 mm measurement range, and temperature corrections over the whole range from ambient to cryogenic conditions can be performed. Development of the magnet system weight support (“cryo-leg”) load measurement system was finished, and the sensors were installed on the cryo-legs of all modules. The system was used already during installation of the modules on the machine base.

6.2.2 Signal Transfer and Processing

Analysis of signal transfer and processing was continued. Approximately 30 km cable with double screen was purchased, and acceptance tests performed. The final grounding concept based on the double-screened cable was developed and agreed with diagnostics. All tests concerning signal transfer and process equipment, including auxiliary devices, were performed with this grounding concept. Also long-term stability tests of the whole measurement chain were carried out. The cable for the temperature sensors of the ports was chosen and specified.

6.2.3 Cubicle Development

The instrumentation cubicle, based on a highly modular concept, was developed. Standard equipment is used wherever possible (housing, frames, boards, filter unit, line power connection, cubicle survey, fire extinguisher, mounting rails). Commercial signal conversion modules had to be adapted to meet the special requirements for accurate sensors dissipating minimal power in the cryogenic environment. With the cubicle prototype, safe data collection was tested under different conditions, using the whole measurement chain including 70 m of the final instrumentation cable. The instrumentation cubicle provides some power and space reserve for future expansion, e. g. for additional EMI/EMC (electromagnetic interference/compatibility) filters, if needed. The power consumption per cubicle could be reduced, and the fan-supported convective airflow in the cubicle was optimised. With this the inside air temperature at worst case power dissipation of 450 Watt remains safely below the allowable limits for the electronics. A uniform temperature distribution at the front and back doors, where heat transfer to the ambient air takes place, could be achieved. A cubicle is connected to W7-X via approximately 80 instrumentation cables. The routing of this heavy cable bulk at the entrance and inside the cubicle needed particular attention in order to assure sufficient flexibility for the feed lines to the electronic modules situated on the doors, and to allow good accessibility to all their joints.

6.2.4 Electromagnetic Interference/Compatibility (EMI/EMC)

An EMC-Task Force (EMC-TF) was set up to work out proposals on how to handle the EMI/EMC-aspects at W7-X. Starting point was the requirement to build and operate W7-X and all the related components according to European standards wherever reasonable and possible. Electronic components do not influence each other as long as they comply with the norms either as disturber or disturbed component. Components, which might be disturbed by sources not complying with the standards, like ECRH, need to be additionally protected if necessary. The EMC-TF is preparing proposals whether to purchase equipment for in-house tests to be used already during component development (particularly diagnostics), and, if yes, to which extent such tests should be performed. Alternatively, movable components could be tested in external laboratories and/or in-house by contractors. The EMC-TF highly recommends to install an EMI/EMC expert in the institute who is responsible for the EMI/EMC management and coordination, and who organizes remedial activities when interference between components occurs. Such an expert would also be involved in component design, realization and operation, and would act as a consultant for all persons involved in such activities.

7 Design & Configuration

The subdivision "Design & Configuration" provides the configuration management of W7-X, configuration control of the components in the cryostat, the plasma vessel and the components in the experimental area and provides design solutions and fabrications drawings for many components of W7-X. These tasks are taken care of in the four departments "Configuration Management", "Design in the Torus Hall", "Design of Port Diagnostics" and "Design of In-vessel Diagnostics". This department structure is in effect since the beginning of 2011 in response to the near completion of the design activities in the cryostat and the necessity to focus on the design of the peripheral components and of diagnostics essential for the first operational phase of W7-X. This structure maps design areas with, in general, simple geometrical interfaces into areas of design responsibilities in order to ensure proper simultaneous engineering with minimal risk of lengthy iterations. About 60 different projects in the experimental hall require design activities of various extents. The deliverables range from space reservations for components developed, designed and built within the framework of collaborations to concept design and detail design including fabrications drawings for others. In order to ensure that the design activities meet all functional aspects of these projects and are conform to the boundary conditions a stepwise design development was implemented as a central procedure. The starting point for the design activities are project specifications, which were drafted by the responsible officers for all projects that have interfaces within the torus hall. These specifications compile the functional specifications, the boundary conditions, possibly already existing design concepts, information on interfaces, specific media supply etc. Based on this information the conceptual design is started. In the course of the conceptual design the functional requirements are matched and adjusted to design solutions. A conceptual design review concludes this activity and freezes the found solution if it has been shown that the major functional requirements and boundary conditions are confirmedly met. After this phase the project is given a conceptual space reservation in the torus hall. This space reservation is then considered during the design of adjacent projects and space conflicts are informally mitigated. During the subsequent design phase the chosen concept is further developed to meet all functional specifications and to detail all interfaces. During a major design review involving experienced officers of other subdivisions it is made sure that all aspects of the project meet the requirements of Wendelstein 7-X. Confirmation of the presented design solution constitutes a design freeze, determines the deliverables during the subsequent detailed design and leads to a confirmed space reservation in the torus hall. This space reservation encompasses the actual design space including tolerance areas and additional space needed for minor and major maintenance. The detail design activities finally culminate with the generation of all required fabrication documents and conclude the design.

7.1 Configuration Management

By now the configuration management for system identification, change and deviation management and interface coordination is routinely applied. Currently 958 design change requests are registered in the change data base. 84 % of the requests have been accepted, 5 % are in the decision process and 11 % have either been rejected, withdrawn or became obsolete by revision. 81 % of the accepted change requests have been closed, i.e. the relevant design and assembly documents, CAD-models and drawings have been revised or created according to the change. Highest priority has been given to changes, which may directly affect the progress of W7-X assembly. While in the past interface control had been focused on the components of the W7-X basic device it has recently been extended to the about 60 projects in the W7-X periphery. Thus the W7-X interface matrix increased by 130 additional pairs of components with identified interfaces. The complete matrix now contains about 350 elements, which require a dedicated interface description, 30 % of them already being processed and released.

7.2 Design in the Torus Hall

Within this department design solutions are developed for diagnostics and peripheral components that are predominantly located in the torus hall. Conceptual design work was performed for the ground level platform in the torus hall, for the Thomson bridge, quench gas collection system, the water cooling circuits for the various cooling circuits for the first operational phase and – still ongoing – for the later operation with a fully cooled divertor, the electron cyclotron emission diagnostic, the cable routing of instrumentation cables on the outer vessel, the routing of the exhaust gas system out of the torus hall. Preliminary design work and partially detail design work was performed for the gas inlet system, the vacuum system of the cryostat vacuum, the vacuum system of the plasma vessel, the interstitial vacuum system for private vacuum regions needed mostly by ports, the supports for the trim coils, the cable routing of the electrical supply of the trim coils and control coils. In the process of providing conceptual design solutions it became obvious that in all cases the tightness of the available space in particular near the outer vessel required also a conceptual design of the necessary supports. Thus a heavy duty structure was developed for the centre of the machine, which – in contrast to the Thomson bridge – is able to support all components that do not have particular requirements on the maximum vibrations allowed. Figure 20 shows a view of the torus hall where only the cryostat, the Thomson bridge, the heavy duty structure, the cryostat, the machine base and the present design of the ground level platform are shown.

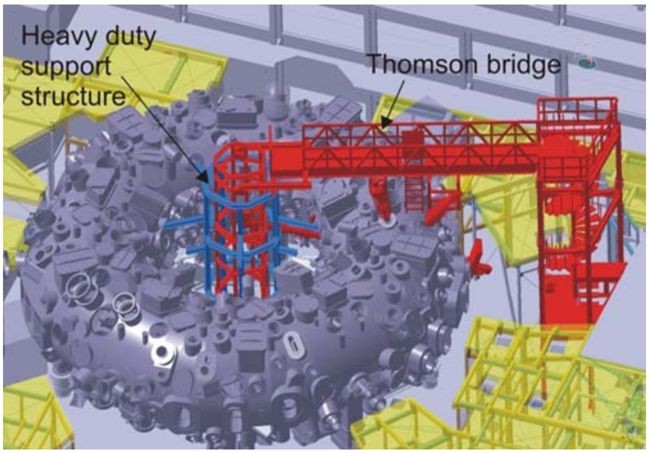

Figure 20: CAD view of the Thomson bridge and the heavy duty support structure in the torus hall. Other peripheral components and diagnostics are not shown for simplicity.

Care has been taken to structure and classify the CAD-data according to the project structure in the torus hall and simultaneously re-check the available space reservations for the actual status. In most cases dating back to the initial space reservations of the project, the conceptual design space reservation was retained even though no underlying conceptual design was available. Tools originally developed for the configuration control were adopted to assist the simultaneous engineering in the torus hall. Transparent and frequent versioning of intermediate design status in combination with a reference system of up-to-date data was one of the key ingredients to achieve design solutions of the required level of detail without time-consuming iterations. In addition, residual work is being performed that in the past belonged to the back office and the department configuration control. These tasks include the creation of stencils of the port plasma vessel contours for the assembly preparation and final configuration checks of the magnet and cryo insulation before installation in the outer vessel sectors. Design work in the cryostat was performed to fit the shims of the central support ring and for modifications of the current lead support.

7.3 Design of Diagnostics in Plasma Vessel Ports

Within this department design solutions are developed for diagnostics whose major part is located in a port. Based on the importance for the first operational phase and the scope of the projects, the design activities of the charge exchange resonance spectroscopy (CXRS), the magnetic flux surface measurement diagnostic, the electron cyclotron diagnostic, the bolometry and the Thomson scatting diagnostic continued to have the highest priority and were being continued. The proximity of their front end to the plasma requires these diagnostics to be actively cooled. In addition, some of these diagnostics require shutters that operate in vacuum in order to expose sensitive electronics or optical elements to the plasma radiation only during the measurements. To that purpose ultra high vacuum compatible transducers had to be developed. Since the space requirements were different in each case, it was not possible to develop a generic solution that could be adopted to all applications. Rather individual solutions had to be found. One example is shown in figure 21 taken from CXRS. There the shutter consists of a shade mounted on a long rod that pivots on an axis mounted on a support structure on the port flange. The rod is swivelled via an air pressure actuator and vacuum tightness is achieved via a flexible bellow.

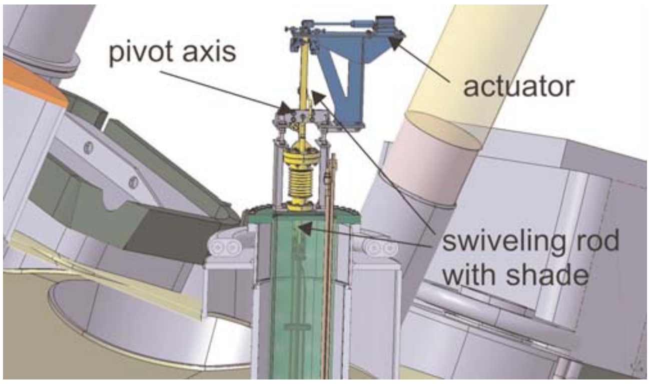

Figure 21: CAD view of one section of the charge exchange resonance spectroscopy diagnostic (CXRS).

7.4 Design of Components in the Plasma Vessel

Within this department design solutions are developed for diagnostics that are located in the plasma vessel. In addition, design work coordinated by the sub-division KIP is being performed. Latter is described separately. Diagnostics that are located in the plasma vessel close or behind the in-vessel components are the Mirnov coils, the Rogowski coils, the diamagnetic loop, the x-ray multi camera tomography system (XMCTS), the glow discharge electrodes. In addition, just before commissioning, a neutron counter calibration unit will be temporarily mounted at a time when all the components in the plasma vessel have already been mostly installed. The design of the diagnostics in the plasma vessel is challenging due to the restricted space available behind the wall lining, the need to provide separate cooling to compensate for plasma radiation and thermal radiation of hot wall liner elements, the misalignment during thermal expansion of components and required shielding of the cable insulation against the absorption of stray radiation stemming from incompletely absorbed electromagnetic radiation from electron cyclotron resonance heating (ECRH). Thus the cables are typically routed in copper tubes that are thermally connected to the plasma vessel. These tubes have a perforation sufficiently large to preclude trapped air volumes, but still small enough to constitute waveguides beyond cutoff for the ECRH stray radiation.

Only in selected cases high-temperature resistant cables have been used. Various stray radiation tight distribution boxes are required to combine the individual cables into large bundles that are routed towards the feedthroughs.
Figure 22 shows a section of the XMCTS system with five cameras. Three additional sections poloidally arranged around the plasma constitute the complete diagnostic. Each camera contains a linear array of x-ray sensitive detectors that observe a section of the plasma via a pin hole. Each camera needs to be supplied with cooling water since the detector array is temperature sensitive, with gas pressure to close the pin hole with a shutter, and an ECRH stray radiation proof rooting of glass fiber optics and electrical cables. Since the diagnostic is located behind a heat shield with small openings for plasma operation, each section is attached to the heat shield in order to maintain proper alignment under all load cases.

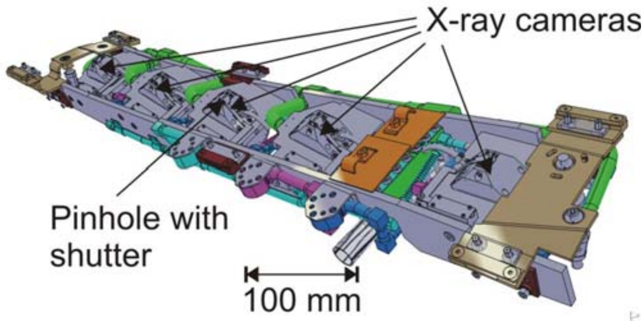

Figure 22: CAD view of one section of the x-ray multi camera tomography system (XMCTS).

8 Heating

8.1 Project Microwave Heating for W7-X (PMW)

The 10 MW ECRH system for W7-X is designed for continuous wave (CW) operation (30 min) at 140 GHz, which is resonant with the W7-X magnetic field of 2.5 T. The total power is generated by ten Gyrotrons and is transmitted to the plasma by a quasi-optical transmission line and versatile in-vessel launchers for both, high field side and low field side launch. ECRH will support also W7-X operation at reduced magnetic field, because the gyrotrons can be tuned to 103.6 GHz with about half the output power. The ECRH-system is being developed and built by the ”Karlsruher Institut für Technologie” (KIT) as a joint project with IPP and IPF Stuttgart. The ‘Project Microwave Heating for W7-X‘ (PMW) coordinates all engineering and scientific activities and is responsible for the entire ECRH system.

8.1.1 The W7-X Gyrotrons (KIT/IPP)

The production the series gyrotrons at THALES started after the successful completion of a four-year lasting R&D-program. The first series gyrotron SN1 passed the site acceptance test (SAT) successfully in 2005 with an output power of 920 kW for 1800 s. The reproduction of the SN1 performance, however, turned out to be difficult and the following series gyrotrons failed to meet specifications. Parasitic oscillations were identified in the beam tunnel region leading to an excessive heating and damage of the beam tunnel ceramic rings and brazed joints. The beam tunnel was redesigned featuring symmetry breaking corrugations to prevent the excitation of parasitic modes. After validation in experimental short pulse tubes at KIT, the first series gyrotron SN 4 (repair) was equipped with the improved beam tunnel. In the Factory Acceptance Tests (FAT) at KIT the absence of parasitic oscillations originating from the beam tunnel region was confirmed. The electrical efficiency of the gyrotron was, however, lower than designed, and the collector dissipation capability had to be improved. An advanced collector beam sweeping system (IPP-KIT patent) was thus applied during the SAT at IPP, allowing the increase of the output power towards 1.02 MW at the output window, as seen from figure 23. This corresponds to 0.95 MW in the absorber load after transmission through the beam matching optics and five additional transmission mirrors. The maximum pulse length at this power level was limited to 353 s due to arcing in the absorber load. The gyrotron was accepted and mothballed.

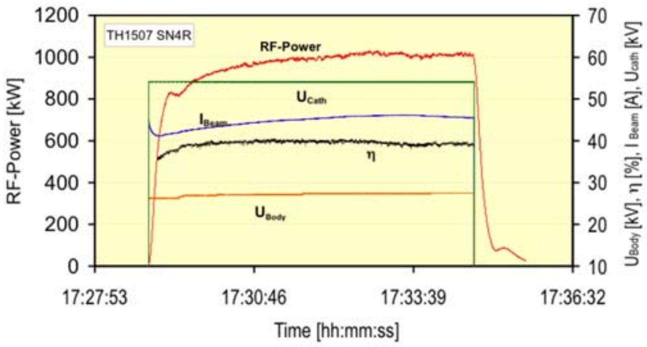

Figure 23: Gyrotron TH 1507, SN4R: RF-power, beam current I_{Beam} , efficiency η, and operating voltages U_{cath} and U_{Body}, respectively, as a function of time.

The next series gyrotron TH 1507 SN6 was shipped to KIT by end of October. First tests show an output power of 1.024 MW at 50 A in short pulse operation. The Gaussian beam content of the RF output beam as measured with an IR system is 97 %, the analysis of the profiles is performed at IPF and IPP with two different methods. Further conditioning and extension of the pulse length is presently being performed.

8.1.2 Transmission System (IPF/IPP)

The power transmission from the gyrotrons to the plasma is provided by a quasi-optical mirror-based system, which operates under atmospheric pressure. The manufacturing and installation of the basic transmission system was completed already in 2010. Final assembly and alignment of the elements close to the W7-X torus is planned after W7-X completion in late 2013. Further remaining work includes improvement of diagnostics and calibrated, cw-compatible rf-power detectors. Reliable high power cw dummy loads for calorimetric measurements are still a matter of concern. Commercially available 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 the development of uncoated metallic absorbers both in industries and in-house. A water-cooled version of a "Long Load", which consists of a 22 m long straight absorbing stainless-steel waveguide, which operates under normal pressure, was developed and installed in the ECRH-beam duct. The installation is seen from figure 24. The load consists of four segments, three of them with different diameter, which are connected with linear tapers in areas, where the wall currents and thus the power deposition have a minimum to avoid arcing problems. A standard dummy load absorbs the residual power of approx. 23 %, and terminates the "Long Load", which serves as a calibrated pre-attenuator. High power tests were successfully performed.

Figure 24: The "Long Load" in the ECRH-beam duct. The input taper is seen on the right.

A different approach of a compact stainless steel load with a large inner surface-area as developed by the Russian Company GYCOM, was purchased and installed in the module 5 transmission line. The load was performing well at the parameters achieved with the SN 4R Gyrotron.

8.1.3. In Vessel Components (IPP/IPF)

The quasi-optical transmission line enables a broadband transmission and a flexible launch of the ECRH beams into the plasma by front-steering launchers. For high-density operation above the X2 cut-off density, the ordinary wave polarisation will be launched. Here, the single pass cyclotron absorption is expected to be incomplete and a multi-pass scheme with inboard reflectors has to be used. Those reflectors will be integrated into the heat shield opposite to the ECRH antennas. A second reflection is foreseen at the liner between the ECRH antenna ports. These liners have been polished for improved reflection and are ready for installation. The refurbishment of the four ECRH plug-in launchers has been completed and all of them have successfully passed the official vacuum leak test for W7-X in-vessel components. Meanwhile, the corresponding ports have been welded into their final positions at the W7-X vacuum vessel. An assembly test with a launcher dummy model showed that the port misalignment by the welding process was only of the order of 2-4 mm, and thus a sufficiently large clearance of >8 mm for the final launcher plug-in is ensured. The design of electron cyclotron absorption (ECA) diagnostics, which measures the transmitted ECRH power, the beam position and polarization, was finished and the fabrication of the waveguide bundle inside the plasma vessel has started. The counter parts of it are the four B-port inserts with vacuum interfaces for the waveguides. The first B-port insert failed in the vacuum test. A detailed leakage measurement showed that the entire helium penetration rate through the sealing O-rings of all 33 vacuum interfaces of one B-port plug-in would violate the W7-X vacuum restriction. Therefore several alternative sealing methods have been investigated. Finally, CF-type copper sealing with a glued mica window was chosen as shown in figure 25.

Figure 25: Vacuum interface prototype for the microwave waveguides with different types of sealing material.

ECRH stray radiation can cause problems in long pulse operation even with optimized EC-absorption. The power will be distributed all over the vacuum vessel and the ports. In order to calibrate the stray radiation monitors and to achieve material data on stray radiation, an over-moded spherical resonator was build up within a bachelor thesis in cooperation with the Humboldt University Berlin. A 14 W, 140 GHz microwave source powers this resonator and a homogeneous stray radiation field is generated. A data base of absorption properties from relevant materials has been established and is used for the design of the W7-X in-vessel components and diagnostics.

8.1.4 Staff

Staff at IPP (W7-X-HC and ITZ): B. Berndt, H. Braune, V. Erckmann, F. Hollmann, L. Jonitz, H. P. Laqua, G. Michel, F. Noke, F. Purps, T. Schulz, P. Uhren, M. Weissgerber.
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Staff at IPF (Stuttgart University): H. Höhnle, W. Kasparek, H. Kumric, C. Lechte, F. Müller, R. Munk, B. Plaum, P. Salzmann, K.-H. Schlüter, U. Stroth, A. Zeitler.

8.2 ECRH Contributions (IPF Stuttgart)

8.2.1 Development of Improved Remote-steering Launchers for W7-X

The two N-port ECRH launchers of W7-X include a remote-steering design, where a beam is coupled into the antenna waveguide at an angle with respect to the waveguide axis. This angle is reproduced at the output side of the waveguide. Remote steering uses the Talbot effect in a rectangular waveguide to image the input beam pattern at the output side. This means that there are no extra components on the plasma end of the waveguide. For investigations of the antenna geometry required for the installation in the N-ports (cf. annual report 2010), a mock up with a classical square waveguide was built up. It includes a mitre bend to fold the antenna waveguide, and a 22 mm gap for later integration of a vacuum valve. The positions of the gap and mitre bend are located near the half length position of the waveguide to minimize the field deterioration and stray radiation.
Numerous measurements were done and the results were compared with calculations from the PROFUSION code. The complex field amplitudes were measured directly at the output aperture and at a distance of 600 mm, which corresponds to the absorbing location in the plasma. The far-field was also calculated from the aperture field by FFT propagation. Figure 26 shows the comparison for a steering angle of 6 °C. Note that aperture-field measurements are preferable because the area is smaller, reflections from measurement equipment can more easily be suppressed and the dynamic range is increased because of the higher signal level. The experiments were in good agreement with the calculations.

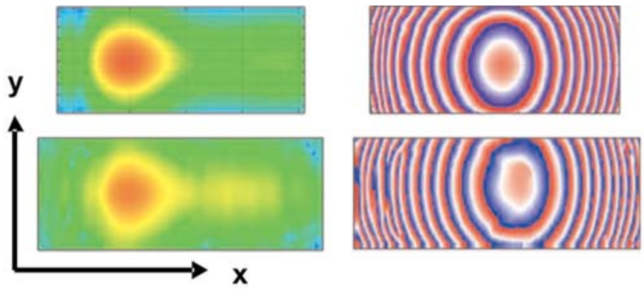


Figure 26: Amplitude (left) and phase (right) of the far-field of the remote-steering antenna for an angle of 6 °C. The far field was calculated from the aperture field (top) and measured directly (bottom).

The results confirm the feasibility of a remote-steering antenna with an integrated mitre bend and a 22 mm gap, provided that they are located near the centre of the waveguide, as is planned for W7-X. However, since the imaging properties of a perfectly rectangular waveguide are only approximate, the maximum angle that the imaged beam can have with the waveguide axis is limited to about 12 °C. In order to increase this angle, the dispersion relation for the perpendicular waveguide modes has to be modified by deformation of the rectangular waveguide shape. The finite-difference code IPF-FD3D has been adapted to this problem by reducing it to finding the resonance frequency of purely perpendicular modes in the waveguide cross section (see figure 27) for a plot of the 2D field pattern in the perpendicular plane of the waveguide). The PROFUSION code is then used to calculate the remote steering qualities of the deformed waveguide. The optimisation effort has yielded an optimised shape for the waveguide that also satisfies the strong constraints of the fabrication process for the final waveguide. It is currently in the process of being analysed numerically and experimentally with a straight test version of the waveguide.

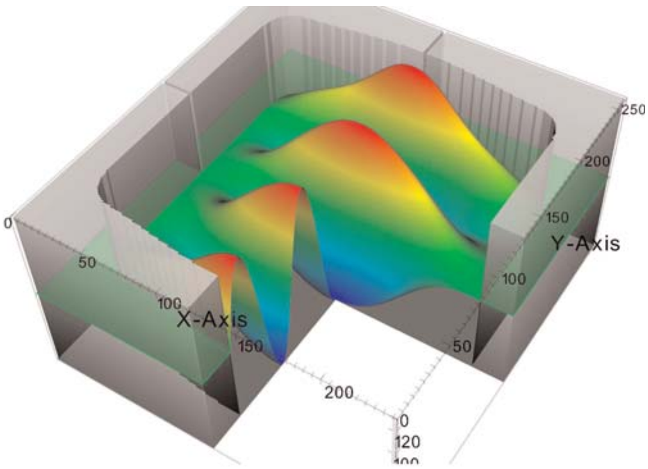


Figure 27: Resonant field pattern of a (1,7) mode in the final waveguide shape. X and y are in grid units of 250 μm.

8.2.2 Investigations of Microwave Material Properties

The cryo-pumps for the neutral beam injectors (NBI) are prone to heating by microwave stray radiation from the electron cyclotron heating (ECRH) system. Therefore, the NBI ports will be covered with graphite tiles, which are coated by a microwave absorber; Al_2O_3/TiO_2-coatings are candidates for this task. In collaboration with the "Institut für Fertigungstechnologie keramischer Bauteile" at University of Stuttgart, various coatings on copper as well as graphite were characterized with the aim to maximize the shielding against stray radiation.

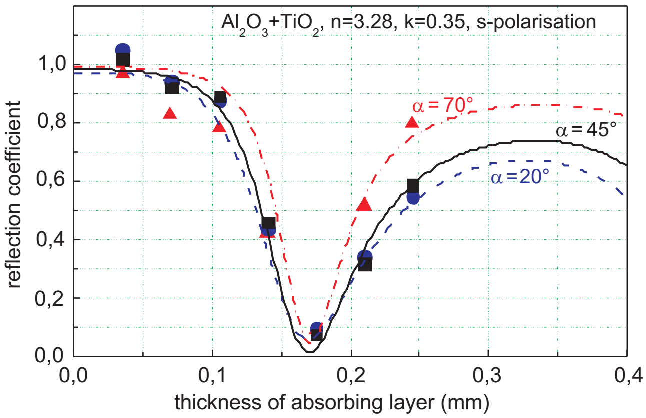


Figure 28: Reflectivity at 140 GHz of Al_2O_3/TiO_2 (87 % / 13 %)-coatings for angles of incidence of 20°, 45° and 70° as a function of the thickness for perpendicular (s-) polarisation.

It is found that the material has high microwave absorption, provided that a resonant thickness of a quarter wavelength (in the material) is used for the coating. An example is shown in figure 28, where the absorption of s-polarised radiation as function of the thickness of a 87 % Al_2O_3/13 % TiO_2-coating on graphite is plotted. The data can be approximately fitted to theory, using a refractive index of n=3.28, and an extinction coefficient of k=0.35. With the present mixture of Al_2O_3/TiO_2 for the coatings, an angle- and polarization-averaged absorption of at least 80 % can be reached, if a coating thickness of about 170 µm is applied. Higher absorptions could be obtained, when the extinction coefficient is increased to values around 0.45. This would require a higher content of TiO_2 (about 20 %) in the spray powder.

8.3 Ion Cyclotron Range of Frequency Heating

Budgetary and personal constraints required the project Wendelstein 7-X to focus on the essential components needed for the first operational phase and thus led to a postponement of a heating system in the ion cyclotron range of frequencies (ICRF) until the second operational phase. However, the need for the possibility to perform plasma vessel wall conditioning between experimental programs with ambient magnetic field and the need for generating target plasmas for neutral beam discharges at magnetic fields where electron cyclotron heating is not possible, exists also during operational phase one. This led to the decision to develop a dedicated, stand-alone radio frequency generator and antenna system that can fulfill both needs. The system consists of a generator with an output power of at least 50 kW, transmission lines and a single strap antenna. Impedance matching is achieved by a lumped element pi-network with adjustable vacuum capacitors and a fixed inductivity solenoid in series with the antenna. A scaled-down 3 kW system has been designed and built for the WEGA stellarator. Major aspects were the electrical and mechanical engineering, the development of broad-band current and voltage probes and the programming of the actuators to drive the capacitors. Installation and tests are planned for 2012. Since in 2011 the Trilateral European Cluster offered to support the project with radio frequency and design experts, first technical meetings have been held and the actual scope of this collaboration is being developed.

8.4. Neutral Beam Injection

The Neutral Beam Injection (NBI)-system for Wendelstein 7-X is planned to be available at the beginning of the operation phase 1. Two injection boxes with a maximum of four ion sources each will be positioned on module 2 horizontally inclined to the radial vector by ±7.4°. The NBI project is supported by a cooperation with partners from the Polish research institute NCBJ in Swierk. Following a rather long preparation period the formal cooperation was started in spring 2011 with the kick-off meeting in Garching. NCBJ will take over the procurement of the torus valves, the cooling systems, the ion deflection magnets and the injector support structures. During the past year a significant progress could be reached: one new torus valve was ordered and manufactured in industry, the second one which was available at IPP is being upgraded for the use on W7-X. They have been almost completed, acceptance tests for both valves will be performed in January 2012, followed then by the installation of electric heating devices and insulation for bake out at 150 °C. For the other components the design work and clarification of technical details has proceeded well to prepare the call for tender documents for placing the contracts. A further cooperation envisaged with the WTP Wroclaw for the development and procurement of the cryo-sorption pumps and cryo supply has not yet reached such an advanced state and is still under discussion for realization. In order to have the NBI system available at the beginning of the experiments it was recently decided to start in parallel the exploration of using titanium evaporation pumps. This type of fast pumping system has been successfully in operation on the ASDEX Upgrade NBI system for almost 20 years. The 4 meter long titanium wires are heated there with a DC power supply with typically 140 A between the pulses.

For their use in the permanent magnetic field of W7-X alternative operation modes will be studied now within a test program in the following year. During the past year the procurement of various other components and the assembly of the system proceeded as planned. The pre-assembly of the injection boxes inside the NBI hall is well advanced up to the level, which is possible there: the installation of the neutralisers and ion dumps on the inside of the ion source flange and the source valves and beam steering units on its outer side. At present each box will be equipped with the components for two ion sources. Furthermore the low pressure water distribution systems have been manufactured with the help of the W7-X assembly group. They are mounted on each box including all instrumentation. Figure 29 shows box NI 21 with the cooling system on the side and a temporary vacuum pumping system attached to the ion source flange for leak testing. The second box NI 20 is slightly behind, the ion source flange is still open, but all components are available.

Figure 29: NBI 21 pre-assembled with source valves and beam steering units on the upper two source positions, a temporary vacuum system on one of the lower source ports, cooling manifolds, and instrumentation along the side.

A calorimeter will be installed in each box, which can be lowered down vertically into the beams right in front of the duct. They are designed to measure four beams individually by an arrangement of 6 inclined target panels each. Initially the target plates for only two beams will be installed, the positions of the other two beams are blanked off by aluminium plates to balance the reaction forces of the water bellows. The pre-assembly of both calorimeter units is far advanced (figure 30). As the production of the target plates is still ongoing, one unit could not be completed yet. Design work on the torus adapter unit, consisting of a box exit scraper, assembly bellows and duct protection elements is proceeding. Some changes in the geometry of the duct liner components have to be considered due to non conformities, which occured during the duct manufacturing. Presently the ducts are being welded into the vacuum vessel and outer vessel. Afterwards the as built dimensions will be taken and the duct protection will be adjusted accordingly to minimize the power loading of the duct by the neutral beams. The design of the magnetic shielding concept was proved to be sufficient not only for the stellarator stray magnetic field but also for the additional field from the external plasma control coils. Therefore the contract for the manufacturing of the ion source shielding house could be placed in industry; delivery is expected early next year. The second part, the internal shielding components are under evaluation for the cheapest possible manufacturing process and will also be ordered early next year.

Figure 30: Calorimeter units, left: completed with target plates for the lower two beams and dummies for the upper two beams, right: target plates for upper two beams partially missing, dummies for the lower two beams installed.

The assembly of the NBI system inside the torus hall has been started last year with the installation of the high voltage cabins and their support structure (figure 31). The design of the routing of cooling pipes and manifolds in the torus hall is well advanced, the manufacturing will be started soon by the assembly group from IPP. Furthermore the low voltage power distribution system was ordered and partially accepted last year.

A test setup for a commercially available data acquisition system has been tested during operation on AUG.

Figure 31: High voltage cabin for NI20 installed on its support structure inside the torus hall, the second cabin for NI21 is hidden behind the port installation tower.

9 Diagnostics

The work has focused primarily on the set of start-up diagnostics. These are the diagnostics that are necessary for safe operation and control of the machine, or indispensable for the physics goals of the first operational phase. In September 2011, a new subdivision W7-X Diagnostics (DIA) was formed. The subdivision is broken into three parts, Edge and In-vessel Diagnostics (DIA-EIV), Core Diagnostics (DIA-COR), and diagnostic engineering (DIA-ENG). The following sections briefly summarise the main activities of the Diagnostics subdivision.

9.1 Edge/Divertor and Magnetics Configuration Diagnostics

9.1.1 Langmuir Probes for TDU Phase

During the high heat load tests of the new mock-up of the flush-mounted Langmuir probe array for the Test Divertor Unit (TDU) in the GLADIS test chamber, the thermo-mechanical behaviour of the system proved to be excellent; however, the AlN insulators failed their functionality test. For this reason the insulator material was changed to Al_2O_3 and the design modified to avoid deterioration of the insulating gaps by carbon dust, believed to be the cause of the failure. The modified mock-up based on the new design was then successfully tested in GLADIS with the probe tips remaining fully functional, with no weakening of the insulation.

9.1.2 Exchangeable Divertor Targets

A mock-up of the special exchangeable Plasma-Wall Interaction TDU-targets for the investigation of surface modifications was manufactured and tested at IPP Garching. The GLADIS tests have led to an improved design, and a change of material for the support structure from stainless steel to TZM.

9.1.3 Monitoring of Plasma-wall Interactions

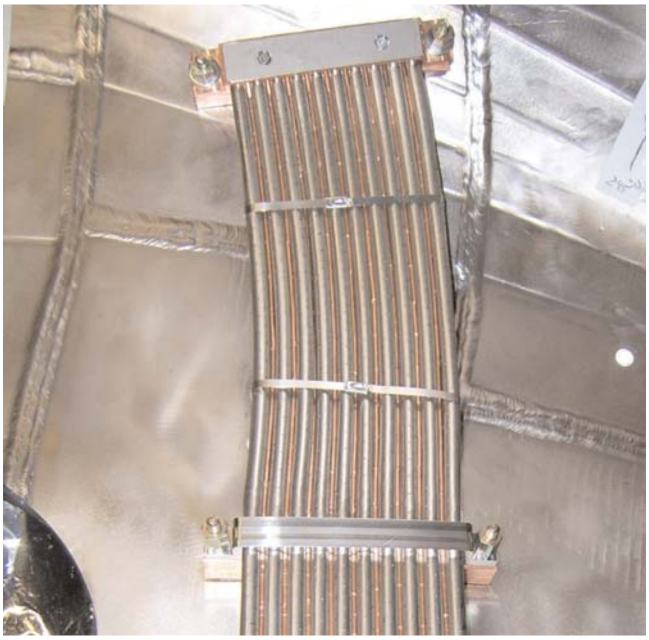
Safe and reliable experimental operation requires diagnostics that monitor the divertor surface temperature, and diagnostics that provide information about the interactions between neutral gas, edge plasma, and the material walls. A common endoscope will be used both for observations in the infrared (IR) range (for measurements of the temperature of plasma facing components), and in the visible range, giving information about neutrals and partially ionized plasma in the edge region. One key challenge is that coatings may appear over time, and may change the reflectivity of mirrors and transmission of windows. Measures are being developed to minimize such coatings, and an in-vessel calibration source, a heated ceramic, has been developed and characterized. This calibration source will ensure that reflection and transmission changes are measured in real time and can be taken into account when the data is interpreted. Several of these calibration systems are being developed in collaboration with international collaborators: Los Alamos National Laboratory in the USA will deliver fast, state of the art IR cameras, which allow studies of heat transport, and hot spot detection on plasma facing componets. Fast video cameras developed by HAS (Budapest, Hungary) will give nearly full coverage of the entire plasma vessel wall. The design of the plasma facing front end of the video diagnostic, consisting of a vacuum window thermally protected by a water cooled front plate with a pinhole and a small shutter, has been completed and manufacturing just started, and proper operation in W7-X's strong magnetic field has been experimentally verified in several facilities. The manufacturing of the last eight video cameras has been completed and acceptance tests will begin in January 2012.

9.1.4 Magnetic Diagnostics

For the magnetic diagnostics, the signal cable for the in-vessel coils has been selected and purchased. The thermal analysis for all in-vessel magnetics was continued and compared with the results of ECR stray radiation tests in the MISTRAL test chamber. The conceptual and detailed design of all in-vessel magnetics has been continued. The development of suitable ECR stray radiation protection and good thermal contacts between coils and plasma vessel as a heat sink have been the dominant task (figure 32).

Assembly tests for the installation of ECRH shielded signal cables in the plasma vessel and the ports have been successfully performed. The electromagnetic behaviour of Mirnov coils and their signal cables has been successfully tested in a magnetic probe test stand at signal frequencies up to 1 Mhz. Vacuum tests for various components of the in-vessel magnetics and signal cables have been performed.

To avoid unacceptably high thermo-voltages at in-vessel cable connectors the diamagnetic loop is a foldable continuous loop, which can be brought into the plasma vessel through a manhole and then unfolded for installation, thereby eliminating many electrical connections. A pre-assembly test of the foldable diamagnetic loop in the bean shaped plasma plane has been successfully completed.



9.1.5 Flux Surface Mapping

The design of the complete manipulators for the magnetic flux surface diagnostic is progressing. In parallel the first component, the pendulum, used for pivoting the fluorescent rods, has been manufactured. The design and manufacturing of the linear actuator units of the manipulators has been outsourced to an external company. The electrical driver motor for this system has been tested successfully in a magnetic field of 65 mT, higher than that which will be present at the final installation position. The design of the gas injection system for the thermal He-beam diagnostic has been upgraded to 63 bar, so that it can also be used as a divertor hydrogen gas injection system. The final design and manufacturing of the thermal He-beam gas injection system as well as the observation system has now been taken over by FZ-Jülich within the framework of a new cooperation agreement.

9.2 Microwave and Laser Based Diagnostics

Microwave- and laser diagnostics are being prepared for measurements of electron density and temperature in the plasma core. These consist of interferometry, reflectometry and electron cyclotron emission (ECE).

9.2.1 Electron Cyclotron Emission (ECE)

The ECE system measures the electron temperature by detecting the cyclotron radiation that the plasma emits. For the ECE system both the Gaussian in-vessel optics and the calibration optics have been aligned in the laboratory and their Gaussian antenna sensitivity has been experimentally measured, showing excellent agreement with the design.

9.2.2 Reflectometry

Reflectometry can measure plasma density profiles and fluctuations by measuring the locations where microwaves reflect off the plasma. For the reflectometry optics a basic concept and geometry combining x-and o-mode launch with bistatic Gaussian telescopes is being pursued. The design includes options to further explore advanced antenna solutions. Such a development may be done within the framework of a Helmholtz Virtual Institute on advanced microwave diagnostics. A proposal for such a virtual institute has been made; this is a collaboration between IPP, University of Stuttgart, FZ Jülich, the École Polytechnique Fédérale de Lausanne, Switzerland (CRPP) and the Laboratoire de Physique des Plasmas, Ecole Polytechnique, Palaiseau, France.

9.2.3 Interferometry

The plasma density can also be determined by measuring the phase shift of electromagnetic waves propagating through the plasma, a method called interferometry. It has been decided to build both W7-X interferometers (a single channel and a multichannel interferometer) based on the dispersion interferometry concept, a concept that allows for a compact optical system without need for a separate reference line. The system uses a frequency doubling crystal so that the primary interferometer beam is accompanied by an overlapping phaselocked beam at twice the frequency of the primary beam. This gives very accurate and robust cancellation of errors due to drifts or vibrations, and is even tolerant against intermittent loss of signal. The multichannel interferometer will be supported by the FZ Jülich, where a similar 4 channel system has been set-up and operated successfully.

9.2.4 Thomson Scattering

The series production at the Institute for Nuclear Physics in Crakow (INP, Poland) of the items for 30 polychromator boxes for the Thomson scattering diagnostics was successfully completed. The assembly of polychromator boxes by IPP is ongoing. The Nd-YAG laser system was delivered in 2011. The commissioning of the laser system is planned in January 2012.

9.3.7 Neutron Counters

A concept for in-situ calibration of neutron counters at W7-X was developed in collaboration with PTB Braunschweig and was successfully tested under simplified conditions during a neutron experiment at only one module (1/5 of the total torus). During this test calibration an Am-241/Be-neutron source with a source strength of about 1.1×10^6 n/s was moved along a railway system inside the module nearly parallel to the torus axis using a small remote controlled driving unit (figure 33). The neutron signals induced in a Long Counter equipped with a BF3-counting tube 50 cm outside the machine vessel have been measured in dependence on the position of the in-vessel neutron source. The experimental results have been compared to MCNP calculations with agreement within 30 %, which is acceptable for neutron calibriations. In order to optimise the amplifier and discriminator techniques different units from the companies Canberra, Tennelec and Ortec were tested.

Figure 33: Neutron calibration test set-up in one W7-X module.

10 CoDaC

The subdivision Control, Data Acquisition and Communication develops the control, data acquisition and computer systems for Wendelstein 7-X operation. This includes operational management, real time plasma control, high performance continuous data acquisition (section CoDa) and the common IT services and infrastructure (section IT/EDV). CoDaC aims to support scientific and administrative work by defining and implementing explicit processes like experiment planning, experiment preparation and execution, data acquisition and archiving, operation and provisioning of modelling and analysis frameworks and compute clusters. Furthermore, the provisioning of central IT services, personal desktops and high speed networks are the foundation for the operation of Wendelstein 7-X. CoDaC constructs the control system on the basis of distributed PLCs (programmable logic controller), real time computers for plasma control and data acquisition systems for continuous operation with a significant and challenging fraction of hardware and software development (see figure 34).

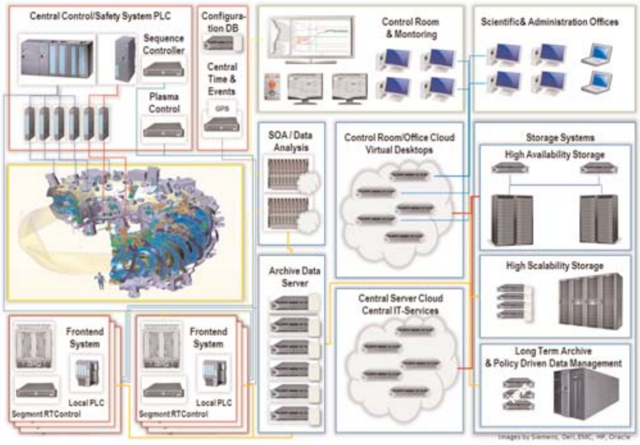


Figure 34: W7-X CoDaC structure and entities to be developed.

An example for a top level process model and the software that has been developed to support this process is given in the following diagram. The developed applications fulfilling these requirements are shown in the comment fields using functional terms. As the process model is rather stable it can be re-used to derive requirements for more sophisticated, future software solutions.

10.1 IT/EDV

W7-X CoDaC has changed its IT infrastructure from a conventional system with single servers and directly attached storages to a SAN (storage area network) based system in combination with server virtualisation. This system, a so called private server cloud, provides high availability and has already led to a hardware consolidation by dynamic resource scheduling, i.e. automated motions of virtual machines among the physical servers for optimal computing resource levelling and exploitation. The same approach is currently under test for the user terminals of control rooms and offices, which is based on the virtual desktop concept. The benefit is a less administration intensive provisioning of personal computers and flexible workplaces due to virtualization, which fulfills the requirement of carrying the desktop session out of the control room into offices and vice versa. A precondition for centralized server and desktop systems is a robust foundation of server, network and storage systems. A storage system has been procured that fulfils the high availability requirement and is operated as a mirrored computer centre in an active/active mode, i.e. all active components are in use continuously. The SAN based storage system comprises fibre channel networks, EMC storages and Data Core storage virtualisation. The storage virtualisation allows an instant mirroring of incoming data, flexible resizing of volumes and thin provisioning, which allows to purchase disks as demanded in order to keep the disk usage at an high fill level for optimum cost efficiency. This HA storage is part of a three tier storage concept, that comprises tiers for high availability, high scalability and long term archiving requirements. In preparation of this storage system, a tape library has been purchased, that fits into the concept of an mid-term archiving tier (with long-term archiving via RZG) and that satisfies urgent needs for server backups due to present network bandwidth limitations to the RZG backup systems.

10.2 Control and Data Acquisition

10.2.1 WEGA Prototype Installation for W7-X Control and Data Acquisition

Extensive tests of the CoDaC developed steady state control and data acquisition is indispensable for reaching a suitable quality level. Using the WEGA stellarator as a CoDaC prototype provides an integrated test of control, data acquisition, diagnostics operation and data analysis in a W7-X like manner. The first phase of the prototype project (from 2006 until end of 2008) had its objectives on the retrofitting of the existing control system towards the W7-X control and data acquisition system. In the second phase (until now), extensive tests of the safety system have been performed and the routine use of segment control for machine and plasma operation has been established including advanced physically motivated experiment programs. In 2011 the WEGA operation team solely relied on the CoDaC system, which added the value of conditional experiment operation. This was demonstrated by reacting on the recognition of an OXB transition in the plasma. Moreover, diagnostics have been developed and operated that can be directly used later on for Wendelstein 7-X operation, like the neutral gas manometers.

10.2.2 CoDaC Frontend Systems

Work on the specification of technical and diagnostics systems has made significant progress and some of the systems are in the implementation phase, like the HEXOS spectrometer, for which the control and data acquisition has been implemented in cooperation with FZJ. Parts of the gas supply system have been reclassified regarding explosion safety and more strict legal requirements have to be fulfilled. This resulted in a comprehensive refurbishment of the gas supply and its control components. It targeted at main parts of the process control, cabling, gas alerting system and sensor technology. Additional requirements by neutral beam heating and the diagnostics injector had to be implemented regarding supply of He, H_2 and D_2 as well as necessary enhancements of the safety system for radiation protection. In order to increase the efficiency of programming PLCs, a basically new programming technique (PCS7) has been introduced and will be applied for forthcoming developments on control components. The basic time synchronisation card (TTE) is in redevelopment, since essential electronic parts of the existing cards are no longer available. The main features are an ethernet interface and combined functionalities of two former card types, TTE and TDC.

10.2.3 Quality Management and Agile Project Management for Software Development

A quality system according to standards like ISO/IEC-15504-5 and ISO/IEC-25010 has been introduced for structuring the development work and improving process and product quality in an automated way by a tool chain (SVN, Maven, Jenkins, Nexus, Java Web Start, Redmine). Additionally, a software project management has been introduced with a SCRUM-like agile process. In this way, CoDaC achieved the structured capability for reacting quickly on priority changes and to give well-founded completion forecasts. The agile method makes use of a four weeks iteration cycle, each starting with presenting plans with work packages, estimates for development time and prioritizing of requirements and then closing with quality assurance and iteration feedback for process improvement.

10.2.4 Accomplished Software Projects

Within the application tool chain (figure 35) Xedit, the experiment program editor, has been finalised and is used routinely at the WEGA stellarator. Starting from an established experiment program, the user is able to modify parts of it like changing parameter values and adding or removing program segments. The implementation is based on the high-level parameter abstraction introducing a more physics-oriented view on the machine parameters and on component models describing the complex dependencies within and between machine components as well as the temporal behaviour during an experiment program. The session leader program Xcontrol is the user interface for loading, running, surveying and logging experiment programs within the W7-X segment control. It provides a program preview and an overview about the resource status for a planned experiment program. Programs are logged with unique log numbers for each program part and processed programs can be listed and commented with the contained logbook application. ConfiX, a generic object editor, has been finalised and provides administrative functionalities. ConfiX enables to create, view, edit and repair any data object in an object-oriented database including navigation through the object structure, viewing contents, searching and browsing, modification and comparison of objects.

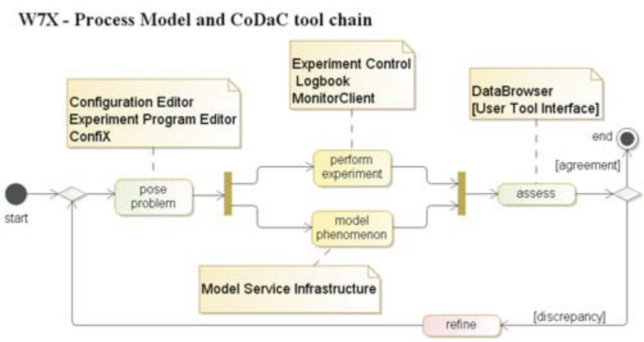


Figure 35: The "Configuration Editor" supports the configuration of experiment setups and to define the parameter spaces needed for specification of experiment programs. The experiment program Editor "Xedit" is used to specify experiment programs and to transform them into executable form. The experiment control application "Xcontrol" is used to load, start and survey experiment programs. The "Monitor Client" provides an experiment synchronous display of measured signals and status. The "DataBrowser" provides temporal and structural navigation in archived data. The "User Tool Interface" is a software interface to the measured data archive.

10.2.5 External Contributions and Cooperations

CoDaC received contributions from the XDV group of the RZG (see RZG section), the University of Rostock for FPGA development, FZ Jülich for HEXOS setup and from the Instituto Superior Téchnico (Portugal, Lisbon) for ATCA based ADC prototype. A cooperation on long pulse operation and steady state control issues has been started with Tore Supra (CEA, France). Additionally, W7-X CoDaC is associated partner within the plasma technology grid (PTgrid, part of D-grid). Many sub-projects have been conducted by students and trainees from the University for Applied Sciences, Stralsund and from Dresden University.

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WEGA, VINETA and Further Activities

Supra-thermal electron components could be generated in WEGA by coupling the 2.45 GHz and the 28 GHz microwave heating system. The international Stellarator/Heliotron database and the cooperation with LHD on 3D effects were continued. Studies of drift wave turbulence have been extended to fluctuation-driven plasma flows. The VINETA experiment has been modified for the study of driven magnetic reconnection.

WEGA

Head: Dr. Matthias Otte

The simultaneous application of the two radio frequency systems operating at 2,45 GHz (26 kW, cw) and 28 GHz (10 kW, cw) respectively, results in synergy effects giving access to otherwise inaccessible plasma parameters. By assistance of the 2.45 GHz system the density cut-off of $1{\cdot}10^{19}$ m^{-3} could be overcome in a target plasma generated by the 28 GHz system at a magnetic field of 0.5 T. Thus it is possible to excite electrostatic Bernstein waves in a two-step (OXB) mode conversion process. During this heating scenario a supra-thermal electron component with an energy up to 70 keV could be detected by means of different energy-resolving X-ray diagnostics. Thus the position of the supra-thermal electrons could be determined within a tube of 25 mm diameter around the equatorial plane. In cooperation with PNSensor a silicon drift detector with 77 cells was applied during these discharges, which gives indication of a radial outward shift of electrons with energies above 30 keV. The existence of supra-thermal electrons is supported by the radiation characteristic of an electron Bernstein wave emission diagnostic measured with a new optimized quasi-optical antenna system. Furthermore, a radiometer of IPP-Prague was tested in combination with the new antenna-system. At lower plasma densities of about $2{\cdot}10^{18}$ m^{-3} generated by the 28 GHz heating system at a magnetic field of 0.5 T the overlaying wave field of the 2.45 GHz system results in a supra-thermal electron component in the MeV-range and plasma currents of the order of >100 A/kW. Experimental investigations suggest that these relativistic electrons are propagating on stable drift orbits in one toroidal direction, which are, however, strongly shifted to the outer plasma edge. Due to the collision with the antenna system, which is the closest in-vessel component, gamma rays were produced, detected by an assembled Geiger-Müller-counter based hard X-ray diagnostic. Simulations with the help of the w7 magnetic field line tracing code support the thesis of the confinement of the relativistic electrons in one magnetic preferential direction. Utilizing an inward moving probe crossing the expected position of the MeV-electrons a collapse of this electron beam component could be diagnosed in the magnetic and the X-ray diagnostic. With the help of two fast 16-channel diode arrays arranged in one toroidal plane a tomographic reconstruction of the emitted plasma radiation is now possible. OXB-heated plasmas indicate centrally peaked radiation profiles. Fluctuations of the diode signals coupled with supra-thermal electrons have been observed. Utilizing an electron beam the incident angle between magnetic field lines and a graphite tile was determined experimentally by optical observation. The angle was determined between the illuminating beam in background gas and the tile and furthermore, from the shape of the beam-footprint onto the tile when covered with fluorescent material.

International Stellarator/ Heliotron Database

The Stellarator/Heliotron database has been maintained within an international collaboration (NIFS, CIEMAT, U-Kyoto, ANU, PPPL, U-Wisconsin, U-Auburn, U-Charkov, U-Stuttgart, and IPP). Joint experiments for the validation of neoclassical transport models have been performed (W7-AS, LHD, TJ-II) with LHD. First transport analyses have been conducted indicating the strong entanglement of particle and energy transport in large stellarators/heliotrons. Studies of the plasma response due to RMPs have been started also entering joint activities with the ITPA Transport and Confinement group.

3D Effects in Tokamaks and Stellarators

Continuing the collaboration with the National Institute for Fusion Science (NIFS) new experiments on 3D topological effects were conducted at the Large Helical Device (LHD). The heat flux pattern onto the helical divertor in LHD was investigated and a comparative study of the magnetic field topology in the edge was conducted with HINT2. The experiments focused on the development of the edge heat flux pattern during comparable plasma discharges at different plasma beta. Magnetic equilibrium codes like HINT2 predict changes of the edge magnetic field intersecting the divertor. These changes are connected to pressure driven plasma currents, which induce a displacement of the magnetic axis position (Shafranov shift) and an increase of the width of the stochastic edge region. The observation of the temperature distribution on the divertor surface and the following calculation of heat flux profile confirm these predictions experimentally. Also a series of experiments were performed in order to study the effects of external resonant magnetic perturbations on density and temperature profiles. The perturbation with 1/1 main Fourier component depending on the plasma configuration either creates a relatively large 1/1 magnetic island with stochastic boundary or just the stochastic boundary with healed 1/1 island. Both configurations have rather different effects on transport and confinement. As expected in a case of enhanced 1/1 island radial transport is stronger with significant increase at the location of the island.

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VINETA

Head: Dr. Olaf Grulke

Fluctuation-driven Plasma Flows

In previous investigations it was shown that drift wave turbulence as observed in the VINETA device can be distinguished into two distinct regions: In the maximum radial plasma pressure gradient region a quasi-coherent m=1 drift wave structure is observed, which azimuthal propagation is determined by the electron diamagnetic drift. In the far plasma edge turbulent structures are observed propagating azimuthally with time-averaged E×B drift, which is anti-parallel to the electron diamagnetic drift direction. The transition region between both fluctuation propagation directions is localized to a narrow radial region. The same features have been observed in the three-dimensional numerical simulations of the CYTO code. Figure 1a) shows the radial run of the fluctuation phase velocity as obtained from the simulation data with the sharp transition in phase velocity indicated by the shaded region. This transition region is associated with an increased radial divergence of the azimuthally averaged Reynolds stress, which indicates the occurrence of a fluctuating azimuthal velocity shear layer. Indeed, the intermittent occurrence of a m=0 mode structure of the plasma potential fluctuations is observed as shown in figure 1b).

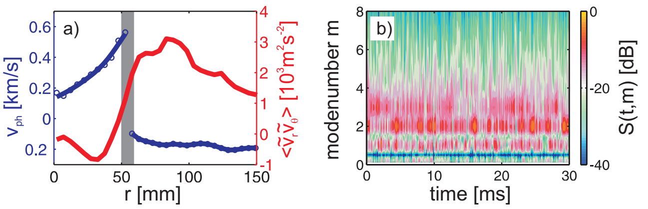

Figure 1: Simulation results of a) fluctuation phase velocity and azimuthally averaged Reynolds stress, b) time-resolved modenumber spectra of potential fluctuations.

From the simulation results evidence is found that the generation of the shear layer is correlated with the generation of edge plasma fluctuation structures, which are observed to being sheared off the quasi-coherent mode structure. The probe diagnostic setup at the VINETA experiment has been extended to diagnose the generation of turbulence-driven flows and clarify the link to the generation of edge fluctuation structures.

Device Modifications for Experiments on Magnetic Reconnection

The VINETA experiment has been significantly modified in 2011 for studies on driven magnetic reconnection. Two vacuum modules have been separated from the original VINETA setup and act as an independent experiment to continue the studies of the dynamics in drift wave turbulence. The remaining two modules form the basis for the magnetic reconnection setup. An additional large vacuum module is included with an inner diameter of 1 m and a length of 1.5 m as shown in figure 2a). The module is magnetized by a set of four large magnetic field coils, which together with the VINETA modules generate a homogeneous magnetic guide field with a magnetic ripple on axis less than 1 %.

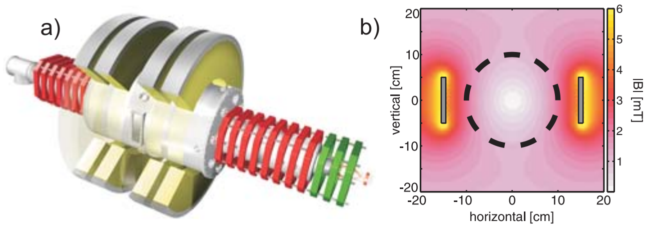

Figure 2: a) Device setup for reconnection studies, b) calculation of the in-plane magnetic field generated by the two internal conductors (shaded boxes).

The reconnecting magnetic field, figure 2b), is driven by one period of a sinusoidal current (peak currents ~1 kA) in two conductors aligned parallel to the cylinder axis inside the large vacuum chamber. A magnetic X-point is formed on axis and the magnetic induction in the plasma region indicated by the dashed circle in figure 2b) is typically 5-20 % of the guide field. A plasma gun has been developed and successfully tested up to a total current of 700 A, which will provide the plasma current establishing in response to the reconnecting field. The plasma is generated by rf heating in different antenna geometries. The different discharge mechanisms – inductive and helicon discharge – allow for a variation of the plasma density over three orders of magnitude at rather constant electron temperature, thereby tuning the regime from collisionality dominated magnetic reconnection to fast collisonless reconnection, where kinetic effects are expected to occur. All technical aspects of the device modification were finished in 2011. In the upcoming experiment program special attention will be paid to the role of global boundary conditions on the plasma dynamics and particle kinetics in the reconnection current sheet. A close collaboration with Prof. R. Schneider (University of Greifswald) and Prof. R. Sydora (University of Alberta) was established to compare the experimental findings with the results of global electromagnetic Particle-In-Cell simulations, in which the actual device geometry will be fully incorporated.

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ITER

ITER Cooperation Project

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The IPP contributions to the ITER Project range from R&D for heating systems and diagnostics to development of integrated plasma scenarios. In addition, IPP is playing a leading role in contributing to the ITER physics via contributions to the International Tokamak Physics Activity (ITPA) and by participating in the EFDA Workprogramme. Furthermore, IPP participates in European training programmes for young scientists and engineers.

Introduction

The most obvious incident to affect ITER in 2011 was the devastating earthquake and the subsequent tsunami in north-eastern Japan on 11th March. A special task group was installed to assess and mitigate potential delays. While ITER-related Japanese industry recovered quickly, a huge amount of financial investment will be required in Japan in the coming years. Thus, the other ITER partners will have to help the Japanese government to reduce its financial burden by delaying some procurement packages to arrive at a realistic schedule. The task group optimised planning and approval processes at ITER and identified technical issues for balancing risks against costs and schedule with the outcome that it were desirable not to pursue the design of the second divertor any longer but to start ITER operation with a tungsten divertor. A final decision on this issue needs to be taken soon. Furthermore, some heating systems and diagnostics will have to be deferred.
Within the European Union the funding for ITER for the next two years has finally been agreed upon at the end of November. The three statutory bodies have agreed to cobble together 360 M€ from anticipated unspent funds in the still-to-be-decided 2013 budget. Another 840 M€ will be found by shifting money from 2012 and 2013 budget lines for farm and fishing subsidies, rural development and environment, into the ones covering research. The remaining 100 M€ had already been allocated to ITER in the 2012 budget.
Meanwhile the ITER site shows significant progress. The poloidal field coil winding building is almost finished and in the tokamak pit the lower basemat is completed and work started on the seismic isolation system. Also, the building of the ITER headquarters will be completed in mid-2012.

Heating Systems

Development of RF Driven Negative Hydrogen Ion Sources for ITER

The development of the IPP RF source – being since 2007 the ITER reference source – was on-going in 2011 with the construction and assembly of new ELISE test facility, the continuation of long pulse experiments at MANITU, basic experiments regarding the magnetic filter field and electron suppression at BATMAN and with ITER-relevant RF experiments at RADI. Due to the use of components for ELISE, MANITU and RADI were decommissioned finally in July 2011.
The construction of ELISE, being supported by a 4 M€ F4E service contract, is in its final stage. Almost all components have been manufactured and delivered. The assembly is proceeding (figure 1), but not yet finished, also due to problems during manufacturing. In order to save time during the experimental phase, a dedicated diagnostic calorimeter is presently in manufacturing and will be installed in March 2012 from the beginning. The integrated commissioning with the first pulses is now expected in spring 2012.

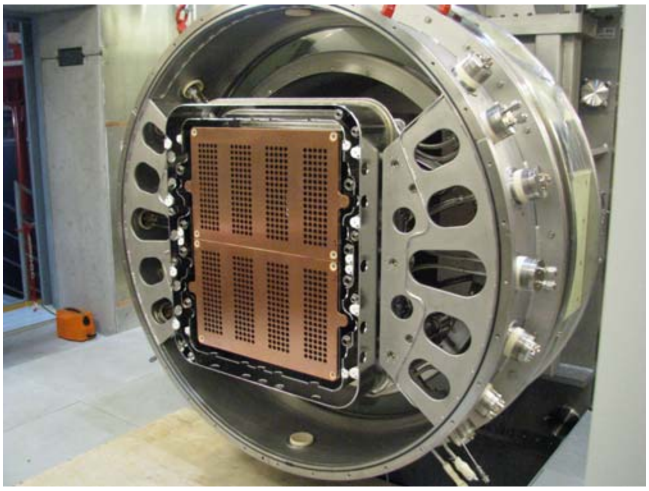

Figure 1: Assembly of the grounded grid within the HV ring of ELISE.

Furthermore, IPP continued to contribute to the construction of the PRIMA test facilities at RFX Padova (consisting of the full size, full power 1 MeV test facility MITICA and the full size 100 kV ion source test facility SPIDER) in the design of the RF source, the RF circuit and the layout of source and beam diagnostics. Tests of SPIDER diagnostic tools at BATMAN have been prepared, IPP personnel is involved in the tender procedure for the SPIDER ion source. Similar supporting activities are under way with the Institute of Plasma Research in Bhat, India, which is responsible for the construction of the ITER diagnostic neutral beam. In order to gain experience with RF driven negative hydrogen ion sources, a copy of BATMAN named ROBIN (Replica of BATMAN in India) is presently being constructed and partly commissioning there with support of IPP.
The experiments at the BATMAN test facility continued on studies of the effects of the magnetic field structure on the source performance, both in hydrogen and deuterium. Similar correlations, but with larger magnetic fields, of the extracted ion density and the amount of co-extracted electrons have been found in deuterium as for hydrogen. In order to have a validated input for models, a detailed diagnostic campaign was then started for spatially resolved measurements of the

plasma parameters from the driver to the plasma grid in hydrogen and deuterium by using movable Langmuir probes and optical emission spectroscopy with a special emphasis on the still unresolved question of the large surplus of co-extracted electrons in deuterium compared to hydrogen.
The IPP modelling activities of the processes in the boundary layer near the plasma grid where the negative ions are generated are concentrated on electron suppression, also by collaborations with French groups at the Universities Paris-Sud and Toulouse. Another focus is laid on the modelling and measurement of the distribution of caesium during and between the plasma pulses, supported by experiments regarding Cs chemistry, diagnostics and supply at the University of Augsburg (see chapter 14). The new laser absorption diagnostic technique for a reliable direct measurement of the neutral Cs density both in the plasma and the non-plasma phase was adapted at MANITU and showed a strong depletion of the Cs density in front of the plasma grid during long pulses, but with almost no effect on the ion current. The electron current, however, correlates in some cases with the Cs density during a pulse; the overall performance is mostly determined by the Cs distribution in the ion source before the pulse starts.
The experiments at MANITU ended finally in July 2011 with the first one hour pulse in deuterium worldwide (figure 2) with ITER-relevant parameters (source pressure at 0.3 Pa, electron/ion ratio around 1). But in order to keep the electron current stable for the second half hour, the RF power and the extraction voltage were rather low resulting in negative hydrogen ion currents well below the ITER requirements. The long pulse stability was achieved by an improved Cs management and a careful conditioning of the source. The stripping losses, i.e. the neutralisation of the negative ions in the accelerator before being fully accelerated, have been measured to be significantly lower than model predictions. As low stripping losses are beneficial for ITER, common activities with RFX Padova for an improvement of the models have been started.

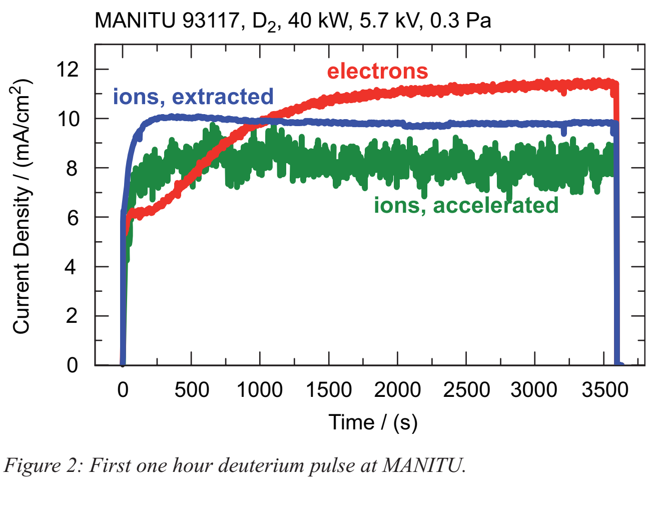

Figure 2: First one hour deuterium pulse at MANITU.

The experiments at RADI, equipped with a large scale RF driven ion source, concentrated on reliable RF operation of an ITER relevant RF circuit. The last experiments before the final shutdown showed that low pressure operation ($p<0.3$ Pa) is, in contrast to the small prototype source, possible even with a magnetic field present in the driver. Furthermore, the RF efficiency is significantly larger for the larger source. Both effects can be explained with the larger volume to surface ratio of the larger RF sources resulting in less plasma losses at the wall and are beneficial for the operation of the ITER neutral beam system. Finally, pulses at ITER-relevant high RF power (2×140 kW) with good plasma homogeneity could be achieved.

Design of the ICRF Antenna for ITER

IPP is involved in the design of the ICRF antenna for ITER through the CYCLE consortium. This consortium had successfully bid for an F4E contract to design the ICRF antenna. The contract was to end in February 2012, after an extension of scope from conceptual design to preliminary design and an extension from 18 to 24 month. It will now run for an additional 6 month. The CYCLE consortium agreement, which ended in 2011 was renewed for 3 years to the end of 2014.

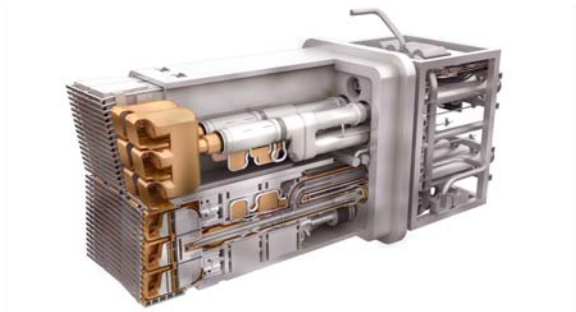

Figure 3: Current design status of the ITER ICRF antenna.

The ITER ICRF antenna has to couple 20 MW in the plasma for pulses of more than 1000 s. It consists of 24 straps, combined in 4 modules with 6 straps. In a module, the six straps are combined in two triplets, which are each connected via a 4 port junction to one transmission line. Eight transmission lines feed the antenna. The whole system is cooled in steady state. The state of the current design is shown in figure 3.
The IPP contribution to the project in 2011 focused on the mechanical and cooling aspects: the structural integrity of the 4 port junction during a major plasma disruption and the dimensioning of the cooling channels in the strap housing module and port plug. IPP further contributed to the choice of fabrication methods and the adaptation of the design for the straps, the strap housing module and the port plug.

ECRH Upper Launcher

In 2011, the "EU Consortium for the ECRH Upper Port Plug System for ITER (ECHUL-CA)" was formed by CNR Milano, EPFL Lausanne, KIT, IPP and ITER-NL. Within this consortium, IPP takes over the responsibility for the physics area, i.e. making sure that the design is adequate to meet the envisaged physics objectives. The Consortium was awarded a Grant for "Design, Analysis and Documentation to Produce the ITER EC H&CD Upper Launcher Final Design" at the end of 2011. Work in this area has just started and will be reported in more detail in the next Annual Report.

EFDA Tasks

As part of arc detection studies the GUIDAR system was tested on the Manipulator experiment. The detector triggered a signal when a high voltage arc occurred, but it could only be a reaction to the electromagnetic noise of the arc. The second part concerned the hardening of the SHAD against noise: it was discovered that the detector reacted not only to plasma instabilities but also to arcs within the vacuum vessel and unrelated to ICRH operations.

Diagnostics

ITER Bolometer Diagnostic

With the Grants and Framework Contracts for the development of the diagnostics for ITER still not having been issued by F4E, the R&D activities for the ITER bolometer diagnostic carried out at IPP are being continued by support of national funding. Without an official contract the access to information about the design of components having interfaces with the bolometers is restricted. Thus, several activities, in particular those concentrating on the integration in ITER, had to be postponed or continued based on assumptions. However, at the end of 2011, the period, for which the dedicated national funds of 5.7 M€ were granted, was prolonged by one year up to 03/2013 so that an overlap with the expected Grants and the conclusion of all projected work packages still seems feasible.
The main focus of the investigations in 2011 was on the development of bolometer detectors suitable for the application in ITER, which is carried out in cooperation with the Institut für Mikrotechnik Mainz GmbH (IMM). The first samples featuring the 12 µm thick Pt absorber, required for detecting the radiation from the centre of the discharges of the ITER standard scenario, were tested. Their calibration parameters are in the expected range but the mechanical stability of the membranes at high temperatures is not yet sufficient for ITER. Therefore, an intensive effort has been started to determine the cause for the high stresses in the membranes, which, after a few thermal cycles up to temperatures above 250 °C, ultimately lead to breaking. Finite-element simulations managed to reproduce the deflection of the membranes observed in measurements (figure 4). They also helped in the decision, which of the proposed improvements for the production processes of the detectors might yield the most promising results. Four changes to the geometry of the absorber, which affect the stress concentration in the membrane have been implemented in the production processes and will be available for tests in 2013.

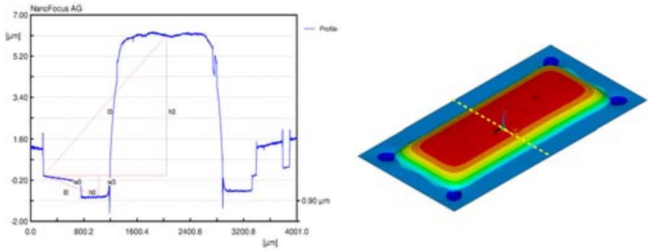

Figure 4: Measured and simulated deflection of the membrane for a prototype bolometer detector with 12 µm Pt absorber. The measurement on the left is taken across the short side as indicated in the simulation result on the right.

In parallel, irradiation tests of the detector prototypes have been initiated in cooperation with the Atomic Energy Research Institute of the Hungarian Academy of Science. The initial tests reached an accumulated neutron dose of 10^{14} n/cm^2, showed the expected variation of the meander resistance with temperature and no impact of the irradiation. Further tests are now planned to increase the neutron dose gradually to ITER relevant levels.
During the last year the design of the diagnostic components matured and several prototypes for collimator, mini-camera housing and electrical connectors have been manufactured and tested. The control of the light-weight robot is continuously being improved. Several collimator prototypes have been manufactured and their geometric functions have been measured in order to determine the optimal approach towards reducing the impact of stray light (see chapter 17).

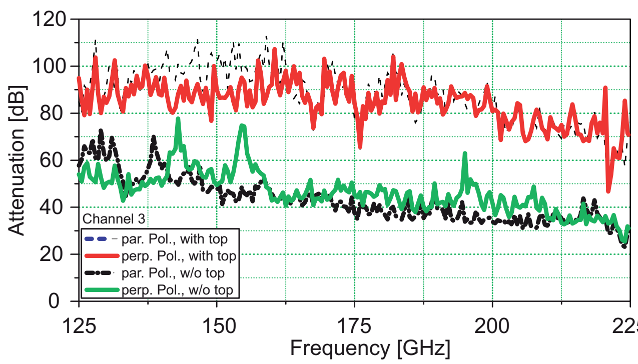

Figure 5: Attenuation of the coated channel 3 in the frequency range 125-225 GHz, for parallel and perpendicular polarisation, and with or without the TopPlate mounted (see legend).

A successful approach was to decouple the collimating apertures from the body. This allowed to increase the size of the channels and to manufacture the body out of two halves. The first reduced the impact of stray light significantly while the latter provided the option to coat the inside of the

channels using Al_2O_3/TiO_2, a ceramic developed to absorb microwave stray radiation. Collimator prototypes have then been tested at IPF Stuttgart with respect to their ability to prevent the impact of microwave radiation onto the detector area before and after coating. The latter was done in cooperation with the IFKB of the University of Stuttgart. The damping of microwaves in the range of 125-225 GHz is above 70 dB when using the TopPlate and above 40 dB without it but with coated channels (figure 5). Depending on the requirements of ITER this offers the possibility to evade the use of the TopPlate and thus to increase the light yield of the bolometer camera.
Additionally, a complete assembly of a bolometer camera and collimator was tested in the MISTRAL facility at Greifswald with respect to its ability to screen the detector from an isotropic microwave field. These tests showed that the design of the camera housing still has a leak for microwaves, which could be identified in laboratory tests.
Last but not least the finite-element analysis of components was extended towards the investigation of forces expected during disruptions. Based on simulations performed for the standard scenario in ITER it could be shown that significant forces in the order of 10 kN on single bolts have to be expected, which will now be considered during the subsequent design improvements. The detector membranes proved to be stable when loaded by acceleration forces as expected during disruptions. This was demonstrated in prototype tests using a shaker, which exerted a sinusoidal acceleration onto the detector. Further prototype tests simulating a shock on a complete bolometer camera are planned for 2012.

EFDA Tasks

The EFDA task on the development of a plasma position reflectometer has been successfully completed. In three discharges the radial position was feedback controlled using reflectometry instead of magnetic data. The control of the outer plasma radius was switched several times during L-mode and ELMy H-mode phases between the standard magnetic reconstruction and the estimation from the edge density profile computed by a real-time reflectometry diagnostic algorithm.
A comprehensive forward modelling of the ECE diagnostic was developed with emphasis on the challenging region of an optically thin plasma. Within an Integrated Data Analysis approach, combining the data of different edge and core diagnostics, this allows to estimate reliable electron density and temperature profiles also at the plasma edge where a straightforward interpretation of the ECE data is usually not possible.
Additionally, EFDA granted financial support for the development and test of hardware for the fast ion loss detectors (FILD) and the fast ion D_α (FIDA) spectra analysis on ASDEX Upgrade. The results of these tasks are reported in chapter 1.

ITER Support

Contracts with F4E

IPP conducts several tasks, which are financially supported by contracts with F4E. The results and activities of the most prominent among those have been presented in previous sections of this chapter (NNBI and ITER ICH antenna design). Additionally, the following activities were active in 2011.
A capacitive dust monitor (CDM) is proposed as safety diagnostic in ITER. The instrument was developed at CCFE and provided by F4E to IPP for tokamak tests. As the amount of dust in AUG is below the detection limit of the CDM, the test focuses on the disturbance of the CDM by plasma operation such as electromagnetic noise, radiation heating and neutral pressure fluctuations. Realistic tests to simulate conditions in the ITER divertor region can be done in AUG. A complete redesign on the electronics, housing and cabling was necessary to enhance the long term stability of the instrument. The cabling turned out to be a key component as ITER requires a distance of 40 m between sensor and electronics. Hence, the capacity of the cable is 100 times larger than the capacity of the sensor. A special kind of signal cable, based on the kind used at the bolometry diagnostics, was developed. Finally, an accuracy of 20 mg was reached under vacuum conditions. The instrument was qualified for the operation in AUG and two sensors were installed: one close to the outer strike point area, the second under the middle of the roof baffle where it is protected from divertor radiation. Both sensors were loaded to study a realistic behaviour. An outline design for the CDM components in ITER was done. Unfortunately, the cabling in ITER is presently not exactly defined, which hinders this conceptual design.
As a first step for the three dimensional "Study of Power and Particle Fluxes to plasma-facing components during ELM control by in-vessel coils in ITER and evaluation of plasma response effects" the Edge Monte Carlo 3D-Eirene (EMC3-Eirene) code package was benchmarked against the standard ITER 2D transport model SOLPS for the axisymmetric situation. Different input parameters were varied for the two codes, the heating power (P_{SOL}=50 MW and P_{SOL}=100 MW), the edge gas puff rate (ϕ=0 and ϕ=0.6 %$\phi_{recycling}$) and the impurity radiation level (1. no impurities, 2. carbon radiation losses computed by the EMC3-Eirene transport model and 3. by a 'Coronal' equilibrium model). In general a very good agreement was found in the main chamber in all plasma parameters as well as for the energy deposition in the divertor. Small differences, however, were found for density and temperature immediately in front of the divertor target plates, but these were within the expected accuracy of the simulation. This successful benchmark justified the following application of EMC3-Eirene for the study of the non-axisymmetric situation of the magnetically perturbed edge plasma in ITER.

The contract and first task order for the ITER PCSSP (Plasma Control System Simulation Platform) with a consortium composed of GA, IPP, and CREATE was signed. The objective of the task is the development of an environment to run open and closed loop plasma control simulations with a flexible choice of models for sensors, diagnostics, controllers, actuators and plasma. This shall help to find the optimum distribution of protective actions between interlock and control systems, to investigate advanced plasma exception handling strategies, and to test plasma controllers under development against simple and complex plasma models. During ITER operation the environment shall also support discharge schedule validation. The parties agreed on the work distribution in a kick-off meeting in July. The joint activities of the first project phase since September focused on the identification of the stakeholders, the definition of interfaces, and the requirements capture and analysis. Upon a formal requirements review process, the start of the follow-up architecture development phase is scheduled for early 2012.

ITPA Microwave Working Group

The microwave-based diagnostic suite for ITER includes ECE, Reflectometry, Collective Thomson Scattering and Refractometry. A common feature is their use of simple in-vessel radiation insensitive metallic antennas and waveguide transmission lines. However, once installed they will be difficult to replace or modify, hence, their careful design is a pressing issue. The ITPA Microwave Working Group, under the chair of an IPP member, has prepared several reports on topics critical to the diagnostic designs. These include: (1) Requirements for component and system calibration, and (2) a review of calibration methodologies. (3) Identification of options and techniques (e.g. fast acting shutters, waveguide filters, fuses etc.) to protect the sensitive diagnostic electronics and TL components from stray radiation damage due to non-absorbed ECRH & CTS gyrotron beams and fast electron generated Bremsstrahlung. (4) The Low-Field-Side Reflectometer system is at a crucial design phase – systematic studies of the design drivers as well as the placement and alignment of the antennas using beam-tracing codes have been performed. A major issue is the sensitivity of the probing beam to vertical movements of the plasma column, which is linked to the selection of antenna gain and placement, monostatic vs. bistatic antenna arrangements, and fixed antenna alignments vs. steerable antennas. The timeliness of these assessments have directly impacted on the detailed diagnostic designs – which are now in the hands of the respective ITER domestic agencies.

Development of High-power Diplexers

In collaboration with IPP, FOM and TNO in the Netherlands, the IAP Nizhny Novgorod and IFP Milano, research and development on diplexers for combination of high-power microwave beams and/or switching ("FADIS") on a fast timescale with low loss and without mechanically moving parts, continued. The compact HE_{11}-resonator diplexer MC IIIb was characterized in detail, which yielded an HE_{11}-transmission efficiency of 96 % in the resonant, and 99 % in the non-resonant channel, i.e. very near to theory. Therefore, this concept was taken as basis for the design of a diplexer compatible with the ITER ECRH system at 170 GHz. It consists of a massive vacuum box with precise outer machining to accommodate the matching mirrors, coupling gratings, and the resonator mirrors, which simultaneously are used as vacuum flanges. Both, matching and resonator mirrors are designed as phase-reversing elements for the fields radiated from and to the HE_{11} input/output waveguides. One resonator mirror will be equipped with a controlled mirror drive needed for gyrotron frequency tracking. The resonant diplexer Mk IIa, which had been tested last year at the W7-X ECRH system (annual report 2010), was installed at the ASDEX Upgrade ECRH system. Presently it is being prepared for plasma experiments on synchronous stabilization of neoclassical tearing modes, as well as in-line ECE measurements.

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, but not mentioned in chapter 1.

The Fibre-Bragg-Grating sensing technology has been successfully implemented at ASDEX Upgrade and thereby qualified for the environment of a medium-size tokamak experiment with respect to radiation and vacuum requirements. The low noise of the strain signals allows to study the mechanical impact of e.g. disruptions, saddlecoils and ELMs as well as the dynamical properties of in-vessel components.

AUG torque modulation experiments confirm the presence of an inward momentum pinch and show that the Prandtl number is close to one. An intrinsic toroidal rotation database was created and shows that counter-current intrinsic rotation is produced when R/L_{ne} is sufficiently large and the turbulence is either TEM or close to the ITG-TEM transition. Additional information can be found in chapter 1.

The inter machine comparison of pedestal width data containing data from ASDEX Upgrade, DIII-D and JET was carried out in the framework of a PhD thesis. The analysis showed that there exists a clear difference in the H-mode pedestal width of temperature and density. The density pedestal width scales with $\rho^{*0.6}$, while there is no ρ^* dependence for the temperature width. The scaling yields predictions for ITER, with a temperature pedestal width about 3 times wider than the density pedestal width.

For the lithium beam diagnostic a new optical head with toroidal viewing geometry was designed and built in cooperation with the Hungarian and Austrian associations. The optical head is installed, an additional set of deflection plates together with a new chopping circuit is inserted in the Lithium beam line and the fast data acquisition systems are ready for fluctuation measurements in the next campaign.
Modelling of Divertor detachment remains an unresolved issue for the high field side divertor. The numerical model cannot capture the experimentally shown existence of high particle fluxes in the far SOL during periods of enhanced and highly fluctuating volumetric radiation. An extended grid has been produced for an L-mode case and will be tested.

Plasma-Wall-Interaction (PWI) Task Force

The use of Be and W as wall materials in ITER require active methods to reduce the thermal wall load to avoid excessive erosion and melting. Radiative edge and divertor plasma by impurity injection, such as nitrogen, are considered and investigated with success in ASDEX Upgrade. Within the IPP contribution to the EU PWI Task Force several tasks were completed on the interaction of energetic N ions with Be and W surfaces and its influence on fuel retention. In the case of W nitrogen quickly saturates once the implantation range is filled with a nitride phase thus reducing the W erosion yield. D retention considerably increases at high fluences and depth profile measurements show an enhancement of the D diffusion into the bulk. It must be assumed that N-containing layers on the W surface act as a diffusion barrier for D desorption leading to an increased D diffusion into the bulk. For Be also a nitride layer is formed with similar hydrogen retention values as in pure Be, but with higher temperatures needed for hydrogen release. Further studies on the influence of N on the co-deposition of hydrogen with Be are ongoing.

Advancement of Young Scientists

The NIPEE (Negative Ion Physics and Engineering Expertise) programme was continued with common meetings of the six trainees (one IPP, one KIT and four RFX Padua). The IPP trainee was strongly involved in the construction of ELISE and of the W7-X neutral beam system.
The IPP LITE trainee spent six months at IPP and six months at ERM-KMS. At IPP, he worked on a new phase regulation system for the signal generators of the ASDEX Upgrade's ICRF system, using DDS (Direct Digital Synthesizer) technology and on calculating vacuum tube parameters.
Several trainees from other associations (ERM-KMS, CEA, POLITO, Frascati), increased their knowledge through training activities in the ICRF group, while at the same time participating and contributing to the work of the group.
With all EnTicE trainees having terminated their training by the end of 2010, the very successful EnTicE programme is running to a close. The number of trainees is eight, rather than six as originally foreseen. Four of the trainees are female, and all eight obtained a position after their training, six of them in fusion, one in industry and one in research outside of fusion. The cost of the programme was 97.5 % of the original budget (1198 k€). The programme ran longer since some trainees obtained a position before the end of their programme, and the remaining training month were used to hire additional trainees.
Additionally, IPP took a leading role in the submission of a proposal to the European Commission for an Erasmus Mundus International Doctoral College in Fusion Science and Engineering, together with other European partners and with the University of Gent as coordinator. The proposal was one of only 10 selected from 140 submitted and will provide funding for about 8 three-year doctoral fellowships, during 5 consecutive years. This corresponds to a grant volume of about 5 M€. The first fellows will be selected in February 2012, and starting their Ph.D. in September 2012.

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DEMO

DEMO Design Activities

Head: Prof. Dr. Hartmut Zohm

The project 'DEMO Design Activities' was newly established in 2011 to acknowledge the important role of DEMO as a next step after ITER in defining the needs of the Fusion Programme. The project builds on work being done in virtually all IPP departments in Garching and Greifswald and should ensure that the IPP programme is aligned with the strategic needs arising from DEMO design studies.

Introduction

The work in this new project aims at introducing the boundary conditions set by a DEMO or fusion power plant step after ITER into the strategic orienta early stage. An important aspect is that the often conflicting boundary conditions set by physics and technology should be taken into account simultaneously when discussing design options and the project aims at doing integrating both fields. Finally, IPP with its expertise in both stellarator and tokamak physics sees it as important to adequately represent the stellarator option in the DEMO discussions.

On the organisational side, the project has strong links to the other German Fusion Associations FZJ and KIT and regular workshops about technology and physics questions for DEMO are being conducted by the three partners under the coordination of IPP. These discussions further serve to give guidance to the future development of the German fusion programme. Within the EU programme, there is a strong link to the EFDA Power Plant Physics and Technology programme to ensure coordination also at this level. Finally, the project is also prominently involved in discussions on a worldwide level, such as the newly founded IAEA DEMO workshop series.

Physics Base for System Studies

System studies for DEMO and fusion power plants are usually conducted using a set of 0-d assumptions on physics and technology that constrain the machine design together with some optimization criteria. In 2011, we assessed the physics assumptions made in these codes and reviewed critically the status in the different fields involved. Our analysis showed that new input is needed especially in the following areas:

- High density operation: studies of tokamak DEMOs show that at the β-values foreseen, the temperature would reach values in excess of the optimum for D-T fusion in the core plasma if operation below the empirical Greenwald limit is envisaged. Hence, there is a strong need to understand better the limitation set by the Greenwald limit. Assuming for example (consistent with many experimental findings) that it is an edge limit, the real limitation on the line average density depends on the amount of density peaking. Since the latter is a function of collisionality and present experiments cannot reach the DEMO regime of high Greenwald fraction at low collisionality, theoretical considerations have to be invoked to assess the real limitations to the achievable density in DEMO. First studies indicate that a peaked density profile may be expected for DEMO and hence, operation at line averaged density above the empirical Greenwald limit could be possible.
- Power exhaust using impurity seeding: due to the much higher ratio of plasma heating power to major radius than in present day devices (and even in ITER), it is expected that impurity seeding to remove power before it can reach the target plate must also include a sizeable amount of core radiation. This problem is even aggravated by the technological constraint that the acceptable power per area in the divertor will most likely have to be reduced with respect to present day experiments due to the high neutron fluence reaching the first wall in DEMO. It must hence be studied, which impurity mix can provide sufficient radiative cooling from both the confined plasma and the scrape-off-layer without deteriorating too much the plasma performance. Likewise, models of divertor detachment have to be developed that predict the conditions required for detached divertor operation in DEMO. Here, IPP is involved in an effort to understand better the physics of detachment and its implementation in predictive divertor modelling.
- Contribution of fast particles to the β-limit: since a non-negligible amount of fast particles is expected for a tokamak DEMO, it must be assessed how they will contribute to the β-limitations set by MHD instabilities. For this, it will be necessary to treat these kinetically, since fast particles can introduce stabilizing and destabilizing effects, which have to be carefully balanced. This is presently not taken into account. In addition, there are instabilities that only exist in the presence of fast particles, like TAEs or EPMs. Also, their stability should be taken into account in the DEMO designs in a proper manner.

In addition, the present confinement scaling used for ITER (ITER98(p,y2)) needs to be updated to reflect the DEMO operation point at higher density, β and radiation than that foreseen for ITER. Another conclusion from the review of the physics basis was that steady state scenarios based on very large bootstrap fraction presently lack experimental demonstration and hence a steady state tolamak will have to rely quite heavily on external current drive. Alternatively, pulsed designs should be studied. These are usually larger major radius devices with larger aspect ratio to accommodate for a big central solenoid.

We have started to address the above listed issues in a combined effort in theory and experiment, where as a first step, experiments in ASDEX Upgrade will be used to widen the database in all three areas. The activity described here aims at establishing a 'DEMO physics assumptions' document, similar to that prepared for ITER in the conceptual design phase. For the stellarator line, IPP has undertaken further studies to assess properties of a W7-X like DEMO or Fusion Power Plant. On the engineering side, these involve improvements in coil design including a novel 'building block' approach to address the challenging 3D problems of inter-coil support. In addition, a first version of a stellarator module has been included in the PROCESS code developed by CCFE. Further results are reported under the theory project.

Heating and Current Drive Assessment

The requirements for heating and current drive (H&CD) systems in DEMO will strongly depend on the assumptions about its operation point. While stellarators or pulsed tokamaks may need mainly heating to ignition and burn control, it seems clear that a steady state tokamak will require efficient current drive schemes in order to operate at an acceptable level of recirculating power. On the technology side, this necessitates a high wall plug efficiency of the H&CD system used. On the physics side, it means that it is important to study the current drive efficiencies that could be achieved by the different H&CD systems. Work at IPP has started by optimizing an ECRH system for DEMO under this aspect. Since it is assumed that DEMO will operate at a very restricted operational point, experimental flexibility is not a design driver (as is still the case for ITER). Consistent with previous studies, it was found that the current drive efficiency can be raised by going to higher ECRH frequency. Usually, this route of improvement is limited by the occurrence of downshifted second harmonic absorption in the hot plasma. However, we found that this could be circumvented by using a top launch position, which avoids that the wave must travel through the region of enhanced higher harmonic absorption. First evaluations of the current drive efficiency indicate that it can be more than doubled compared to a low field side midplane injection at lower frequency and reach values that come close to that quoted for neutral beam current drive under some circumstances.
However, in order to compare the efficiencies of the different systems in a fully appropriate way, one has to specify a consistent set of kinetic and current profiles and evaluate the power needed for a certain physics target, e.g. achieving zero loop voltage. Such a study is under way using the ASTRA transport code package and mimicking at least two DEMO operational points that come from 0-d systems studies conducted under the EFDA Power Plant Physics and Technology studies mentioned above by CCFE using the PROCESS code. In particular, also the above mentioned assumptions about the density peaking will have a strong impact on the CD efficiency since they lead to very different temperature profiles, which in turn affect the current drive efficiency, even when the fusion power is the same.
Other activities on H&CD systems cover an assessment of technology of future NBI and ICRF systems, which will be crucial in determining the wall plug efficiency as well as availability and reliability of such systems. reliability. One important step for the increase of the wall plug efficiency for NBI is a laser neutralizer system. Here a factor of two can be gained. Activities to explore this option will be started on small laboratory scale experiments. On the other hand, NBI systems above 1 MeV energy for enhanced current drive efficiency seem to be unfeasible with the present technology.
In summary, the DEMO project has already made important contributions in highlighting strategic issues that can impact the future programme of IPP and it is expected that this role will continue, especially in view of the upcoming start of operation of W7-X in 2014, which will have a strong implication for stellarator DEMO options.

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Plasma-wall-interactions and Materials

Plasma-facing Materials and Components

Head: Dr. Wolfgang Jacob

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

Optimised Analysis of Deuterium Depth Profiles in Beryllium

Various accelerator-based ion beam analysis techniques have been reviewed in simulations as well as experimentally with emphasis on their depth resolution and sensitivity for detecting deuterium in beryllium. The advantages and drawbacks of elastic recoil detection analysis (ERDA) with medium-heavy ions compared to He-ERDA and nuclear reaction analysis (NRA) were addressed. The sensitivity of ERDA is generally higher than that for NRA and increases strongly with increasing atomic number of the projectile. However, the impact on the analysed sample also increases, leading to faster depletion compared to lighter projectiles and NRA. The depth information contained in the α particles that originate from the nuclear reaction with ^{3}He was compared to ERDA with various projectiles. For the geometries at the RKS apparatus, the depth resolution (2σ) for D close to the surface in mirror-polished Be is 140 nm for NRA and 116 nm for He-ERDA. Using ^{28}Si ions for ERDA, a substantially improved resolution of 47 nm can be achieved. In test experiments, ERDA with ^{4}He and ^{28}Si as well as NRA were applied to analyse a Be sample implanted with 3×10^{22} Dm^{-2} at an energy of 3 keV per atom. The resulting depth profile can only be resolved with medium-heavy ion ERDA using ^{28}Si projectiles. The experimental profile resulting from this analysis is in good agreement with simulations employing SDTrim.SP (see figure 1). In these simulations the upper limit of the local D atomic fraction was set to 0.1. The D concentration features a plateau close to the sample surface with a constant D atomic fraction of 0.1 and drops to zero around a depth of 150 nm.

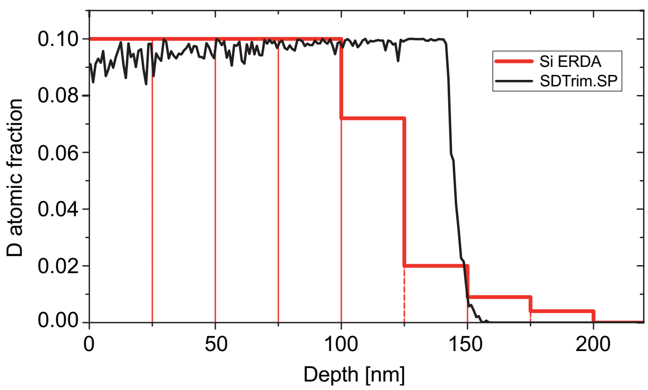

Figure 1: Rectangular columns: D concentration in the target used for the SIMNRA fit to the experimental Si-ERDA spectrum (not shown). Black line: D depth profile from an SDTrim.SP calculation with the maximum allowed D atomic fraction set to 0.1. σ_d indicates the thickness of a layer used in the SIMNRA fit (25 nm for the shown example).

Oxidation of Beryllium and Exposure of Beryllium Oxide to Deuterium Plasmas

The oxidation behavior of Be in air was studied as a function of temperature. Good agreement of oxygen areal densities measured by various complementary analysis methods (weight increase, Auger electron spectroscopy and Rutherford backscattering spectrometry) is found (see figure 2).

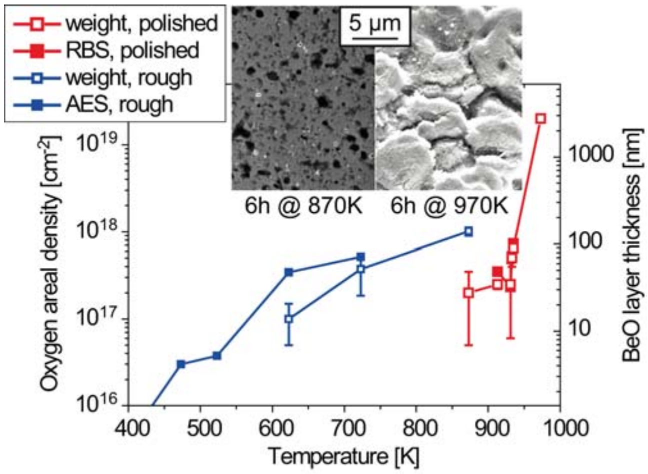

Figure 2: Temperature dependence of the oxide thickness as measured by various methods on rough and polished Be samples. Inserted are two SEM micrographs after oxidation at 870 and 970 K.

Surface roughness is observed to increase the rate of oxidation. Below 930 K the oxidation rate is limited by diffusion of Be through the growing BeO layer and closed oxide layers of less than 100 nm thickness are formed. Above this temperature a rapid increase in the oxidation rate sets in. Secondary electron micrographs show that this fast oxidation goes along with massive structural changes of the surfaces. Samples oxidized below the critical temperature were mounted on the witness-manipulator of PISCES-B at UCSD, San Diego and exposed to a flux of deuterium atoms reflected from a tungsten target. The temperature of the BeO samples during exposure was systematically varied between room temperature and 520 K. The energy of the reflected D atoms was varied by varying the bias voltage on the W target (0, 50 and 100 V). In the following, ion beam analysis was applied for investigating the erosion of the exposed surfaces as well as the uptake of D. The deduced erosion yield at 100 V bias is below 0.2 %, and thus in the range expected for erosion by physical sputtering. The retained amount of D increases with increasing bias voltage.

Accumulation of D in a thin surface layer and saturation of retention similar to the behavior in metallic Be is observed. The retention of deuterium in BeO layers strongly depends on the temperature during exposure. In fact, at 520 K the retention of D is reduced by a factor of 10 with respect to room temperature exposure. No enhanced chemical reduction of the oxide due to D_2O formation is observed.

Migration of Materials in Fusion Devices

Migration of Impurities in ASDEX Upgrade

The transport of carbon and nitrogen was studied by injecting isotopically labeled $^{13}CH_4$ and $^{15}N_2$ from the outer midplane on the last day of the operational campaign 2011. About 40 tiles from different areas of the machine were dismantled and analyzed. Redeposited ^{13}C was detected using SIMS, deposited ^{15}N was measured using ion beam analysis utilizing the $^{15}N(p,\alpha\gamma)^{12}C$ nuclear reaction. Due to the high sensitivity and short measuring time of this reaction a large number of data points can be analyzed, thus allowing to study impurity transport with a previously unreachable level of detail. The experimental results were compared to 3-dimensional ASCOT simulations. The calculations predict a complicated 3-dimensional deposition pattern, which cannot be described assuming toroidal symmetry. First results show qualitative agreement between the experimental results and ASCOT simulations.

Erosion in the ASDEX Upgrade Divertor

Erosion of W, Mo, Cr, and Al and deposition of B and C were investigated at the outer strike point using marker tiles. Since 2007 the amount of deposited C decreased from campaign to campaign while the amount of deposited B was correlated to the number of boronizations. For W, the maximum erosion was about 200 nm during the 2011 campaign. The erosion was two times larger for Mo and four times larger for Cr; aluminium was almost completely eroded. Redeposition of W originating from other parts of the machine was significant at the outer strike point, thus substantially decreasing the maximum net erosion with typical values of 500-1000 nm determined after earlier campaigns. This is probably due to the more powerful plasma operations in 2010-2011. The influence of surface roughness was investigated with W markers having different initial roughness. With increasing roughness the net erosion decreased. The roughest coatings also showed the largest mixing of elements due to step-by-step erosion of material from plasma-inclined areas and re-deposition in valleys shadowed from direct plasma contact.
X-ray fluorescence was used to determine the 2-dimensional erosion pattern on complete outer strike point tiles with a lateral resolution of 2 mm × 2 mm, special areas of interest were scanned with a lateral resolution of 0.1 mm × 0.1 mm. The results were compared to results obtained by Rutherford backscattering and showed good agreement.

Results on Material Migration and Hydrogen Retention Modelled using the WallDYN Code

The use of three different materials in ITER will give rise to the formation of mixed materials. Details of their formation depend both on the plasma transport and the local evolution of the surface composition. Therefore the modelling of mixed-material formation requires an integrated approach that tightly links plasma transport with surface evolution. To that end the WallDYN code has been developed in 2010. Since the initial version the model has been greatly improved, in particular, all calculations are now performed in a charge resolved manner. Using the improved WallDYN code the deposition of Be, C and W with the current ITER-first-wall material mix was calculated using B2/E background plasma solutions for ITER standard discharges. Two different plasma extrapolation methods with and without radial attenuation were compared. The main difference is that without plasma attenuation the deposition of Be, originating from Be erosion at the main wall, results in mitigation of C erosion in the divertor. As a consequence, this also greatly reduces co-deposition of D/T with C. In contrast, strong attenuation of the plasma leads to reduced Be erosion and thus to very little C erosion mitigation and a higher level of D/T co-deposition with C. These results show that given the numerous assumptions that have to be made about the fluxes and plasma temperatures at the wall, a reliable prediction about fuel retention in ITER is not possible at this moment.
In addition to the work devoted to fuel retention in ITER there has also been some work done on the extension of the WallDYN surface model. In its current state WallDYN does not have a deposition history making it difficult to model situations were initially layers are formed and are then subsequently re-eroded. To remedy this shortcoming a new surface model based on a diffusion/convection differential equation has been developed. This allows the simultaneous modelling of diffusion, layer growth by deposition and layer recession by erosion.
Also a C++ version of WallDYN has been implemented such that the equations can be solved by the IDA solver, which is part of SUNDIALS ODE solver package. IDA can solve differential algebraic equation systems, which makes it ideally suited for solving the WallDYN equations, which consist of a non linear algebraic equation system for the fluxes and a differential equation system for the surface composition evolution.

Tritium Inventory – Understanding and Control

Release of Deuterium from Beryllium

Thermal release is foreseen as a tritium removal technique for ITER. Present predictions for tritium release from beryllium by thermal treatment are based on results from thermal desorption experiments with thin deuterium containing beryllium co-deposits with a maximum thickness of 100 nm or ion-implanted beryllium where the fuel is stored in an even shallower surface layer. These results are, therefore, only representative for net erosion zones. However, tritium will be dominantly retained by co-deposition in micrometer thick co-deposits. In order to assess the efficiency of the wall baking scenarios foreseen for ITER – namely 510 K (240 °C) for the main wall and 620 K (350 °C) for the divertor – thermal release of D from thick co-deposits was investigated for the two relevant temperatures as a function of the baking time. A large batch of identical samples was prepared in a magnetron sputter device at the PISCES laboratories of the University of California San Diego (UCSD). Tungsten spheres with 2 mm in diameter were used as substrates. Biasing of the substrates produces films with a density of more than 99 % of the beryllium bulk density. 20 % D_2 was admixed to the argon discharge to produce 1 μm thick beryllium films with a D concentration of 3 % as determined by thermal desorption spectroscopy (TDS) and nuclear reaction analysis (NRA). The experimental procedure for the release studies was the following. First the sample temperature was ramped to the desired hold temperature with a linear ramp of 0.3 K/s, kept there for different hold times and then ramped down to room temperature. In all cases the released D flux decays only slowly when the sample is kept at the hold temperature of 510 K and 620 K, respectively, but the release of D stops abruptly when the temperature drops. From these experiments the total amount of D released during the ramp and the hold phase was determined by integrating the mass spectrometry signal over time. For the 510 K case the results are shown in figure 3. Obviously, more D is released if the sample is kept at a constant temperature for longer times. But the release is very slow, following a logarithmic behavior with a time constant of several hours. In a second step, the identical samples were again investigated by TDS after cooling down to 300 K, but this time the temperature was ramped up to 920 K, For this case it is known that all D is released. In the second run, D desorption only started above the hold temperature of the previous experiment. D is therefore not redistributed, but the lower energy states emptied in the preceding run remain empty. However, the onset of desorption is shifted to higher temperatures the longer that film was held at the given hold temperature. Obviously higher bonding states can be depleted to some extent during the holding period. By integrating the mass spectrometry signal over time these measurements reveal the total amount of D still retained in the sample after the first run. This is also shown in figure 3 together with the sum of all three phases: first ramp, hold, and second ramp. These experiments also show that not all D can be released even for the longest hold time of 24 h. After 24 h at 510 K the remaining D fraction is 0.8 at.%. For the 620 K case the general trends are the same. Not all D can be released even after the 24 h hold. In this case the material still contains 0.2 at.% D. These results are especially important when discussing the expected removal efficiency of transient methods like laser flash desorption or tailored discharge ramp down. Clearly higher temperatures must be envisaged for those methods in order to remove similar amounts of D.

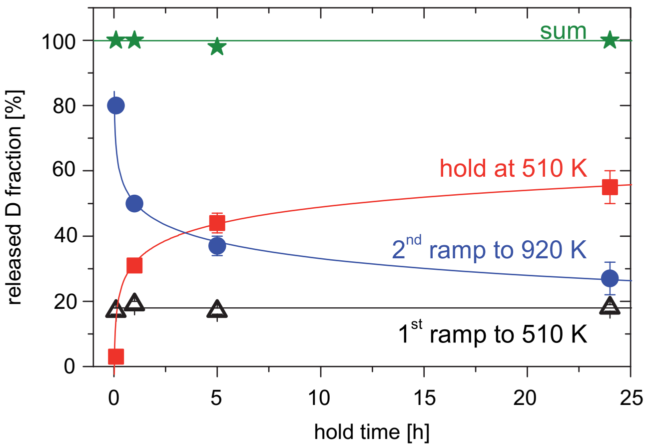

Figure 3: Deuterium released from 1 μm thick beryllium co-deposits at 510 K as a function of the time held at that temperature (red squares) and D that is still retained after the hold and only released in the second ramp to 920 K (blue circles). The black triangles show the release during the first ramp up to 510 K and underline the reproducibility of the experiments. The green stars show the sum of the three individual measurements. The lines are only shown to guide the eye.

Molecular Dynamics Modelling of Hydrogen Diffusion in Tungsten

A detailed understanding of the hydrogen transport and retention properties in plasma-facing materials is crucial for the choice of first-wall materials in fusion reactors: From a safety point of view tritium retention and tritium transport are the most crucial aspects. Due to the low solubility of hydrogen in tungsten the retention of tritium in undamaged tungsten is considered as uncritical. The situation may be different if high-energy neutrons create additional trap sites in the material. However, based on one-dimensional bulk trap-diffusion models for hydrogen propagation it was estimated that the effective tritium diffusion rate is low and that the subsequent (slow) diffusion limited saturation of tungsten is within tolerable limits. Those 1-d models, however, do not take into account the ubiquitous structural anisotropies (in particular grain boundaries) of tungsten, which may alter the permeation properties, thus rendering the basic assumptions of the trap-diffusion models invalid. For many metals the transport properties along such grain boundaries are known to be quite different from the bulk. For that reason a refined model of the hydrogen transport in tungsten has been derived. Based on classical molecular dynamics simulations of hydrogen in tungsten the networks of possible hydrogen migration paths have been elucidated for selected single-crystal and polycrystalline tungsten samples. Based on an exhaustive mapping of first-order saddle points of hydrogen in tungsten and corresponding minimum energy sites the activation energy distributions and the most likely (minimum activation energy) transition paths were derived. Based on the structural information provided by the network structure and the asymmetric transition probability matrix, the effective propagation speed of hydrogen atoms along grain boundaries in polycrystalline tungsten has been computed in the tracer limit employing quantum-corrected transition-state theory. The results emphasize the need to take structural anisotropies into account: the propagation speed of hydrogen in the considered test cases exceeded the values for perfect single-crystalline tungsten by one order of magnitude. The computationally challenging extension of the modeling towards mesoscopic (sub-µm) sized structures is ongoing.

D Inventory and W Enrichment in Mixed C/W Films

Retention and enrichment of a model system for mixed layers, tungsten-containing carbon films (a-C:W), were investigated with respect to the interaction with deuterium ions. The use of a well-defined model system and the exposure to a mass-separated, mono-energetic D beam (200 eV/D, 1.2×10^{15} D $cm^{-2}s^{-1}$) permitted quantitative investigations. The W concentration in the films (0-7.5 at%), the specimen temperature during D beam exposure (300-1300 K) and the fluence (Φ) of incident D (10^{15}-10^{20} D cm^{-2}) were varied. The results are compared with the data for pure carbon films (a-C) and pyrolytic graphite.
The retention of D in a-C is identical to that in pyrolytic graphite: At low fluences 100 % of the not reflected D is retained within the ion implantation zone. At fluences close to 10^{17} D cm^{-2}, the amount of retained D in the implantation zone saturates (saturation level). Above ~10^{17} D cm^{-2} the D inventory increases with fluence according to Φ^x (x=0.1 at 300 K and 0.23 at 900 K). This increase is interpreted to be driven by a diffusive process of D into the depth, which is retarded by bonding processes between D and C. In this context, the binding energy between D and C influences the diffusion of D into the bulk and thus the increase of the D inventory.
At 300 K and fluences below 10^{19} D cm^{-2} the increase of the D inventory with fluence in a-C:W can not be distinguished from that in a-C and pyrolytic graphite. However, above fluences of 10^{19} D cm^{-2} the D inventory depends strongly on the W concentration. At a fluence of 10^{20} D cm^{-2} the D inventory is for 1 and 2.5 % W-doped films 50 % higher than in pyrolytic graphite while it is a factor of 50 % lower in 7.5 % W-doped films. For 7.5 % W in a-C:W the lower D inventory at 10^{20} D cm^{-2} is attributed to enrichment of W at the surface due to preferential erosion of C in a-C:W. Initially, all implanted D is retained as in pure a-C. With increasing fluence C is preferentially eroded and W accumulates until, at steady state, the ion implantation range consist predominantly of W. Since D retention in W is much lower than in C, this leads to a reduction of D retention. It is worth noting that the initially trapped D is released together with the eroded C. At temperatures above 300 K the following overall trends are observed: with increasing temperature the saturation level in the implantation zone decreases, but for fluences above saturation of the implantation zone, the D inventory increases more strongly with fluence than at 300 K and D reaches depths far beyond the ion penetration range.

Erosion of Carbon and Doped Carbons Layers in Oxygen Plasmas

Tungsten-doped amorphous carbon films with 0-9 at.% W concentration were produced by magnetron sputtering and eroded in oxygen plasmas applying different bias voltages and substrate temperatures. The partial C and W erosion rates were determined by Rutherford backscattering spectrometry (RBS). The erosion rate of a-C:W films is clearly lower than the rate of pure amorphous carbon film. The initial C removal rate increases with increasing ion energy and temperature and decreases with increasing W concentration. Addition of only 1.8 at.% W leads to a reduction of the C removal rate at 300 K by almost a factor of 6 compared with a pure carbon film. For W-doped films the erosion rate decreases with increasing plasma exposure duration, i.e., with increasing accumulated fluence. At low bias voltages the erosion process stops after W accumulation at the surface. This W-rich layer protects the carbon underneath from further erosion. The W-rich layer at the surface is carbon free and consists of porous WO_3. Biasing to 200 V leads to removal of W by physical sputtering and, therefore, inhibits the formation of the protecting W oxide layer and the C erosion proceeds. The morphology of the W-rich layer that is formed during erosion at low ion energy depends strongly on the initial W concentration in the films. It is more compact but thinner for films with higher initial tungsten concentration (8 % and higher). For W concentrations of 8 % and higher it blocks the transmission of reactive oxygen species and/or the release of the erosion products and prevents further erosion. Only applying a sufficiently high bias voltage to enable physical sputtering to remove the W oxide layer from the surface allows continuous removal of such films. Our results indicate that for efficient removal of W-containing carbon films with W concentrations higher than about 8 % by oxygen glow discharge cleaning procedures intense ion bombardment of the respective surface is required. This can only be achieved on plasma-facing surfaces. On the other hand, it is presently not assumed that W migrates to remote areas. Therefore, we do not have to assume that re-deposited layers in remote areas will contain high W concentrations. Although the film removal rate is significantly reduced due to W addition, films with low (<8 %) W concentrations can still be removed even without energetic ion bombardment.

Comparison of Hydrogen Retention in W and W/Ta Alloys

The extreme brittleness of tungsten (W) is one of the challenges of using W as first wall material. W/Ta alloys were recently suggested as possible alternative; therefore, the retention of deuterium in W/Ta alloys was investigated. The retention of deuterium (D) due to bombardment with D ions in W samples containing 1 % and 5 % Ta was compared to that in pure W samples under the same implantation conditions: Temperature: 330 K, Flux: 3×10^{19} D/(m^2s) with 200 eV per D, Fluence: 1×10^{23} to 1×10^{24} D/m^2. The retained D was investigated by measuring

the near surface (8 µm) D depth profiles using nuclear reaction analysis (NRA) and the total retained amount of D by TDS. The TDS measurements show that the W/Ta alloys contain significantly (factor 5) more D than pure W. This difference in retention is also visible in the NRA D depth profiles: The W/Ta alloys show flat D depth profiles extending far beyond the accessible 8 µm near surface region while the D depth profiles measured in pure W show a decay within this region. In contrast to previous studies the NRA depth profiles were determined from the raw experimental data by a newly developed sophisticated automated program (NRADC) applying Bayesian statistics. In contrast to the previously used manual fitting method, this procedure produces an unbiased depth profile with statistically sound confidence intervals.
By using a diffusion-trapping model implemented in Mathematica it is possible to explain this difference between pure W and the W/Ta alloys. The model reproduces both the measured near-surface depth profile and the exact shape of the TDS spectra by assuming a different trap site density profile for pure W and W/Ta alloys. The same trap site parameters (number of traps, de-trapping energy and attempt frequency) were used for the W and W/Ta calculations. This means that the difference in retention is due to additional trap sites distributed homogeneously throughout the sample due to the presence of Ta.
Our finding of increased hydrogen retention together with the fact that it was recently shown that the Ta alloying did not improve the brittleness makes W/Ta alloys an unfavourable choice for the first-wall of fusion devices.

Materials and Components

Silicon-free W Alloys as Plasma-facing Material for Fusion Reactors

A potential problem with the use of pure W in a future fusion power plant may occur under certain accident scenarios. A loss-of-coolant accident in a He-cooled reactor could lead to a temperature rise to 1400 K after 30 days due to the nuclear decay heat of the in-vessel components. Additional accidental air ingress into the reactor vessel would lead to the oxidation of tungsten and subsequent evaporation of radioactive WO_3. The use of self-passivating W alloys either as bulk material or as thick coating on the steel wall may be an alternative and passively safe approach for protection of plasma-facing W components. In previous studies the good performance of the system W-Cr-Si was demonstrated. Thin films of such alloys showed a strongly reduced oxidation rate compared to pure tungsten. However, the formation of brittle tungsten silicides may be disadvantageous for the powder metallurgical production of bulk W-Cr-Si alloys if a good workability is needed. Screening tests have been carried out to identify suitable silicon-free alloys with distinguished self-passivation and a potentially good workability. From all tested systems W-Cr-Ti alloys showed the most promising results (see figure 4). The oxidation rate was even lower than that of comparable W-Cr-Si alloys, the reduction factor was about four orders of magnitude compared to pure tungsten. This performance was conserved even if the content of alloying elements was reduced. Since self-passivating tungsten materials are also of interest for applications outside the nuclear fusion community the activities in IPP lead to collaboration with a manufacturer of tungsten parts for the automotive industry in frame of the Bavarian Programme "New Materials".

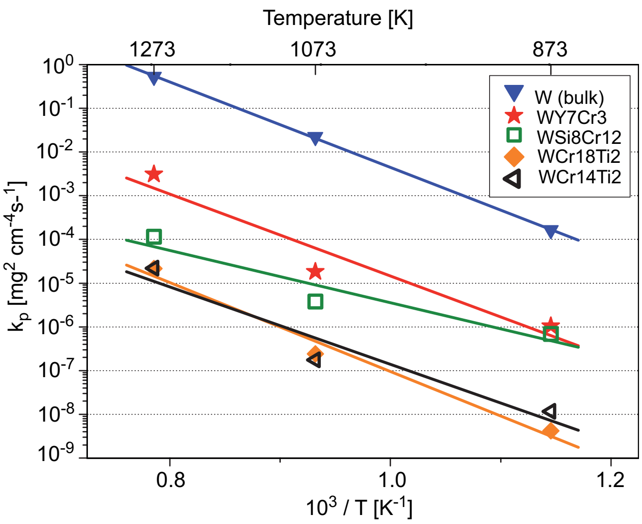

Figure 4: Arrhenius plot of parabolic oxidation rates of pure tungsten and different tungsten-based alloys.

Tungsten Wire-reinforced Tungsten Composites

Development of tungsten wire-reinforced tungsten composites has been one of the major research efforts in IPP in the sector of plasma-facing materials. This composite is a novel tungsten material, which is expected to have a significantly enhanced toughness. The focus of our activity was placed on the demonstration of proof-of-principle for the desired pseudo-toughness caused by energy dissipation via crack deflection and controlled cracking along the engineered fiber/matrix interfaces. A recent achievement with respect to this goal is the in-situ observation of crack deflection and interfacial cracking in miniaturized bending tests by means of micro-tomography in the ESRF X-ray synchrotron radiation facility in Grenoble. The test was carried out using a mono-fiber mini composite with an oxide interface coating. As the applied load increased the primary matrix crack first propagated, was then deflected at the interface, and finally continued to propagate at the opposite side of the fiber while the interface was increasingly debonded (see figure 5). The fracture process progressed in a semi-controlled manner as the fiber bridged the crack planes. The test revealed that a notable amount of energy is absorbed by debonding and frictional sliding. A similar mechanism was also observed in a fully recrystalized composite where the fiber had lost ductility.

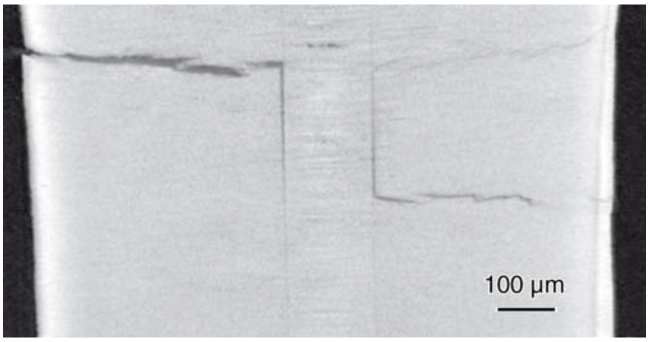

Figure 5: In-situ micro-tomography image of interface debonding and crack bridging in a mono-fiber mini W_f/W composite in the miniaturized bending test.

W/CuCrZr Optimized Graded Interface

Based on the previous campaign focused on single layers with variable W content, the development of a multilayer structure (three layers, W30,50,70 [vol-%]-CuCrZr) with a fully percolating hardened CuCrZr phase, has been successfully achieved. The project was developed in cooperation with the Institut für Werkstoffwissenschaft of the Technical University of Dresden in the frame of a DFG project. The metallurgical challenges were: 1) to obtain a mechanically stable W skeleton with close to 100 % open porosity and 2) to maintain the stability of the precipitation-hardened CuCrZr alloy within the skeleton. This last feature is a milestone of the project and a considerable improvement compared to common Cu infiltration as it allowed to improve the thermo-mechanical strength throughout the interface. In parallel, modeling efforts were continued and focused on the prediction of macroscopic residual and thermal stress fields across the multilayer structure by varying the heights of the layers as an optimizing parameter. Two opposite configuration trends were identified between minimizing the residual stress (due to cooling from aging temperature to room temperature) and minimizing the thermal stresses during operation (steady-state power density of ~10 MW/m^2). As expected, a critical stress peak in the mock-up configuration was predicted between the W tiles and the W70 % layer (>1500 MPa). In the experimentally investigated specimen a 50 µm thick interlayer was observed after infiltration of the W tiles+multilayer system, which may have a beneficial impact on the stress peak reduction and the component fatigue-life extension. Tomographic investigations were performed for W/CuCrZr single layers. Although the measurements are challenging due to the high X-ray absorption of W, it helped to assess the amount of residual porosity and clustering of the W inclusions after manufacturing.

High Heat Flux Test Facility GLADIS

Research at the GLADIS facility is dedicated to the investigation of highly heat and particle loaded materials and components for plasma-facing applications with heat loads similar to the expected operating conditions in current and future fusion experiments. The envisaged long pulse operation of W7-X, ITER or DEMO requires more and more a study of the material degradation at high temperatures and high number cyclic loading. Especially for tungsten materials, the experimental investigation of the surface and bulk morphology modifications occurring during heat loading using H and He particles in a divertor relevant ratio is indispensable.

The main GLADIS contribution to the manufacturing of the W7-X high heat flux divertor (see Wendelstein 7-X, section 4) is the quality assessment of the delivered target elements on the basis of a statistical method. In previous years qualification criteria based on a statistical analysis of the pre-series IV test results were established. As extensive testing of previously qualified elements showed (see annual reports 2009-2010), the statistical analysis of the local surface temperature increase of individual CFC tiles during loading with 100 cycles at 10 MW/m^2 allows the reliable assessment of the bonding quality. Based on the application of a modified Six-Sigma method the effort for quality assurance tests was greatly reduced. As a result, monitoring of the manufacturing quality requires HHF tests of about 10 % of the finally 890 elements covered with about 18,000 CFC tiles.

In support of the divertor III at ASDEX Upgrade, GLADIS tests for exploring the heat load limits of the design were performed to provide data for the development of realistic FE models. Contributions to the JET ITER-like Wall Project are described in the section “JET contribution”.

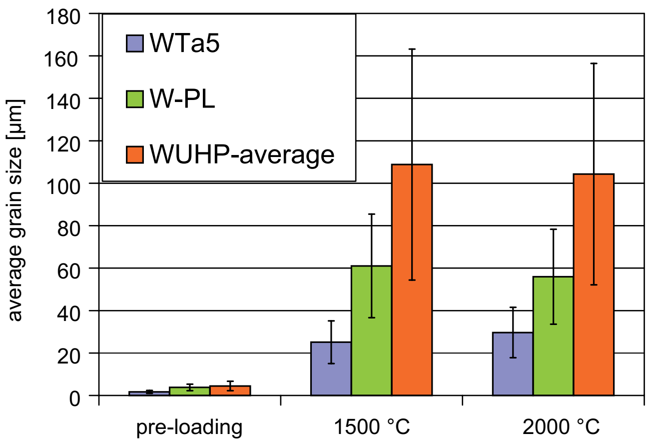

Figure 6: Average grain sizes of the investigated tungsten grades before and after 10 MW/m^2 loading at 1500 and 2000 °C, respectively. WTa5 is a 5 % tantalum doped material, W-PL is a commercially available standard material, and the W-UHP data are an average over different orientations of an ultra-high purity uni-directionally forged material.

Research on tungsten as a divertor material was focused on the investigation of actively cooled European tungsten grades in the frame of the EFDA Topical Group Materials. Long pulse loading with 90 % hydrogen and 10 % helium particles, which simulates the expected divertor operation conditions was performed on materials provided by KIT. The effects seen, erosion, gas retention and cavity formation, depend on both the loading conditions and the operating temperature. The processes of recrystallization and grain growth influence the thermo-mechanical performance of tungsten as plasma-facing material. A comparative study in the temperature range between 1500 and 2000 °C was performed at 10 MW/m^2 and a total loading time of 3000 s. In all cases substantial grain growth was observed after this relatively short time. As figure 6 shows, doping with tantalum leads to the smallest grain growth compared to standard and ultra high purity material. Depending on the temperature, strong structuring of the near-surface region is caused by the 10 % He fraction of the beam. The complex interaction of the competing processes of helium diffusion with subsequent cavity formation and grain growth requires further experiments for developing an understanding. Figure 7 shows a Focussed Ion Beam cross-section of He induced cavity formation in tungsten at 2000 °C.

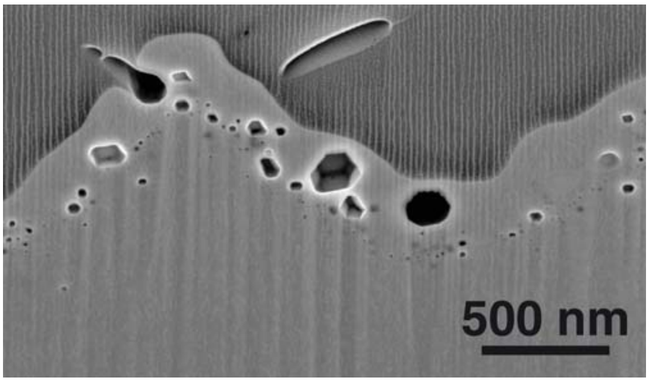

Figure 7: Focussed Ion Beam cross-section of the W-PL sample after loading with 90 % H / 10 % He beam at 2000 °C. The ensemble of cavities are formed below the surface within a depth of about 200-500 nm. The corresponding implantation depth of He atoms is about 70 nm and 40-110 nm for the H fraction of the beam. The dark grey top part is a protection layer from the preparation process.

Integration of and Collaboration in EU Programs

EU Task Force on Plasma-Wall Interaction

As in previous years, in 2011 the contribution of the project PFMC to the EU PWI Task Force has been very intense: The Task Force leader and the expert group leaders for "Fuel Retention" and "ITER-relevant mixed materials" are members of the project at IPP. In addition to leadership activities, PWI research within the PFMC programme is largely related to ITER through numerous priority tasks grated by the EU PWI Task Force, thus enhancing further the intense international collaboration with European associations. Especially the contribution to the on-going ITER-like Wall experiment at JET has started with one Task Force and several topics lead by IPP experts. In 2011, contributions of the project to the EU PWI Task Force have amounted to 6.4 ppy Priority Support and 24 ppy Baseline Support with main emphasis on fuel retention in plasma-facing materials and on material migration in fusion devices.

Further contributions have been made to the EU Topical Group "Materials" on W materials development and high heat flux investigations. Within the EFDA Fusion Programme the project provides two mid-size facilities: The High-Heat-Flux Test Facility GLADIS and the Integrated PWI Facility.

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

The FP7 EU Coordination Action "Fusion Energy Materials Science" (coordinated by IPP) aimed at integrating large-scale facilities and university groups not yet active in the fusion materials field by stimulating, organizing and financing collaborative activities, training courses, workshops and conferences. With the completion of the project in 2011, these goals have been reached through the FEMaS-CA initiatives. During the execution of the project, around 120 cooperative activities have been carried out, each of them on average involving several scientists and mutual visits. In particular, the European large-scale facilities providing synchrotron, ion or neutron beams, are now deeply integrated into fusion materials science activities, which has not been the case before FEMaS-CA. The cooperative activities started within FEMaS-CA received strong recognition also within the fusion community, which was in particular visible through contributions at the "International Conference on Fusion Energy Materials Science", jointly organized by FEMaS-CA and the "International Workshop on Plasma-Facing Materials and Components", a well-established meeting within the fusion materials community. By integrating the FEMaS-CA activities and partners into the European EFDA structures, it is guaranteed that the FEMaS-CA-specific activities will be continued on a long-term scale.

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Helmholtz-Russia Joint Research Group “Hydrogen Behaviour in Advanced and Radiation-damaged Materials”

Heads: Dr. Matej Mayer (IPP), Dr. Alexander Spitsyn (Kurchatov Institute)

This joint research group comprises scientists from the IPP, from the Kurchatov Institute, from the Troitsk Institute for Innovation and Fusion Research (TRINITI), and from the National Research Nuclear University “MEPhI”, all three located in Moscow region, RU. The research group is funded by the Helmholtz Association and by the Russian Foundation for Basic Research.

Annealing of Defects in Tungsten

Heavy ion irradiation of tungsten by energetic tungsten ions is used as a proxy for material damage created by fast neutrons. The samples were either implanted by 20 MeV W ions, or 4 different energies were used in order to obtain a relatively flat damage profile, which is typical for damage created by neutrons. The maximum damage was 0.89 dpa. Deuterium is trapped by the created defects. From deuterium depth profile measurements no significant difference between the mono-energetic W implantation and the flat-damage implantation was observed. Post-annealing of the damaged samples at temperatures between 700 and 800 K reduced the retained amount of D by a factor of 2, annealing at temperatures above 1000 K turned the samples back to the state before self-implantation with no significant difference to non-damaged samples. This can be interpreted as annealing of damage created by the W ions.

Hydrogen Retention in Damaged Tungsten Exposed to Pure and Seeded Deuterium Plasmas

Different W grades were pre-damaged by W-ions implantation in order to simulate neutron damage and subsequently exposed to deuterium plasmas at temperatures from 300 to 650 K. Pre-damaging of W results in D accumulation in radiation damage, thus increasing the D inventory. The D retention in damaged W does not depend on the W grade and correlates with the calculated damage level. The D retention decreases with increasing exposure temperature. Seeding of helium into deuterium plasmas reduces the deuterium retention, while seeding of nitrogen increases deuterium retention for all tungsten grades. The He effect was more pronounced with irradiation temperature. The nitrogen effect was more pronounced with irradiation fluence.

Deuterium Retention in TiC Doped Tungsten

Tungsten is a perspective plasma facing material. However, its main problems are the poor mechanical properties. The addition of doping materials may solve this problem, but can influence deuterium retention. Retention in 1.1 wt% TiC doped tungsten, produced at Tohoku University, Japan, was investigated. Samples were irradiated by 200 eV D ions at room temperature and 200 °C at fluences up to 10^{24} D/m^2. While the total amounts of trapped D are comparable to pure tungsten, depth profiles and thermal desorption spectra show significant differences.

Deuterium Permeation through Tungsten Coated with a Carbon Film

A new model of deuterium transport through carbon-coated tungsten was developed. The microstructure of the carbon film (pores and cracks) plays an important role. Four types of pores or cracks are taken into account: I - through-the-film, II - embedded in the film, III - open to gas, and IV - open to the carbon/tungsten interface. The first one can result in gas driven permeation (GDP) due to transport of molecular gas to the C/W interface. These cracks can also result in a new effect, which can be named “ion driven GDP”, and which is connected with saturation of the ion range, release of the molecules into through-the-film channels and their subsequent permeation as in GDP. The second and third types lead to retardation of the permeation process, the fourth one can result in an effect similar to the effect of “ion driven GDP” as in the case of through-the-film channels. Ion driven GDP through pores of type IV can yield the major contribution to permeation. Numerical calculations based on this model gave a good agreement with experimental results obtained at the PERMEX device.

Deuterium Retention in and Permeation through Low-activation Steels

Deuterium retention in the two low-activation materials RUSFER ferritic steel and V-4Cr-4Ti alloy produced by Bochvar Institute, Moscow, was investigated after plasma irradiation with 300 V bias. Retention was measured by means of TDS and NRA. The V alloy traps very large amounts of deuterium in a broad range of conditions, the trapped amount is 3 to 5 orders of magnitude higher than in RUSFER steel. Gas-driven deuterium permeation through a RUSFER tube was investigated in the temperature and pressure range of 300 to 600 °C at 10^{-4} to 1 mbar. The permeation flux increases with temperature and is three orders of magnitude higher at 600 °C than at 300 °C. The permeation flux depends on pressure at the inlet surface as $\propto p^{0.8}$. This means that the permeation regime is intermediate between diffusion-limited and surface-limited. The conditions at the gas-loaded surface significantly influence the permeating flux.

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Plasma Theory

Theoretical Plasma Physics

Heads: Prof. Dr. Per Helander, Prof. Dr. Karl Lackner

The project "Theoretical Plasma Physics" is devoted to first-principle based model development for toroidal plasma confinement and combines the efforts of the divisions Tokamak Physics and Stellarator Theory, of two independent Junior Research Groups, and of the HLST Core Team of the EFDA HPC Initiative. We maintain also strong links with other fields of plasma science, in particular as a major partner in the new Max Planck Princeton Research Centre.

Tokamak Physics Division

Head: Prof. Dr. Karl Lackner

Tokamak Edge Physics Group

A new kinetic code KIPP (KInetic code for Plasma Periphery) was developed and tests of 0d2v features were carried out. The code showed good consistency with classical collisional expressions for parallel plasma conductivity, ion-electron energy equipartition rates and equilibration rates between parallel and perpendicular temperatures. High precision of the code calculations allowed one to establish certain deviations from the classical expressions, due to the (not fully justified) assumptions of Maxwellian distributions of plasma species in velocity space made in analytical theories. The results were presented at the 13th Plasma Edge Theory workshop (paper O-13).

Work continued in supporting and developing the SOLPS package. The code is in wide use around the world and supporting such a package represents a non-trivial resource commitment. To support detachment modelling and PWI/material migration studies, a development project was started in collaboration with CNRS LSPM (Paris) to enable the SOLPS5.0 code to compute plasma backgrounds covering the whole vessel, including the far scrape-off layer (SOL). As a first step the CARRE grid generation code was extended to create suitable cut-cell type grids. Current work focuses on the required extensions to the B2.5 plasma fluid code. Development of the numerics of the adaptive SOL fluid code B2.6 is ongoing, focusing on detailed verification of the code against existing versions.

The unexpected departure of one of the members of the group left a hole in the areas he had covered (edge MHD stability, ITM equilibrium and stability, GOTiT Course Coordinator). Significant time of members of the group went into the EFDA Task Force on Integrated Tokamak Modelling, reported separately. A PhD project has been started in the area of edge turbulence modelling. The main focus of the thesis is on resolving the geometrical problems to enable efficient 3d simulations in a domain extending from the plasma edge across the separatrix into the scrape-off layer.

MHD Theory Group

Linear Stability in the Presence of 3D Wall Structures

Resistive walls close to the plasma boundary reduce the growth rates of ideal external kink modes by about three orders of magnitude. Since these Resistive Wall Modes (RWMs) grow slowly, their feedback stabilization is technically feasible. While tokamak plasmas are approximately axisymmetric, external walls with a complex three-dimensional shape, and feedback coils break that symmetry. The 3D STARWALL/OPTIM code computes growth rates of RWMs and designs robust feedback controllers for their stabilization in the presence of 3D multiply-connected wall structures taking into account coupled toroidal harmonics. However, STARWALL/OPTIM is limited to ideal, non-rotating plasma configurations, while realistic tokamak plasmas are resistive and viscous, and may rotate in toroidal direction. Therefore, STARWALL has been merged with the code CASTOR_3DW. The combination of the linearized resistive MHD equations (CASTOR_3DW) and the set of equations derived from a vacuum energy functional (STARWALL) leads to an extended eigenvalue problem, where both sets of equations are coupled by the boundary terms. In order to solve this extended eigenvalue problem, it has been necessary to adapt the STARWALL routines and to implement them into CASTOR_3DW. Furthermore, using SLEPc, the Scalable Library for Eigenvalue Problem Computations, a fast parallelized eigenvalue solver for large sparse eigenvalue problems is currently implemented. First results have already been obtained for a simple test case.

Non-linear MHD

Non-linear numerical simulations of the early phase of edge localized modes (ELMs) have been carried out with the reduced-MHD code JOREK based on a typical ASDEX Upgrade H-mode equilibrium. In contrast to most JOREK-simulations found in the literature, the focus was put on high toroidal resolution to examine the coupling between toroidal modes. Analysis of the ballooning-type instabilities observed in the simulations with diagnostic tools that have been improved further reveals that dominant toroidal mode numbers, poloidal filament sizes, and radial filament propagation velocities are in good agreement with experimental observations for type-I ELMs in ASDEX Upgrade. The perturbations of magnetic and kinetic quantities exhibit a strong toroidal and poloidal localization, which seems to be related to solitary magnetic perturbations (SMPs) discovered experimentally in ASDEX Upgrade very recently. Simulations of full ELM crashes are in preparation, which will allow us to do more involved qualitative and quantitative comparisons and benchmarks with experimental findings and thereby provide a basis for future predictive simulations. Also, the basic reduced MHD (RMHD) model of JOREK has been extended to cover the effects of differential toroidal rotation.

Apart from simple toroidal advection, the model includes the generation of poloidal vorticity by differential rotation profiles. Although more rotation effects are included in the theoretical formulation of the extended RMHD model, they turn out to be negligible for realistic Alfvén Mach numbers <<1. This is part of an effort to improve the realism of JOREK simulations based on ASDEX Upgrade data.
Neoclassical tearing modes observed in experiments often grow from seed magnetic islands induced by triggers like sawteeth. The formation of seed islands is studied using both the reduced MHD and two-fluid equations, with the trigger being modelled by externally applied resonant magnetic perturbations. The results are: (1) In the linear phase a slowly growing trigger drives a tearing mode, while a fast one drives an ideal kink mode. The kink mode becomes a tearing mode later when the trigger's growth slows down. (2) Comparing with the results obtained from reduced MHD equations, finite ion sound Larmor radius (ion Larmor radius by using electron temperature) extends the tearing mode regime to a wider range of plasma parameters and leads to larger seed islands in the nonlinear phase. Electron inertia effect also increases the seed island width for a given external perturbation. (3) Plasma rotation or electron diamagnetic drift, when increasing the relative rotation frequency between the trigger and the driven mode, decrease the seed island width as expected. (4) For typical ASDEX Upgrade parameters and a frequency difference 8 kHz between the trigger and the driven mode, the size of a m/n=2/1 seed island caused by an ELM is about 0.007 a (0.35 cm), being much smaller than the poloidal ion gyroradius, where a is the plasma minor radius, and m and n are the poloidal and toroidal mode numbers, respectively. (5) For a fusion reactor like ITER, if one neglects the frequency difference between the trigger and the driven mode and assumes that $b_{ra}/B_t=2\times10^{-4}$ lasts for 2 ms, the m/n=2/1 seed island caused by an ELM has a width of about 0.003 a, which is again much smaller than the poloidal ion gyroradius. Here, b_{ra} is the radial magnetic field perturbation of the m/n=2/1 component at the plasma edge caused by the trigger, and B_t is the toroidal field.
To study the effect of a two-fluid plasma model onto reconnection and magnetic field perturbation in full toroidal geometry we use the XTOR code. Field line reconnection has been studied at hand of the m=1 internal mode. Present emphasis is on the penetration of externally applied perturbation fields into a plasma, for boundary shapes, coil currents and plasma profiles approaching the realistic ASDEX Upgrade conditions.

Kinetic MHD and Fast Particle Physics

In order to model the properties of NBI-driven Alfvénic modes at ASDEX Upgrade, the linear gyrokinetic code LIGKA has been extended to include anisotropic distribution functions for the beam ions based on TRANSP simulations. With this extension the drive mechanism of recently reported beta-induced Alfvén Eigenmodes was investigated: it could be shown that the anisotropy increases the linear mode drive compared to an isotropic slowing down distribution function and changes the mode structure, in agreement with experimental trends. By detailed comparison of code results and Electron-Cyclotron-Emission-Imaging data both beta-induced Alfvén Eigenmodes and reversed-shear Alfvén Eigenmodes could be identified. The splitting of the radial harmonics of the RSAEs can be used to determine the curvature of the safety factor profile at its minimum, q_{min}, and also for estimating the on-axis value of q (see figure 1).

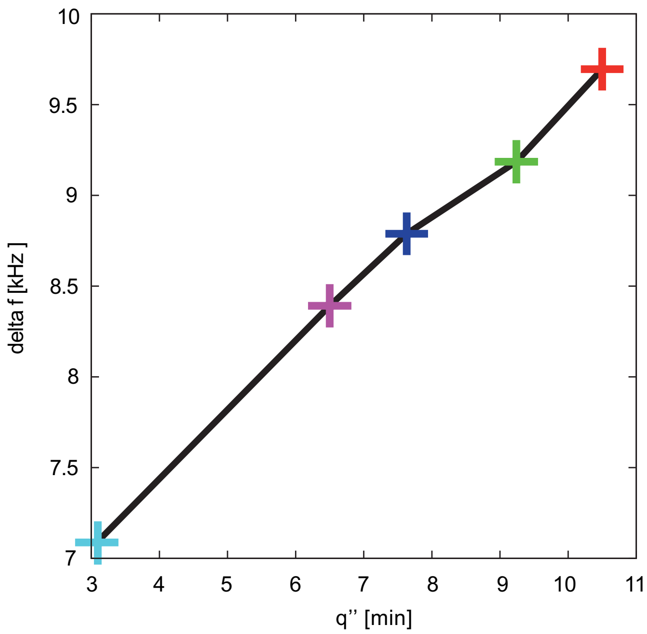

Figure 1: Frequency separation of two RSAE modes with different radial mode numbers as a function of the curvature of the safety factor q at $q=q_{min}$. Comparing this splitting with the experiment allows to estimate the on-axis value of q.

A non-linear analysis of energetic particle transport in the presence of single and multiple Alfvénic modes has been carried out for a series of equilibria with reversed and flat q-profiles using the code HAGIS. It has been found that there is a complex coupling mechanism between different global Alfvénic modes due to both the radial overlap of these modes and due to double resonant particles, i.e. particles that are radially trapped between two modes. Their interplay influences the linear growth rates as well as the non-linear phase. The resulting particle losses were classified in prompt losses, resonant losses and losses due to phase space stochasticity. Comparisons with the experimental FILD (fast-ion loss detector) data are ongoing.

Transport Analysis Group

In the field of toroidal momentum transport, theoretical research has been dedicated to the impact of electromagnetic effects on the turbulent viscosity and the turbulent convection of momentum, with both analytical and numerical gyrokinetic calculations. Finite β impacts toroidal momentum transport mainly by affecting the parallel mode structure and the parallel wave number. The averaged parallel wave number increases in size with increasing β and by this reduces in size the so-called Coriolis momentum pinch. The effect is usually rather weak at low β, but can become significant close to the threshold of kinetic ballooning modes, where the ratio of the Coriolis pinch to the viscosity is strongly reduced. In addition, an extensive analysis has been performed on a database of observations of intrinsic toroidal rotation in AUG, which lead to the identification of a correlation between the radial gradient of the core intrinsic rotation and the logarithmic gradient of the core electron density over a large parameter range, encompassing both L- and H-mode confinement regimes. A theoretical explanation is presently sought, inspired by the result that the observed correlation with the logarithmic density gradient can be recovered in linear gyrokinetic simulations of a large set of observations by assuming a constant tilting angle of the turbulent eddies.

In the field of impurity transport, an effort has been dedicated to the study of the impact of centrifugal effects. The gyrokinetic formalism has been extended to include the impact of the centrifugal force, in the presence of a radial gradient of the background toroidal rotation, which enables consistent two dimensional reconstructions of the impurity density over the poloidal cross section. Centrifugal effects on turbulent impurity transport have been investigated for parameters obtained in previous Ni transport experiments at JET, and have been found to be large. However, their inclusion did not allow the experimental observations to be explained by the theoretical predictions to a level that enables a conclusive identification of their impact in the experimentally observed Ni transport. Further comparisons with the experiment, taking into account more correctly the poloidal asymmetries of the predicted impurity density distribution are planned in the near future.

Finally, more complete investigations of the transport during current ramps have been performed thanks to the additional measurements of both the ion temperature and the toroidal rotation obtained in the last AUG experimental campaign. This study, based on the analysis of both current scans and current ramps with and without ECH, has revealed that the TGLF model is a better predictor than the GLF23 model in the core, but, like the latter, underestimates transport in the outer region of the plasma column. A semi-empirical recipe, based on a critical dimensionless parameter for edge turbulence, has been identified, which allows the missing transport in the outer region to be satisfactorily modelled. The theoretical foundations of this additional transport component are presently sought in nonlinear simulations with edge turbulence codes.

Kinetic Theory and Wave Physics Group

The Beam-Tracing method has been applied to the analysis of the low-field-side reflectometer for ITER. The TORBEAM code for EC waves has been augmented with relativistic corrections to the electron mass and with a beam-antenna coupling model. The received power is affected by the intensity of the beam, by its offset with respect to the receiver and by the angle of incidence. For bistatic operation it is found that the receive antenna should be tilted to match the phase front of the reflected beam. A poloidal or toroidal tilted bistatic antenna pair appears to offer a robust (and cheap) solution for a reflectometer intending to diagnose the SOL/edge density profile. The problem of beam displacement at large plasma height variations might be solved with a limited number of additional antennas. On the ion cyclotron side, a new algorithm has been implemented in the code SSFPQL to evaluate the recursive relations for the integrals involving triple products of Legendre polynomials, which appear in the coefficients of the quasilinear operator. The new algorithm avoids the accumulation of roundoff errors typical of recursive algorithms. This has been achieved using integer-arithmetic routines of the multi-precision GMP library. This new development opens the possibility of taking into account the effects of toroidal trapping on IC heating in SSFPQL within a zero-banana-width approximation. The numerical algorithm for the evaluation of the Monte Carlo ICRF quasilinear operator has been completed. For this purpose, the Stokes formulation for the divergence of a vector field on an unstructured mesh has been implemented. An international benchmark activity of ICRF codes coordinated by R. Budny (PPPL) has been concluded in 2011. The TORIC code has been compared with other full-wave solvers on different IC heating scenarios. The integration of both TORBEAM and TORIC within the Integrated Tokamak Modelling platform has been advanced during the year.

In the H-mode pedestal, the density and temperature gradient lengths are of the order of the poloidal gyro-radius and a localized strong electric field is present. Neoclassical physics under such conditions has been studied with guiding-centre particle simulations with the code HAGIS. We find that the effect of the orbit squeezing by the gradient of the electric field on the plasma flow and on the bootstrap current is reduced with respect to the often-used large aspect ratio theory. Here, the localization of the strong electric field and the effect of a realistic aspect ratio are important. An analytic calculation for the orbit squeezing at arbitrary aspect ratio taking into account also the second derivative of the electric field can explain this result.

Owing to the steep pressure profile, the poloidal variation of the parallel neoclassical current is very large. The poloidal velocity also differs from the result of neoclassical theory, as a consequence of the change in the parallel velocity, since the cross-field particle drifts are not changed.
The electrostatic potential related to a magnetic island with imposed width and rotation frequency has been investigated by means of gyrokinetic simulations, which allow its self-consistent determination via the Poisson equation. An adiabatic response of the trapped ions at the island separatrix leads to a significant smoothing of the potential with respect to analytic calculations based on the assumption of complete pressure flattening inside the island. As a result, the magnitude of the classical polarization current is found to be overestimated by the analytic calculation. The neoclassical polarization current is not even visible when the self-consistent electrostatic potential is considered, at least for realistic values of the island rotation frequency. Thus, it is very likely that other contributions play a more significant role in determining the stability of small islands.

Turbulence Theory Group

Gyrokinetic Studies

Work with global gyrokinetic computation with the ORB particle in cell model continued on two fronts in 2011. Global electromagnetic computation of turbulence to full saturation, first demonstrated at the 2009 ICNSP, was advanced by implementation of a new control variate iteration scheme to solve Ampere's law for the magnetic potential. The theory was presented by Roman Hatzky at the 2011 EFTC and the computations by Bottino at the 2011 EPS Fusion Conference. This enabled converged global nonlinear simulations for M_i/m_e=1000 for higher beta values than before, into the MHD regime (the electron dynamical beta, $\mu_0 p_e/B^2$, was 0.008). The collisional dissipation model was improved by introduction of a coarse-graining algorithm in phase space, based on a treatment by Chen and Parker (2003). The convergence of the spectrum with the size of the coarse-graining grid was verified in both electromagnetic collisionless and electrostatic collisional simulations.
The second front concerns the physics of collisional effects on ion temperature gradient (ITG) turbulence, in collaboration with Thibaut Vernay of CRPP/EPFL Lausanne. The starting point was a neoclassical equilibrium. A general increase in ion heat transport due to collisions was observed, in agreement with previous studies within the adiabatic-electron model. The Lorentz approximation for self-collisions was tested against the linearized Landau self-collision operator in ORB. While a physically accurate self-collision operator is required in order to predict correctly the neoclassical transport, the Lorentz approximation captures the essential features of the turbulent collisional transport in ITG regimes. However, the wrong predictions given by the Lorentz approximation for the neoclassical transport due to ion-ion collisions lead to a slight lack of accuracy in estimating the total transport.
The previous annual report contained information on the gyrokinetic theory relevant to tokamak transport computation and the ongoing work on the fully nonlinear, total-f electromagnetic code FEFI. In December FEFI began producing edge simulation cases with turbulence run to saturation. In this context fully nonlinear means that the full distribution function is the dependent variable and that there is no role for a background Maxwellian anywhere in the problem except for the initial state. It is possible to run these computations to transport equilibrium with sources (or as decaying cases without one) because the confinement time of the edge layer by itself is short enough to be covered by a computational run covering a few milliseconds. The state of progress up to September was reported at the 2011 ICNSP, and while the effort is still preliminary it is expected to come to fruition in 2012.

Gyrofluid Studies

Gyrofluid turbulence simulations were done using both the standard field aligned geometry (GEMR code, using poloidal as parallel, with the option to truncate the flux surface) and global conformal geometry (GEMZ code, using toroidal as parallel and keeping conformal grid cells). The two codes were benchmarked using edge plasma parameters on a magnetic equilibrium taken from an experimental ASDEX Upgrade case calculated with the HELENA Grad-Shafranov solver. The resolution tests showed that, near the separatrix, the GEMZ simulations converged to the same qualitative solution. The same was not true for the GEMR simulations due to the grid deformation inherent to its coordinates close to the X-point. This confirms our previous experience on the failure of high-resolution fluxtube simulations on shaped, separatrix tokamak geometry to converge in the vicinity of the separatrix.
Synthetic diagnostics were developed using the GEMR code in conventional simplified tokamak geometry. A reflectometry study was done in collaboration with F. Da Silva of IPFN/IST Lisboa. The REFMUL reflectometry diagnostic was run on plasma turbulence calculated with GEMR to produce temporal spectra and histograms of the synthetic reflectometry signals, and the electron density amplitude and radial position of the turbulence. Their differences allowed for an assessment of the diagnostic capabilities to characterise edge turbulence. In collaboration with B. Nold from the University of Stuttgart, plasma turbulence was investigated with Langmuir probes in the near SOL of the tokamak ASDEX Upgrade and in GEMR simulations. Qualitative agreement was found for density, potential and temperature fluctuations between simulation, self-emissive

probe measurements and conditionally sampled I-V characteristics. Plasma density fluctuations were found to be well reproduced by ion-saturation current measurements. Floating potential fluctuations, in contrary, showed to be strongly affected by electron temperature fluctuations, therefore providing no direct information on plasma potential fluctuations. This questions the common practice to neglect temperature effects on probe measurements between nearby probes close to the separatrix of tokamaks.

An effort was initiated to study the effect resonant magnetic perturbations (RMPs) on the ELMs, in collaboration with A. Kendl of the University of Innsbruck as a followup to our work on (Edge Localised Mode) ELM scenario simulations. The work focused on the implementation of the RMPs in GEMR. A first model consistent with the global geometry was developed and is on a testing phase. In the meantime a study of the magnetic structures found in the ELM scenario simulations has been done by the Innsbruck group.

The fluxtube gyrofluid GEM model was used to study the nonlinear dynamics of collisionless magnetic reconnection. Here, electron inertia rather than resistive friction of electrons against ions controls the breakage of magnetic flux conservation, leading to higher growth rates. Strong acceleration of growth has been found at the onset to nonlinearity, while at all times the energy functional was well conserved. Explosive reconnection, defined by nonlinear growth rates more than one order of magnitude higher than linear growth rates, was found in the relevant regime of scale separation (collisionless skin depth small compared to the width of the current layer). The behaviour of the nonlinear growth rate curve, measured in terms of the logarithmic rate of change of the perturbed energy with respect to time, was similar to the one found by similar studies of the nonlinear kink instability by H. Naitou. It is a counterexample to our previous studies of pressure-driven MHD turbulence in tokamak edge plasmas (the ELM studies referred to above). The indication is that nonlinear acceleration is a feature of current-driven dynamics, in contrast to the lack of such observations in cases driven by the pressure gradient.

Following the experiences gleaned from Integrated Tokamak Modelling (ITM) workflows, an instance of GEM with eight fluxtubes, each placed at different minor-radius locations with a 3 cm separation, was run to search for edge-to-core transition effects, which might be explained simply by the radial dependence of normalised parameters. Here, edge means that the square of the parallel/perpendicular scale ratio is large enough to compensate the small mass ratio to make thermal parallel responses nonadiabatic, while core means that mass ratio effects are small. In addition, the common paradigm for core transport is of weak turbulence near threshold, while the edge is strongly hydrodynamic. Each fluxtube has its (ion and electron) temperature gradient parameters adjusted to produce a prescribed flux level (power transported across the flux surface). This indicates an adjustment of the temperature profiles to transport equilibrium. For this study the density profile was fixed, with particle transport not treated. The input profiles are from transport analysis of experiment (from the ASTRA code), to which the final equilibrated GEM profiles are compared. Current-ramp scenarios were studied. In ITG-dominated regimes the agreement can be quite close, while electron regimes show a level of discrepancy explainable by trapped-electron effects. In either case, the range of normalised radii between about 0.65 and 0.9 is neither deep-core nor edge, the turbulence is far from threshold (equilibrated R/L_T values are much larger than 10), and a significant long-wavelength MHD component is involved in controlling saturation (this does not correspond to instabilities, but is a set of dissipative transients). In other words, moving from core to edge the edge effects turn on gradually, until in the last few cm, usually the outermost flux tube, the fully developed edge turbulence with little relation to linear drive scaling is found. It is planned to try this with the nonlinear gyrokinetic model delta-FEFI on the IFERC platform in the future, as due to the long wavelengths and high degree of MHD nonlinearity as well as the long run length (at least 4000 in normalised gyro-Bohm times are needed), well resolved cases are too expensive even for HPC-FF.

Model for Spontaneous Rotation in the Tokamak Edge

An analytical model of differential transport of kinetic ion orbits by background drift-wave turbulence was proposed. This addresses the concepts of residual stress and intrinsic rotation, which are active topics in the transport community. In the absence of dissipation charged particle orbits describe closed curves when projected onto the poloidal plane (motion in 4-D phase space constrained by three conserved quantities: energy, magnetic moment, and canonical toroidal momentum). Particles moving in the co-current direction are outside of their reference flux surface, while those moving counter-current are inside of it (represented in the model by major-radius shifts of the orbits). Collisions act on these features to produce neoclassical transport effects. In this work, collisions are neglected and the ions are treated in a passive-advection model of spatially inhomogeneous turbulent diffusion. Differential transport refers to the effects of the result that diffusivities calculated for co- and counter-current passing ions are different. Turbulence decreasing in absolute amplitude across the separatrix into the scrape-off layer will preferentially diffuse the particles moving counter-current, leading to a net rotation in the co-current direction (see figure 2). The mathematical model once proposed can be solved asymptotically with no further orderings or approximations, and then the solutions are joined smoothly across all values of the control parameter.

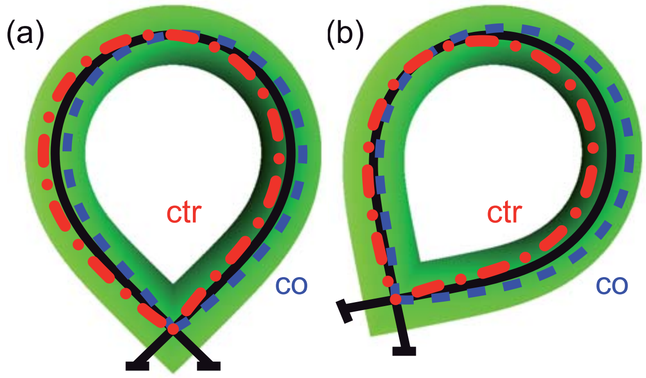

Figure 2: Drift orbits for co- and counter-current passing ions for straight-down (a) and inboard (b) X-points, sketched over shading indicating turbulent diffusivity (dark is strong). The orbit-averaged diffusivity is weaker for co-current than for counter-current ions.

The model produces residual stress and intrinsic rotation at experimentally relevant levels, also capturing the experimentally observed dependences of H-mode pedestal-top rotation on ion temperature and plasma current. Due to the sensitivity of the near-separatrix orbits to geometric effects, the model predicts a strong dependence of the intrinsic rotation on the poloidal angle of the X-point. In particular, spontaneous co-current rotation should be enhanced if the X-point cut is rotated poloidally towards the symmetry axis. Experimental tests of the idea are being proposed.

Mathematical Theory

Work started in 2010 on structure preserving discretisation schemes for kinetic and gyrokinetic equations has led to first results. One focus of this research was the application of discrete variational integrators to the Vlasov-Poisson system. The usual procedure of discretisation for a physical system possessing a Lagrangian is to derive Euler-Lagrange equations of motion via a variational principle and then to discretise them. With the method of variational integrators, the Lagrangian itself is discretised and then the resulting equations are at once the discrete system to be solved. In general it is an attempt to extend the methods behind symplectic integration for particles to a system of fields, ideally with time and space coordinates treated on an equal footing. In principle one preserves symmetries and thus the resulting constants of motion of the continuous system. In practice the errors are finite but bounded (oscillatory).

We have found that the familiar action principles for the Vlasov-Poisson and Vlasov-Maxwell systems are not suitable for application of the variational integrator method, since they either use parameterisations with pathological properties in phase space or rely on non-holonomic constraints, which are not part of the original theory. However, we have applied the phase-space part of this approach to the discretisation of the Poisson bracket in Vlasov-Poisson system, with the benefit that the variational integrator formalism leads to the well known and widely used Arakawa scheme for brackets. The generality of the formalism has enabled derivation of similar schemes on different grids (Cartesian, triangular, and combinations thereof) as well as brackets in more than two dimensions (Nambu brackets). In principle generalisations to higher order as well as unstructured grids are also possible. The full potential of this approach is still to be explored. Several of these schemes are being tested in our existing codes.

We have explored the discretisation of the noncanonical Hamiltonian description. We found that the Lie-Poisson bracket, describing the dynamics of the Vlasov-Poisson system, is equivalent to a Nambu field bracket (similar to R. Salmon's 2005 demonstration for incompressible fluids). The antisymmetry property of this bracket can be used in the course of discretisation to derive well-behaved numerical schemes. Again, the Arakawa scheme is produced in one of the cases. Finally, we are exploring applicability of the Euler-Poincare formulation of the Vlasov action principle for use as a variational integrator. Although more complicated than the alternatives, it is the most natural geometric formulation of the Vlasov-Poisson system. Work has been started on the discretisation of this action principle as well as the derivation of an Euler-Poincare formulation of gyrokinetic field theory.

EFDA Task Forces, Topical Groups and Other Activities

Integrated Tokamak Modelling (ITM)

IPP has continued to provide significant support to the EFDA Task Force on Integrated Tokamak Modelling, providing a deputy Task Force Leader, the leaders of two physics projects, and two deputy project leaders (through part of the year). In addition, significant physics contributions were also supplied in the areas of equilibrium and linear stability; edge transport physics; heating and current drive; and ITER scenario modelling. Twelve posters were presented at the EPS Conference in Strasbourg summarizing the progress in Integrated Tokamak Modelling, with strong input from IPP. In addition, an oral presentation on the ITM efforts in MHD equilibrium and linear stability was made by a member of the IPP edge physics group. Much of the ITM activity is centred around two-week Code Camps, five of which were held in 2011 (Cadarache, Helsinki, Prague, Nicosia, Innsbruck), and smaller working sessions or mini-Code Camps (Riso, Nice). There was significant IPP attendance at these events.

Significant progress was made on the ITM general grid description, resulting in a powerful concept for efficient and flexible storage of space discretizations using a generalized data structure. Software components were developed to support operations on this representation and interfacing it to general-purpose visualization tools. Building on this new technology, a first version of the SOLPS package was made available to the ITM platform, resulting in the successful demonstration of a consistent coupled core-edge simulation in combination with the European Transport Solver (ETS). The core-edge coupling targeted steady-state consistent simulations involving multiple species (D, D+C+He, or D+C+Ar+Ne+He) using SOLPS for the edge part and the ETS and IMPURITIES code for the core. The ITM standardized AMNS routines were used to provide consistent atomic rate coefficients for SOLPS and the IMPURITIES code. The results of such a simulation are visualized using ITM tools in figure 3.

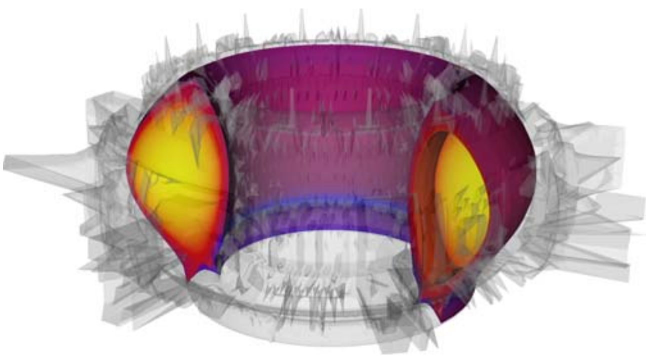

Figure 3: Results from a core edge simulation using SOLPS and the ETS, together with a 3D representation of the AUG vessel.

EFDA Goal Oriented Training in Theory (GOTiT)

IPP continued as coordinator of GOTiT (http://solps-mdsplus.aug.ipp.mpg.de/GOTiT/) as well as leader of WP2 (High Level Courses) in the first half of 2011. The high level course Resonant and non-resonant interactions in beam-plasma systems and magnetic fusion plasma at ENEA, Frascati, has been organised by IPP.

Transport Topical Group (TTG)

During 2011, IPP has contributed to research activities within the EFDA Transport Topical Group and in the related definition of the research activities on transport in the 2012 EFDA Work Programme. An IPP scientist has been directly involved as Topical Group Chair, and as responsible officer in the organization of the WP 2012 in the research area dedicated to electron heat transport. During 2011, important scientific contributions have been provided in the characterization of the pedestal in H-mode ASDEX Upgrade plasmas, contributing to an inter-machine comparison of the pedestal width, in the investigation of the interaction among edge turbulence, fluctuating and mean radial electric fields at the L-H transition in ASDEX Upgrade, in experimental investigations of momentum transport through torque modulation experiments and in the characterization of the intrinsic rotation through the development of an extended database of observations in ASDEX Upgrade, and, finally, with an upgrade of the Lithium beam diagnostic system, including also a new optical head, which is now ready for measurements of the impact of 3D fields on edge and SOL turbulence during the 2012 ASDEX Upgrade campaign.

ITPA Group on Energetic Particles

The world-wide code benchmarking for energetic-particle-driven global modes has been continued. A benchmark with non-linear codes in the linear phase for a large aspect ratio case (A=10) with an n=6 TAE has been performed, focusing on the influence of finite Larmor radius and finite orbit width on growth rate, real frequency and mode structure. Furthermore, calculations for stability boundaries in JET and ITER have been started.

Peaked Toroidal Currents and Iota in W7-X

The toroidal current-profile I(s) is given by $I(s)=c_* s_* (1-s)^5$ where s is the normalized toroidal flux and is related to the normalized minor radius r/a by $s=(r/a)^2$, c is a constant determining the current amplitude. The current profile is peaked at s=1/6 (corresponding to r/a=0.41). The resulting iota-profiles using the VMEC/MFBE code are shown in figure 4 for the Wendelstein-7-X standard configuration for beta=3 % and various current amplitudes (work with F. Herrnegger).

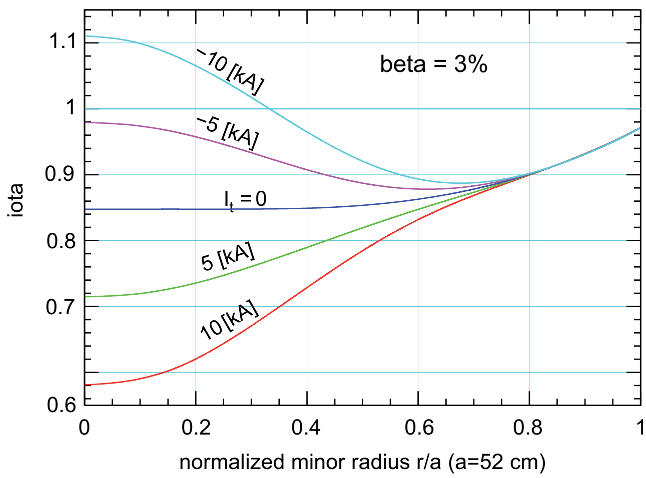

Figure 4: Iota of W7-X standard configuration vs. minor radius for different toroidal current amplitudes.

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Stellarator Theory Division

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Fast-Particle Confinement in W7-X Equilibria

Wendelstein 7-X has seven different types of superconducting magnetic field coils, enabling a six-dimensional space of configurations to be accessed. This configuration space has been explored for optimal fast-ion confinement. Preliminary results indicate that at a volume-averaged normalised pressure of $<\beta>\sim 0.04$ the core-plasma loss cone usually present in stellarators can almost be eliminated if the local pressure gradient is large enough. In fact, several quite different magnetic configurations have been identified with good central fast-ion confinement. In order to assess which of these could be useful for fast-ion physics experiments, Monte Carlo simulations have been carried out using the ANTS (plasmA simulatioN with drifT and collisionS) code. Realistic neutral-beam-injection (NBI) deposition profiles were calculated, and the fast ions were followed in a large number of magnetic configurations, taking Coulomb collisions against the background plasma into account. Although the collisionless confinement is good in the plasma centre, it is not straightforward to find configurations, in which the energy losses of NBI ions (60+30+20 keV protons) do not exceed 10-20 %, because many of these ions are deposited at outer radii where their confinement is inadequate. In addition, a large fraction of all the NBI ions are born onto trapped orbits since the injection angle is almost perpendicular to the magnetic field, and collisions act to scatter the NBI ions into the remaining loss cone. The situation is however predicted to be much better for alpha particles in a stellarator reactor, partly because of better magnetic-field optimisation and partly because pitch-angle scattering is less important for alpha particles than for NBI ions.

Bootstrap Current in Stellarators and Tokamaks

Several new results concerning the bootstrap current in stellarators and tokamak have been obtained. First, the usual expression for the bootstrap current originally derived by Shaing and Callen has been recovered by a method that makes no distinction between tokamak and stellarator geometry. This expression applies to arbitrary magnetic geometry with nested flux surfaces in the long-mean-free-path limit. Second, the correction due to a small but finite collisionality has been considered, following a calculation by Hinton and Rosenbluth, which has been generalized to arbitrary axisymmetric geometry. This correction is proportional to the square root of the collisionality and tends therefore to be important in practice. In fact, in most stellarators the long-mean-free-path limit is approached so slowly at small collisionality that the correction is predicted to increase or decrease the bootstrap current significantly in most relevant plasma scenarios. Third, it has been shown that although the finite-collisionality correction does not apply to a general stellarator, it is applicable to quasi-isodynamic configurations. In particular, if the net toroidal current in the plasma volume inside a flux surface vanishes, then so does the bootstrap current (including the finite-collisionality correction) on that surface. This conclusion strengthens an earlier result that the bootstrap current automatically becomes negligible in a sufficiently well optimized stellarator of the quasi-isodynamic type. Finally, the drift kinetic equation has been solved numerically using the DKES code, and the dependence on the collisionality has been found to agree very well with the analytical result in spherical tokamak geometry. In a classical stellarator, the finite-collisionality correction to the bootstrap current appears to have scaling similar to that in the tokamak, with a coefficient that depends on the radial electric field for reasons that are still not well understood.

Kinetic MHD

In tokamaks, the problem of linear wave-particle interaction can be tackled in a completely gyrokinetic manner using the GYGLES code. A toroidal Alfvén Eigenmode (TAE) has been calculated in a circular tokamak with aspect ratio 3 and low mode numbers ($-1 \leq m \leq 4$). This setup resembles TFTR and is numerically extremely demanding because the electromagnetic cancellation problem gets very large and because there are other modes with a similar growth or damping rate. With improvements in numerics and diagnostics, a very good agreement with the TAE eigenfunctions from reduced MHD has been achieved. The numerical improvements addressed especially the accuracy of the interpolations, while on the diagnostic side a singular value decomposition of the perturbed field signal has been combined with Prony's method for a more accurate determination of the fields.

To get a fast and reliable tool to calculate growth rates due to wave-particle interaction for stellarator applications, the 3D gyrokinetic particle-in-cell code EUTERPE had been coupled to a reduced MHD eigenvalue solver (CKA). The first stellarator benchmark case has been calculated with this hybrid model (CKA-EUTERPE). A TAE in W7-AS, destabilized by fast ions from NBI has been investigated, see figure 5. While for lower energies (up to $v_{beam}/v_A \approx 0.4$) the agreement with the CAS3D-K code was excellent, for higher fast particle energy the orbit width has been found to play an important role. Compared with the zero orbit width model of CAS3D-K, the growth rate dropped by approximately a factor of five for $v_{beam}/v_A \approx 0.8$.

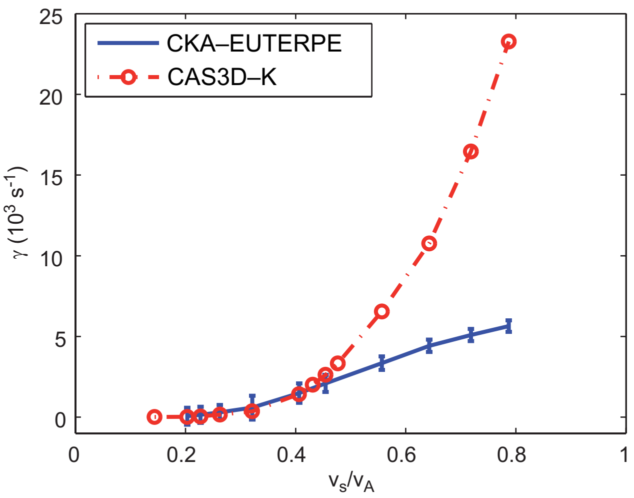

Figure 5: Growth rate of a TAE in Wendelstein 7-AS, calculated with two different codes. CAS3D-K neglects the orbit width of the particles, whilst CKA-EUTERPE accounts for it. It is seen that the orbit width is strongly stabilising.

Ideal MHD

The impact of error fields on stellarator equilibria has been assessed using the code CAS3D. This code was orginally developed for studying ideal MHD stability and can also address the question of how a given equilibrium is affected by small perturbations. As an example, it has been shown that a perturbed-equilibrium calculation reliably determines the effect of a periodicity-destroying m=1 n=1 perturbation causing a dislocation of the magnetic axis of the W7-X high-iota-variant plasma.

Gyrokinetic PIC Simulations

In collaboration with the High Level Support Team (HLST) in Garching the EUTERPE code, a global three-dimensional gyrokinetic particle-in-cell code, has been extended and optimised. These improvements have allowed it to demonstrate that global, electromagnetic simulations of linear ITG modes in stellarator configurations are feasible. A systematic study of the influence of kinetic electrons and electromagnetic effects has been started for a sequence of finite-β Wendelstein 7-X equilibria.

When the electron response is taken to be adiabatic, the flux-surface average of the electrostatic potential appears in the gyrokinetic field equation, making it an integro-differential equation. For three-dimensional geometry this equation is difficult to solve since the matrices involved are non-sparse and badly conditioned. A new solver based on the Woodbury formula has been developed, which calculates the solution to the field equation without the averaging term by an iterative solver and then gets the final solution by adding a correction. The performance and parallel scaling of this new solver is the same as for solving the equation without the averaging term.

In order to simulate reconnection and tearing instabilities, slab geometry has been implemented into EUTERPE. The collisionless tearing mode has been simulated with and without gyrokinetic ion dynamics. For the purpose of verification of the electromagnetic code version, the eigenvalue problem describing tearing modes has also been solved using a shooting method. Growth rates and eigenmodes obtained from both approaches agree very well (see figure 6). Also the nonlinear saturation of island growth could be simulated.

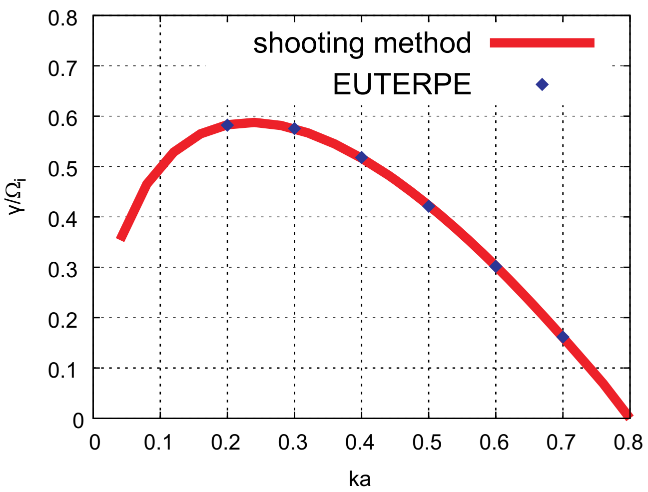

Figure 6: Growth rate oft he collisionless eigenmode in a slab.

The invalidity – for impurities with moderate and high atomic numbers – of the usual assumption of constant density and electrostatic potential on the flux surface in neoclassical theory requires the solution of the drift kinetic equation in a five-dimensional phase space, and the quasineutrality and ambipolarity conditions need to be satisfied simultaneously. This problem has motivated an extension of EUTERPE for neoclassical simulations and its benchmark with fluxes obtained from traditional mono-energetic transport calculations. This should make it possible to simulate neoclassical impurity dynamics with the necessary accuracy, and to calculate the electric field self-consistently, as well as to find neoclassical equilibria suitable as starting points of gyrokinetic simulations.

Effect of the Radial Electric Field on Zonal Flows in Stellarators

The linear response of a collisionless stellarator plasma to an applied radial electric field has been studied in detail. This response involves an oscillating state instead of the steady Rosenbluth-Hinton flow residual obtained in tokamaks. These oscillations are caused by locally trapped particles with radially drifting bounce orbits, and are sensitive to the ambient (neoclassical) electric field. The frequency of the zonal-flow oscillations is determined by the time scale of the poloidal (mostly E×B) drift of locally trapped particles. The zonal flow oscillations can be damped by phase mixing either in velocity space (a kind of Landau damping caused by radially drifting orbits) or in real space. The latter damping is similar to continuum damping of shear Alfvén waves. Numerically, these effects have been demonstrated in W7-X and LHD configurations using the global gyrokinetic particle-in-cell code EUTERPE. In these simulations, the importance of the magnetic configuration for the zonal flow evolution has been observed. This dependence of the zonal-flow dynamics on the magnetic geometry provides a new link between the anomalous transport (turbulence) and neoclassical properties of stellarators.

Stellarator Turbulence Simulations and Optimisation

The effect of zonal flows (ZFs) on ion-temperature-gradient (ITG) driven turbulence in W7X has been investigated within the framework of gyrokinetic theory. First, the linear ZF dynamics predicted by analytical theory has been confirmed numerically. As mentioned above, when an initial ZF is imposed on a stellarator plasma and left to evolve, there exists an intermediate oscillatory phase between the (well-known from the tokamak literature) fast geodesic acoustic mode (GAM) oscillations and the Rosenbluth-Hinton residual. Second, it appears that these oscillations can affect the turbulent transport. Nonlinear simulations using the GENE code suggest that the damping rate of the ZF oscillations can be more important for the transport than the residual level itself, which is very small in W7-X. In the geometry of LHD, however, ZF oscillations are practically absent and the turbulent transport is instead regulated by a non-negligible residual level. The geodesic curvature of the magnetic field lines plays in important role: when it is reduced, the ZF damping rate is small and the ITG transport drops. Since small geodesic curvature also implies low neoclassical transport, there is a correlation between the reduction of transport in the turbulent and neoclassical channels. Nevertheless, cases have also been found where orbit optimization has little to offer in the context of ITG turbulence. Typical examples are the W7-X mirror configurations: while the low-mirror configuration has much higher effective ripple (towards the edge) than the standard configuration, the two configurations were found to have very similar levels of saturated ITG turbulence. Therefore, turbulence optimisation should be treated as separate from neoclassical optimisation in stellarator designs. Finally, the first nonlinear benchmarking for LHD (standard and inward-shifted configurations) was successfully accomplished, comparing GENE with the Japanese GKV code.

Neoclassical Distribution Functions

With the DKES code, the neoclassical distribution functions needed to determine radial transport, the bootstrap current, the Ware pinch and the parallel electric conductivity are calculated. These distribution functions have been analysed for tokamak and a number of different stellarator configurations. Barely trapped particles with long orbit lengths between the reflection points close to the field maxima in stellarators can have a significant impact on the bootstrap current coefficients since they influence the boundary condition with passing particles (which dominate the bootstrap current). A radial electric field can affect these orbits leading to the significant radial electric field dependence of the bootstrap coefficients at low collisionalities (which is absent in tokamaks). The analysis of the parallel electric conductivity distribution function allows for a generalization of the collisionless limit of the ECCD modeling with parallel momentum conservation to small, but finite collisionalities. Furthermore, the parallel momentum correction technique based on the solution of a generalised Spitzer problem for the energy dependence has been extended to the mono-energetic neoclassical distribution function with the parallel thermodynamic force (related to the parallel electric conductivity and the Ware pinch). This technique can be applied to the mono-energetic distribution functions calculated by the DKES code. For a circular tokamak configuration, this approach was successfully benchmarked with the NEO-2 code, which uses a Sonine polynomial expansion of the energy dependence.

Predictive and Analysis Transport Modelling

Predictive transport simulations of pure ECRH start-up and ignition scenarios for a fusion reactor based on the W7-X design have been performed. For these purposes the transport code used for W7-X modelling has been extended to a fusion version by adding particle and energy balance equations for deuterium, tritium and helium ions. The magnetic configuration of the fusion reactor has been derived from the W7-X high-mirror $<\beta>=4$ % case by linearly scaling it to a plasma volume of 1500 m^3 with major and minor plasma radii 20.3 m and 1.9 m correspondingly. Heating of the deuterium-tritium mixture to ignition is provided through O1-mode heating by 140 GHz gyrotrons similar to those used for the W7-X stellarator. The cut-off electron density for this type of heating is $2.43 \cdot 10^{20}$ m^{-3} at the resonance magnetic field of 5 T with the average magnetic field on the magnetic axis of 4.5 T. Therefore the conventional technology based on NbTi superconductor, which is limited to the magnetic field of 9 T at the superconductor, can be used for coil construction.

The simulations of D-T plasma with the same ion densities of about $0.98 \cdot 10^{20}$ m^{-3} heated by 50 MW ECRH have shown that self-sustained burn is started at ion temperatures of 10 keV. The transport model has been chosen to be mainly neoclassical in the bulk plasma with large anomalous transport at the edge. The anomalous diffusivity scales as $P^{0.75}/n$, where P is the total heating power and n is the electron density. At a developed stage of burn the resulting energy diffusivities at the plasma edge are between 1-5 m^2/s, while in the plasma core they are about 1 m^2/s for electrons and 1.5 m^2/s for deuterium ions. At this stage the 600 MW internal heating is provided by fast alpha particles resulting from the fusion reaction with total output of 3000 MW. The helium ash density is about $1.2 \cdot 10^{19}$ m^{-3}, which together with an additional 0.7 % of carbon impurity ions ($1.54 \cdot 10^{18}$ m^{-3}) gives Z_{eff}=1.3; resulting bremsstrahlung radiation is 92 MW. The energy confinement time for $<\beta>=4$ % plasma is about 2 s with an improvement factor of 1.35 with respect to the ISS04 scaling based on experimental results of different stellarators. Similar fusion output has been obtained for the same fusion reactor but with the resonance magnetic field increased to 6 T and with the minor plasma radius reduced to 1.6 m. The heating is provided by ITER-type gyrotrons at 170 GHz allowing for higher electron density as the cut-off moves to $3.58 \cdot 10^{20} m^{-3}$. For this reactor Nb_3Al or Nb_3Sn superconductor is required for the coils due to the higher values of magnetic field. The advantage of this design is the enlarged space for the blanket and vessel components.

Anomalous Transport Modelling

To simulate anomalous transport in W7-X the IFS-PPPL transport model $\chi = W \cdot G(R/L_T - R/L_{Tcrit})$ of ITG turbulence has been implemented in the stellarator transport code. The value of critical temperature gradient R/L_{Tcrit} provided by GENE-code simulations is about 11 and does not depend on the minor radius. A set of transport simulations has been performed using different values of the weighting factor W specifying the strength of the assumed anomalous transport. It has been shown that for W>0.3 the anomalous transport strongly dominates over the neoclassical beyond 1/3 of the plasma radius; the energy confinement times in these cases are less then those predicted by the ISS04 scaling.

Finite Collisionality Effects in ECCD

For solving the generalized Spitzer problem necessary for the calculation of electron cyclotron current drive (ECCD) with small but finite collisionality, an approximate off-set model based on the momentum-correction technique (MCT) has been developed. This model is motivated the finite-collisionality correction to the bootstrap current described above. In the model, the pitch-dependence of the generalized Spitzer function is approximated by the collisionless limit with an additional constant term (for passing electrons) proportional to the difference between the effective and the geometrical fractions of trapped electrons. The advantage of the MCT off-set model is its applicability to arbitrary 3D magnetic equilibria.

With this model implemented in the ray-tracing code TRAVIS, current drive in W7-X with the X2- and O2-modes was analysed. In contrast to the X2-mode, for which the plasma is optically thick and the deposition profile is well localized, the case with the O2-mode is more complicated since the plasma is optically gray and trapped electrons directly participate in the absorption. With all plasma and launch parameters fixed (n_e=10^{20} m^{-3}, Z_{eff}=1.5, standard magnetic configuration, oblique launch with 18 near the bean-shaped cross-section), a *Gedankenexperiment* with an electron temperature scan was performed. It was found that finite collisionality contributes to the ECCD up to T_e=10 keV, but the largest effect is obtained for moderate plasma temperatures, 2 keV<T_e<5 keV. For still lower temperatures, i.e. for higher collisionalities, the applicability of the "off-set" model becomes questionable.

Implementation of TRAVIS in the Workflow System ITM – Kepler

Within the framework of the EFDA ITM Task Force IMP-5 project, a new version of the ray-tracing code TRAVIS has been created. The code was converted into a module complying with ITM standards for data structures. In order to do this, a new module for interpretation of the magnetic equilibrium from the ITM data structure was developed for arbitrary grids (the standard version of this module in TRAVIS is written for EFIT-format with uniform grid). The Kepler actor was successfully generated and test-runs performed. The benchmark and verification of this TRAVIS ITM-module is in progress.

Runaway Electron Energy Amplification in Vertical Disruptions

During the current quench of a tokamak disruption, a substantial fraction of the initial plasma current I_{P0} can be converted into runaway electrons (REs). The ease, at which this happens grows with the plasma current, making REs an issue of concern in ITER, where they may damage the first wall upon impact. During the motion of the plasma and its subsequent depletion at the vessel walls the RE current is amplified at the expense of poloidal magnetic field energy. A 2D model describing plasma motion and RE time evolution was developed to estimate the kinetic energy ΔW_{RE} gained by the runaways over two qualitatively different phases of plasma motion. In the *free-motion* phase, magnetic field energy is mainly consumed in order to maintain the initial RE current against slowing down by collisions with thermal background electrons. In this phase, the electric field in the plasma mainly balances the critical electric field strength E_c below, which no RE amplification can occur. At first plasma-wall contact, the plasma enters the *scrape-off* phase where strong electric fields $E>>E_c$ are induced at the plasma edge, thus giving rise to strong RE current amplification and a growth of kinetic energy content.

The final amount of RE kinetic energy strongly depends on the initial RE current and its strength as it enters the scrape-off phase. For ITER conditions (I_{P0}=10 MA, W_{RE0}~20 MJ) it was estimated to be of the order ~100 MJ, unless measures were taken to mitigate REs (J. Riemann, H. M. Smith and P. Helander, Physics of Plasmas **19,** 012507 (2012)).

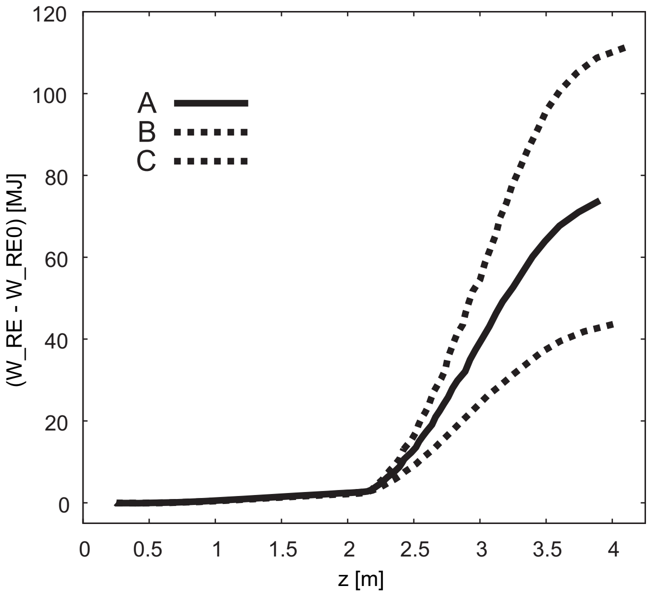

Figure 7: Gain of RE kinetic energy DW_{RE}= W_{RE}-W_{RE0} vs vertical position z. For the initial plasma current three cases are compared: A (I_{P0}= 10 MA), B (I_{P0}= 7.5 MA) and C (I_{P0}= 12.5 MA). The first plasma-wall contact occurs at z = 2.1 m.

Confinement of Alpha Particles with Shielded Resonant Magnetic Perturbations

Alpha-particle losses caused by ELM mitigation coil system in ITER have been estimated for the vacuum RMP model and for the model taking RMP shielding by the plasma into account. As could be expected, the shielding of RMPs strongly reduces the width of the region at the outer side of the plasma volume occupied by ergodic passing alpha-particle orbits. This reduction, however, is smaller than such a reduction for magnetic field lines and it is different for co- and counter-passing orbits. Nevertheless, it is sufficient to prevent noticeable losses predicted by vacuum RMP model. The main channel of losses in the vacuum approximation for the perturbation field is losses of passing particles, which cause 4.7 % loss of alpha-particle fusion power. Together with trapped particle contribution, the alpha-particle fusion power loss would exceed 5 % with particles being lost without significant slowing down by electrons. If shielding of RMPs is taken into account, however, the passing-particle loss channel is practically eliminated. The remaining losses are about 1 %, which is well below the ITER requirement of maximum allowable losses of 5 %.

Edge/Divertor Physics

Island Divertor

The particle and energy exhaust capability of the island divertor under reactor conditions has been numerically examined using the EMC3-EIRENE code. W7-X was linearly up-scaled by a factor of 4 and simulations were made under reactor-relevant parameter conditions. It is predicted that more than 85 % of the power entering SOL (300 MW assumed) must be radiated in order to keep the peak power load below 5 MW/m^2. Such a high radiation fraction, which is inaccessible in W7-AS, has been predicted to be achievable in W7-X. Detachment simulations for the reactor case are planned as a next step. Particle exhaust is another critical issue identified for the reactor case because of the broadening of the particle channels with growing islands. There are, nevertheless, numerical indications of the possibility of slightly separating the power and particle channels by utilizing the specific island geometry to find a compromise solution between the particle and energy exhaust.

Applications to Tokamaks

Within an ITER task, the EMC3-Eirene code is being employed to evaluate the non-axisymmetric heat and particle flows induced by the ELM-controlling RMP fields foreseen for ITER. The work began with a comparison to the SOLPS4.3 (B2-Eirene) code – the major numerical tool used to assess ITER divertor performance in the axisymmetric case. This comparison aims at checking the compatibility in the most relevant physics assumptions between the two codes, in particular under low divertor temperature conditions of interest. The two codes have been compared for an axisymmetric ITER divertor configuration (15 MA H-mode) under various SOL-plasma conditions for cases with and without impurities. In the absence of impurities, the two codes predict almost the same upstream plasma profiles and the same heat flux distributions on both the inner and outer targets. Adding impurities causes slight deviations in these profiles and certain discrepancies in profile details of the downstream temperatures and density have been observed in all the cases used for the comparison. These discrepancies are consequences of differences in the physics models adopted in the two codes and are regarded as being well within the range acceptable for ITER applications.

Possible effects of the RMP-fields on the tungsten impurity transport in ASDEX-Upgrade are investigated numerically using in comparison with the conventional axisymmetric SOL. The first results show a slightly-improved divertor-retention of the target-released tungsten impurities. The EMC3-EIRENE code has also been recently implemented for the NSTX, EAST and Aditya tokamak.

Electron Kinetics in the Solar Wind

In a collaboration with the Max Planck Institute for Solar System Research, the electron velocity distribution function has been calculated in the extended solar corona above coronal holes (i.e. the inner part of the fast solar wind) from the highly collisional corona close to the Sun to the weakly collisional regions farther out. The electron kinetic equation is solved with a finite-element method in velocity space using a linearised Fokker-Planck collisional operator. The ion density and temperature profiles are assumed to be known and the electric field and electron temperature are determined self-consistently. The results show quantitatively how much lower the electron heat flux and the thermal force are than predicted by high collisionality theory.

Scientific Staff

C. D. Beidler, T. Bird, M. Borchardt, M. Drevlak, T. Feher, Y. Feng, J. Geiger; P. Helander, K. Kauffmann, R. Kleiber, A. Könies, H. Maaßberg, N. Marushchenko, A. Mishchenko, C. Nührenberg, J. Nührenberg, J. Proll, J. Regaña, J. Riemann, A. Runov, F. Sardei, H. Smith, T. Stoltzfus-Dueck, Yu. Turkin, P. Xanthopoulos, O. Zacharias.

Guests

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

Head: Prof. Dr. Frank Jenko

The main goal of our research efforts is to better understand the important unsolved problem of plasma turbulence. 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 dialogue and cross fertilization between plasma physics and neighboring fields of science. Below, three examples of current projects are described briefly. For more details, please see the papers cited below or visit the website http://www.ipp.mpg.de/~fsj.

Global Turbulence Simulations of ASDEX Upgrade Discharges with GENE

GENE [1] (see also http://gene.rzg.mpg.de) is a comprehensive gyrokinetic turbulence code employing grid-based numerical methods. It has been developed at IPP since 1999 and is able to retain a large set of physical effects, including an arbitrary number of ion species, kinetic electrons, electric and magnetic field fluctuations, collisions between any pair of particle species, the possibility to fully retain sub-ion-gyroradius scales, as well as interfaces to various magnetic equilibrium and transport codes.

Figure 8: Snapshot from an ab initio simulation of the ASDEX Upgrade tokamak with the comprehensive plasma turbulence code GENE.

Moreover, GENE can be run either as a local (flux-tube) code or as a global (full-torus) code, gradient- or flux-driven. It has been carefully benchmarked against theory and other codes in appropriate limits both for micro-instabilities and turbulence as well as for neoclassical transport [1]. In 2011, the first comprehensive global simulations of ASDEX Upgrade plasmas have been performed, based on realistic experimental data. A snapshot from such a run is shown in figure 8. These capabilities have been used to study, in particular, the residual transport in internal and edge barriers, pointing to an important role of fine-scale electron temperature gradient (ETG) modes [2].

Small-scale Reconnection and Magnetic Transport in Tokamaks

Global GENE simulations were also able to show that microtearing modes tend to be linearly unstable in the outer half of typical ASDEX Upgrade discharges [3]. This came as a surprise, since various analytical studies from about one to two decades ago suggested otherwise. The properties of these peculiar micro-instabilities have been carefully studied, including the linear drive and nonlinear damping mechanisms, as well as the influence of the local plasma parameters. If sufficiently strongly driven, the emerging small-scale magnetic islands overlap and create stochastic field lines. The resulting magnetic transport is well described by a Rechester-Rosenbluth model, and the transport level is such that microtearing modes must be considered capable of contributing to the overall anomalous transport [3,4]. The various consequences of this new discovery remain to be explored and are a topic for future research.

Efficient Gyrokinetic Predictions of Plasma Profiles in Tokamaks

In order to be able to predict the density and temperature profiles in tokamak discharges in an efficient way, one may use a coupling of local GENE simulations at a limited number of radial positions with a transport code like TRINITY [5]. Such runs are much less demanding than a brute-force approach via global flux-driven simulations, but they may still require many million CPU-hours. Further speedups by about one order of magnitude have recently been achieved by means of introducing Large Eddy Simulations techniques (first developed in fluid turbulence research) to plasma physics [6], also taking into account the fundamental dissipative role of damped kinetic Eigenmodes [7]. Interestingly, this approach can be used in such a way that no free parameter occurs and is thus very promising.

Scientific Staff

T. Görler, F. Merz, M. Püschel, D. Hatch, D. Told, H. Doerk, A. Limone.

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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. In toroidal systems, the curvature induced coupling of the flows perpendicular to the magnetic field to pressure fluctuations and parallel flows results in two branches, the oscillating geodesic acoustic modes (GAMs), and the stationary zonal flows (ZF) with a dominant parallel flow component.

Geodesic Acoustic Modes: Nonlinear Dispersion Relation

By manipulating the frequency, i.e., the dispersion relation and transferring energy to the GAMs the turbulence may have a significant influence on the properties of GAMs observed in experiments. In earlier works we have already shed light onto the linear propagation properties of GAMs by expressing the propagation in terms of fluctuation Poynting fluxes. Later, we studied the influence of the turbulence on GAM propagation and in some cases found the group velocity to be enhanced by a factor of up to 100 compared to the linear predictions but with a qualitatively unchanged dispersion relation. Such high group velocities (comparable to the diamagnetic drift) translate directly to GAM eigenmodes with a possible width of several centimetres, which would definitely be visible in today's experiments, may explain the frequency plateaus observed earlier in ASDEX Upgrade and open the possibility to excite GAMs coherently on this length scale.

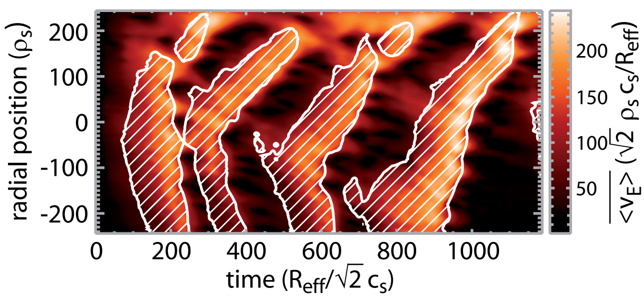

Figure 9: GAM bursts in turbulent nonlocal scenario with single-null configuration. Color coded: short-time rms average of the flux-surface averaged flow velocity. Contours: turbulence intensity. Within the shaded areas, the turbulence intensity is above 70 % of its rms average.

GAM Bursts

Another aspect of the GAM-turbulence interaction apart from the one mentioned before is that the turbulence – via the transfer of energy – also controls the accessible range of radial wave numbers of the GAM activity. For single-null divertor configurations we observed for example that only GAMs with a specific sign of the phase velocity (depending on the orientation of the ion curvature drift with respect to the X-point) are excited. In global turbulence computations with NLET, the dominant radial wave number of the GAMs may change over time within the accessible range due to radial frequency gradient. This can result in a shift of the saturation amplitudes of GAMs and turbulence and, thus, lead to periodic bursts of GAM and turbulence activity. The frequency of the bursts can be estimated by the time the dominant GAM wave number needs to cross the k-space region allowed by the turbulence, i.e., by the radial frequency gradient and the wave number, at which the turbulence induced GAM growth rate is maximal. Using realistic values, the estimated burst frequencies suggest a connection of the GAM behaviour observed numerically with the pulsations during the I phase in ASDEX Upgrade or the quiet periods in NSTX.

External Excitation of GAMs

The external excitation of GAMs due to their ability to reduce the turbulence intensity represents an interesting approach towards an active control of confinement quality in fusion plasmas. In this context a detailed understanding of the radial propagation of GAMs can be helpful and necessary. Therefore, we started to investigate the excitation of GAMs using external magnetic fields. Application of an (m,n)=(2,0) perturbation can drive GAMs due to the inertial forces resulting from the corresponding vibration of the equilibrium. By calculating those inertial forces with an equilibrium solver and incorporating their effect into the NLET code we were able to study the efficiency of externally excited GAMs as internal transport barriers. In preliminary studies forced flow oscillations indeed led to reduced turbulent transport and a steepening of density and temperature gradients if enough energy could be deposited into the GAMs. The drive efficiency depends on the magnetic geometry and the pressure gradient, which controls the screening due to the plasma conductivity.

Zonal Flow Studies: Reynolds Stress Functional

The evolution of the ZFs in core Tokamak turbulence is governed by the perpendicular and parallel Reynolds stresses. A characteristic wave length and flow saturation is observed in the ZFs restricting the functional dependence of the stress on the shearing rate. Extensive computer studies of ITG turbulence were used to construct an approximation of the evolution of the total stress resulting in

$$R_t = Q\left(\alpha u\left(1-\beta u^2\right) - \gamma\partial_\rho^2 u - \delta\partial_\rho^4 u\right), \quad u \equiv \partial_\rho v_\theta$$

where Q is the radial heat flux, v_θ is the poloidal velocity and α, β, γ and δ are numerical coefficients. It was found that the contributions of the parallel stress to all coefficients are important to obtain the correct coefficient signs and to describe the ZF evolution adequately, contrary to contemporary analytic ZF models, which largely neglect the parallel dynamics.

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 optimization of codes to be used on the dedicated High Performance Computer for Fusion (HPC-FF) located in the Forschungszentrum Jülich Supercomputing Centre (JSC). The HLST consists of a core team based at IPP Garching and of high level support staff provided by the Associates. At present the former has five members and the latter contributes with an additional six scientists. This year the HLST core team was involved in thirteen different projects submitted by scientists from all over Europe. As examples, we present here an overview of the work being done for three projects with IPP participation.

MGTRI Project

The MGTRI project focuses on the gyrofluid GEMT code, which will contain the MHD equilibrium solver GKMHD to evolve the Grad-Shafranov MHD equilibrium. Presently GKMHD is not parallelized. Hence, a major effort in making the code parallel is to implement a parallelized multigrid solver on a triangular mesh.

We have implemented different multigrid solvers for a Poisson problem on a structured triangular grid on a regular hexagonal domain. In this context, it was crucial to derive an appropriate communication pattern between the subdomains to exchange the information necessary for the ghost nodes. To check the correctness of the implementation several tests have been performed. In addition, performance and scaling tests have shown that the preconditioned conjugate gradient method with a multigrid preconditioner with Gauss-Seidel smoother (CGGS) is the most efficient method under consideration. For the given problem sizes of $5 \cdot 10^7$ Degrees of Freedom (DoF) and $2 \cdot 10^8$ DoF the numerical results revealed almost perfect strong scaling up to 384 cores. In addition, the multigrid method as a solver and as a preconditioner yielded a very good semi-weak scaling property up to 1536 cores, which improves for larger test cases.

NEMOFFT Project

The main purpose of the project is to remove, or at least alleviate, a parallel scalability bottleneck of the global gyrokinetic ORB5 code, in its current electromagnetic version NEMORB. This code solves the Poisson equation and Ampère's law in Fourier space and relies on filtering to refine the physical quantities. A parallel two-dimensional (2D) Fourier algorithm, consisting of two 1D Fourier transforms (FFT) interleaved with a distributed transpose, is used. This algorithm requires large amounts of grid data to be transposed across processors and naturally impairs the code's parallel scalability.

In order to ameliorate this bottleneck, the 2D FFT algorithm in NEMORB was modified to use the Hermitian redundancy inherent to its purely real input data. This allowed to reduce to roughly one-half the size of the first Fourier transformed direction, from N complex Fourier modes kept for a N-size real dataset, to keeping only $N/2+1$ of these modes.

The performance measurements yielded speedup factors of about two on HPC-FF for the overall 2D FFT algorithm. They further revealed that, depending on the size of the problem (grid-count), a degradation of the speedup starts to occur when the communication latency becomes significant compared to the total transpose communication cost. This happens whenever the number of MPI tasks becomes too large for small grid-counts. Further improvements to overcome such limitations are already planned. Using different transpose algorithms as well as a hybrid MPI/shared memory segments parallelization scheme is foreseen.

ZOFLIN Project

The ZOFLIN project was focused on the enhancement of the single processor performance and the scalability of the ZOFLIN code. First, we have updated the code to be FORTRAN 2003 compliant, which allows the code developers to follow a more standard method of programming. This also helps to have a more portable code. The use of tools like Forcheck, Automake and Marmot now ensures that certain types of programming errors do not occur anymore, neither in the application nor in the Makefile.

Looking for improvements of the single processor performance, we found the efficiency of the code, with respect to the FLOP rate, to be quite high on single (2.3 GFLOPS) and multiple processors (1.6 GFLOPS per core on 64 cores). Achieving higher FLOP rates seemed to be impossible because of the memory-bound nature of the ZOFLIN code. We analyzed the time spent in communication in the code and found the *MPI_Waitall* to consume around 40 % of the time spent in MPI calls. By combining the data that was sent across cores as part of the boundary exchange, we were able to reduce the number of calls to the asynchronous routines *MPI_Isend* and *MPI_Irecv*.

From the run times and the FLOP rate, as given by performance diagnostics, it is obvious that the code is very well load balanced and there is at most only a 1 % difference between the highest and lowest run times. Accordingly, we found ZOFLIN to perform quite well on HPC-FF.

Scientific Staff

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Supercomputing and other Research Fields

Computer Center Garching

Head: Dipl.-Inf. Stefan Heinzel

The RZG supports optimization of complex applications from plasma physics, astrophysics, materials science and other disciplines for massively parallel high-performance computers and provides data visualization services for the exploration and quantitative analysis of simulation results. Data management and data services are another key area. The RZG has continued its engagement in several large MPG, national and international projects in collaboration with other scientific institutions.

Introduction

The Rechenzentrum Garching (RZG) traditionally provides supercomputing 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. Moreover, the RZG provides data visualization services for the exploration and quantitative analysis of simulation results. Data management and data services are another key area. 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 IT services for the IPP and 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.

Systems

The RZG operates a supercomputer complex with two system parts, 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 cores corresponding to a peak performance of 55 TFlop/s. The IBM p575-based cluster of 8-way Power5 nodes was taken out of operation. Furthermore, 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. They mostly consist of nodes with modern Intel processors in blade technology with InfiniBand interconnect. The largest system has around 4500 processor cores, a peak performance of 54 TFlop/s and 18 TB of main memory.
The RZG also operates a system for developing and testing GPGPU (General purpose Graphics Processing Unit) computing applications comprising an NVidia Tesla S2050 and an S1070 unit, each equipped with 4 GPUs. In order to provide interactive remote-visualization services to scientists of the Max Planck Society a Linux cluster with powerful graphics hardware is in operation since late 2010. The cluster comprises a login node and 6 visualization nodes, each of the latter containing two NVidia FX5800 GPUs. The nodes are connected with a fast InfiniBand network. A 30 TB scratch file system is dedicated to the cluster. In addition, the scratch file system of the Power6 supercomputer and the DEISA file system are accessible from the visualization nodes. Thereby, HPC users can investigate their simulation results directly without having to transfer raw data to their sites.
In the mass storage area, the automated tape library has been expanded to 20 000 tape slots, which means a theoretical maximum capacity of over 40 PB. The old LTO3 tape drives have been replaced by 20 LTO5 drives and all data on LTO3 tapes is being transferred to LTO5 tapes (which have quadruple capacity). For the new HPSS archive system described below in the section “Data Services”, 5 powerful Linux machines were purchased. These machines share a disk storage system with a total raw capacity of 1/3 PB for data cache and a second, fast disk storage system with a total raw capacity of 14 TB for metadata.

High-performance Computing

Support in the field of high-performance computing is a central task of the RZG. The main working fields of the application group that is dedicated to this task are:
- **Basic services**: provisioning and maintenance of software and development tools for creating and optimizing parallel programs and for the visualization of simulation results.
- **Application support**: optimization of codes and troubleshooting of problems at compile time and run time, participation in visualization and graphical preparation of data, evaluation of new parallel programming techniques and models and advice on their use.
- **Project support**: advice and realization of IT projects with advanced needs, often in cooperation with several partners at various institutes.

In the following selected projects are presented in more detail.

GPEC Code

In order to achieve real-time control of fusion plasmas the flux distribution and derived quantities have to be calculated within the time of the machine control cycle, which is typically of the order of 1 ms. This requires a fast solver for the Grad-Shafranov equation together with optimized procedures for the utilization of the result. An algorithm for a fast solver has been implemented and optimized, which allows exploitation of the parallel capabilities of modern multi-core processors. The new code termed GPEC (Garching parallel equilibrium code) is implemented in FORTRAN 90 and is based solely on open-source software components.

For a numerical grid of size 32×64, which is considered to be sufficiently large to derive quantities for plasma control, GPEC requires only 0.04 ms for a single iteration of the Grad-Shafranov solver, when using a standard Intel Xeon quadcore CPU (3.2 GHz). Using the message-passing interface (MPI) standard, a first prototype implementation of GPEC into a complete equilibrium code, where a number of solutions of the Grad-Shafranov equation are computed independently for a whole set of basis functions, has been accomplished recently. The computation of a complete equilibrium cycle including control parameters takes approximately 0.08 ms per basis function on a single CPU. In the new MPI-parallel equilibrium code this runtime is expected to scale with the number of basis functions divided by the number of CPU sockets, which, for example, readily enables real-time applications using eight basis functions and four CPUs of a standard x86 compute server.

GENE Code

GENE is one of the leading codes for gyrokinetic plasma turbulence simulations. GENE has been used over many years on various supercomputer architectures and for different physical settings. It is still under active development both concerning computational performance and physical description. GENE has been further optimized to scale now also in the v_par direction by reassigning the work to different cores. Considerable work has recently been put into the preparation of "lighthouse runs" on the new fusion-science supercomputer IFERC. To this end, the code has been prepared for hybrid use of MPI and OpenMP programming models.

S/Phi/nX Code

The S/PHI/nX code, developed by the MPI for Iron Research, includes a matrix-based formulation of density functional theory, which is implemented in C++ in a completely modular and object-oriented fashion. The RZG has provided support for code development, specifically the distributed-memory parallelization of k-points. Starting from the original serial version of the code, the RZG has developed a first parallel MPI-based version, which achieves good parallel scaling without compromising the clear object-oriented structure of the code. Using the k-point approach efficient parallel scaling was achieved up to 32 cores, thereby reducing the runtime of typical calculations from several days to a few hours. The MPI-parallel S/PHI/nX code is already routinely used on the Linux clusters at the MPI for Iron Research. The RZG is working together with the developers on a further improvement of the parallel scaling by designing and implementing a hierarchical, object-oriented parallelization strategy novel to density functional theory codes.

Scientific Visualization

In late 2010, a Linux cluster was installed at the RZG, which is dedicated to quantitative analysis and visualization of simulation data by scientists of the IPP and the Max Planck Society. It comprises a dedicated file system and 6 visualization nodes, which are equipped with large main memory and two powerful graphics processing units (GPUs) each. The cluster enables scientists to efficiently perform remote visualization of large data sets, in particular without the need to transfer the data to their local workstations. On the cluster, state-of-the-art visualization tools for various purposes are available.

In addition to providing a hardware and software platform, the RZG offers support for the selection and usage of visualization and data analysis tools and for the instrumentation of simulation codes. A close cooperation with the High Level Support Team (HLST) has been established, in particular in the context of the GYNVIZ project (visualization support for several European gyrokinetic turbulence simulation groups). Moreover, the RZG has supported and – in some cases – taken over a number of particularly challenging visualization projects directly. In these cases, either the complexity or size of the simulation data, or specific visualization goals required expert knowledge of existing visualization methods or even the development of tailored software solutions. Recent examples include projects from astrophysics (MPA, MPE) and materials research (FHI).

An ongoing project aims at the visualization and quantitative analysis of molecular simulations performed with the FHI-aims code. In order to enable interactive visualization and quantitative analysis using comprehensive graphics packages like VisIt or ParaView, the relevant scalar fields like the Hartree potential or the electron density, which are used in this DFT code need to be mapped from their code-internal representation to a regular coordinate grid suitable for visualization. To this end output routines of the simulation code were extended and an efficient post-processing tool for the mapping step is being developed at the RZG. The figure shows first, preliminary results for a simple molecule obtained with the ParaView visualization tool, which allows comprehensive quantitative analysis by interactive examination of slices, isocontours, isovolumes or alike of the data.

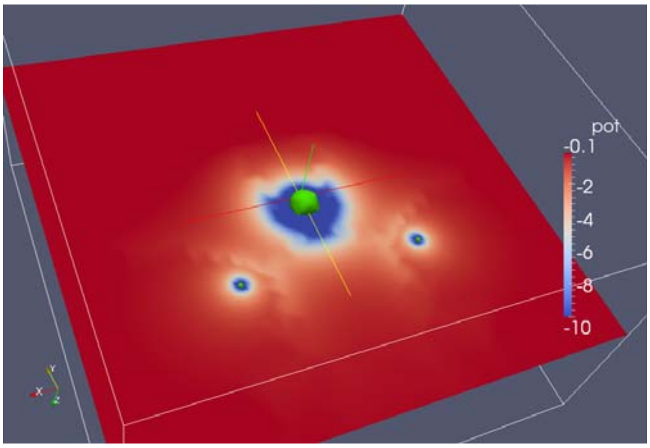

Figure 1: ParaView visualization of the Hartree potential of a water molecule obtained with the FHI-aims code. Simulation and visualization by RZG.

Data Services

Handling of data is more and more becoming a challenge. Besides the unchanged exponential growth of the amount of data to be stored, the need to organize the data and provide comfortable access to it is a demanding task. In order to address these needs a new group, the *Data Service Group,* has been established at the RZG. In this group essential expertise in data-related services is concentrated, covering the whole range of services associated with various types of data, from low-level *bit-stream services* over *metadata services* up to high-level *project-specific data services*. In the following paragraphs the recent major work for these three levels is presented.

High Performance Storage System (HPSS)

In the past the RZG used TSM (Tivoli Storage Manager) not only for backup, but also as backend to HSM (hierarchical storage management) for all users in AFS (Andrew File System) and for the HPC system with GPFS (General Parallel File System). For scalability reasons this software has been substituted by HPSS, a product also used by the largest science labs worldwide. HPSS also offers many new interfaces to access the tape storage system for archival purposes. The installation of this system has been accomplished during 2011 with strong support from IBM and together with the development team of HPSS. The migration of the AFS data and GPFS data from the TSM system into the HPSS is a still ongoing process, which is performed under the control of the Data Service Group and will be finalized most likely in 2012.

Oracle Databases

Apart from file systems another major topic of the metadata services are databases. Especially the support for the Oracle databases is relevant. The two major databases for MPE and ASDEX Upgrade maintained at the RZG have been migrated from two out-dated IBM-AIX machines onto one state-of-the-art Linux system, while upgrading the Oracle versions at the same time. The whole backup system for the databases has been adapted to take advantage of the new features provided by the new Oracle version. The Oracle database in Greifswald, mainly used to handle the data for the construction of Wendelstein7-X, is on the verge to be migrated from Sun-SPARC-Solaris machines onto Linux, too. Here virtualization techniques will be investigated in order to improve administration and availability of the database.

Project-Specific Data Services

Among the data-related collaborations is the MPG project MPG-AAI, which covers infrastructure for authentication and authorization. Furthermore, the support for the Galformod project of the MPA has been continued with the operation of the backend database being in the responsibility of the RZG, while the frontend is developed and evaluated in close collaboration with the MPA. Beyond mere database improvements a whole framework for the data handling allowing for complex workflows to analyze the data was provided. In the Replix project together with the MPI for Psycholinguistics, Nijmegen, the administration of and the access to linguistic data based on iRODS (integrated Rule-Oriented Data System) is examined. Furthermore, the data service group has started consulting and support for the MPI for Ornithology in Seewiesen. Their enormous number of files plainly stored in a migrating file system is a big challenge. Replication of data at the RZG is generally gaining importance.
Finally the data group of the RZG is engaged in several national and international projects (CLARIN-D, DARIAH-DE, EUDAT), which address data-management challenges. Thus the expertise of the group is fostered by being upfront with the recent developments in the data-oriented fields.

Projects in Collaboration

Apart from the already mentioned data-management projects the RZG participates in the following IT projects:

The Munich-ATLAS-Tier2 Project

In collaboration with the MPI for Physics (MPP), LRZ and LMU, the RZG participates in the Munich Tier2 grid project. This project has deployed, and now maintains, a federated Tier2 grid centre for the WLCG (Worldwide LHC Computing Grid), which was created to provide computing power for the CERN particle physics experiments. Although the project provides a federated centre, in which the required resource pledges are met in a shared manner, each site provides a full set of services and as such can act independently. This model allows for improved availability and also enables us to share expertise among partners. The Tier2 deployment consists of the gLite middleware and dCache storage solution, these middleware components are continually tuned and updated to follow the release cycles of the providers and meet the needs of the user communities, which make use of the Tier2 centre. Throughout its life the Tier2 has continually grown to meet the evolving pledges and needs of the WLCG, currently the Tier2 infrastructure at RZG consists of over 1600 CPU cores and over 1.5 PB of disk-based storage. In addition to providing standard services the Munich Tier2 acts as a Muon Calibration centre. As such the Munich Tier2 provides a service, which is only available at three centres worldwide. In this role the Munich Tier2 is used for fast processing of calibration data from the ATLAS experiment. This data must be quickly processed and re-dispatched to CERN for use in calibrating the ATLAS experiment.

ELPA

Eigenvalue solvers for symmetric matrices play an important role in different fields of science. For large simulations they are, unfortunately, often the crucial bottleneck, as observed in the FHI-aims package of the Fritz-Haber-Institute for ab-initio

MD simulations or in the analysis of technological and biological networks at the Max Planck Institute for Mathematics in the Sciences. This problem has been addressed in the BMBF project ELPA by a multidisciplinary team of scientists from the University of Wuppertal, the TU Munich, the Fritz Haber Institute, the Max Planck Institute for Mathematics in the Sciences, IBM Germany and the RZG. The team has developed new methods for direct solvers, which are significantly more scalable than the corresponding, quasi state-of-the-art scale ScaLAPACK routines and also show better performance per processor core. The new solver has been successfully tested on the Blue Gene/P system at the FZ Jülich using the entire machine (294 912 cores), as well as on other computer architectures such as Cray XE6 or Linux clusters with InfiniBand interconnect. Via http://elpa.rzg.mpg.de the new solvers have been made publicly available under an LGPL license and have already been requested by scientists from prestigious institutions worldwide.

PRACE

After seven years of operation of the *Distributed European Infrastructure for Supercomputing Applications,* the DEISA Consortium completed its mission in April 2011 and handed over the services to PRACE, the *Partnership for Advanced Computing in Europe*. PRACE had started to install leadership class supercomputers in Europe, so-called Tier-0 systems, and continues to integrate the national (Tier-1) compute systems into a European High Performance Computing eco system. DECI, the *DEISA Extreme Computing Initiative* was continued by PRACE in 2011, but was renamed to *Distributed European Computing Initiative,* since the label "Extreme" has been shifted to the new Tier-0 systems. The RZG participates in the FP7 PRACE-2IP project from 2011 to 2013, which continues the Tier-1 DEISA services and is taking care of compute proposals and projects of the IPP and the Max Planck Society.

Bioinformatics/Computational Biology

Initiated several years ago in the context of the MPG project MIGenAS, the RZG maintains a hardware and software infrastructure for computational biology applications and offers high-level application support for all kinds of bioinformatics projects of the Max Planck Society. In the course of 2011 a number of microbial genomes were analysed and published with the help of this infrastructure. Specifically, RZG staff participated in the bioinformatics analysis of the microorganisms Thermoproteus tenax, Haloquadratum walsbyi (both published in the journal PLoS ONE), as well as Natronomonas moolapensis and Halobacillus halophilus (about to be published).

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 aggregating and limiting switches at workgroup or storey level. This structure greatly enhances overall network performance, for most of the connections between core-network devices within the RZG are at a speed of 10 Gigabit/s (Ten-Gigabit Ethernet technology). Security and integrity of data have also been improved with this structure, because eavesdropping is almost impossible.
Due to various reasons within the compute and data centre the concept of fat trees with high flexibility and performance, but very expensive routers/switches will probably be ruled out by small and relatively inexpensive switches, which are clustered by specific software to form a "virtual chassis". With additional protocols like TRILL (transparent interconnect with lots of links) or SPB (shortest path bridging) data streams can be routed at level 2 even in a meshed topology in order to abandon the slow and restricting spanning tree protocol and also getting more bandwidth via redundant links.
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. The RZG participates in the eduroam initiative via DFNRoaming. This allows users to make use of the wireless networks of other institutions also participating in eduroam.

Data Acquisition and Data Bases for Plasma Fusion Experiments

The XDV group is engaged in data processing of the large-scale experiments of the IPP and is responsible for the development of the data acquisition system of the experiment W7-X. With the experience gained from previous tests of the system and from intensive communication with the users, the necessary tools to operate and to prepare the experiment were revised and completed. The portfolio of available diagnostic systems was extended through an international cooperation. The new devices are built on ATCA standards and can be used for fast acquisition of data with a high number of channels.

Scientific Staff

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Energy and System Studies

As a reaction to the nuclear accident in Japan Germany plans a fast shut down of all nuclear power plants till 2022. Renewable energies and saving measures are promoted instead. Until now it is not obvious how the new evolving systems should look like. Therefore the development of fusion is more necessary than ever, first to develop a nuclear power source without the problem of afterheat removal and second as addition to the renewable sources.

Fusion Power Plant Models

System Code Studies

The development of a system code to study next-step fusion devices was continued this year. The aim is the identification and analysis of physically and technically feasible regions in the multi-dimensional parametric space in a simplified but self-consistent way. In the framework of the EFDA workprogramme 2011, the system code was used for benchmarks with PROCESS and HELIOS, the corresponding codes of CCFE Culham and CEA Cadarache. Another activity in this context was the review of the assumptions and models used in the physics modules of the EU system codes with the objective to identify improvement needs.

Dual Use in Fusion and Industry

On the way to solutions for the complex requirements of a fusion reactor, researchers are developing new manufacturing processes, constructions, materials, theories etc., to overcome this challenge. At the same time this know-how may refine products and technologies in other applications and thus deliver the industry already today a significant benefit for the high-tech sector and qualify the industrial partners for future tasks. The outline of these multiple-use scenarios and the promotion of cooperations between industry and research is the scope of a project with the TU München and the Siemens AG.

Energy Models

EFDA-TIMES Global Energy Model

Since 2004, the group for energy system studies participates in the development of the global energy system model EFDA-TIMES, concentrating on the evaluation of future pathways for the integration of fusion power in the electricity market of the 21st century. In 2011, the model has been recalibrated according to IEA's global energy statistics to reflect the political and economic developments in the global energy sector. In parallel, several in-depth-studies have been carried out to provide a sound basis for scenario analysis investigating the influence of technological trends and system conditions on the evolution of fusion from the mid-century on. The impacts of future fission development, the influence of CCS technologies and high shares of renewable energies were the main scopes of the studies. The results of the scenario analysis form the basis for an active participation within the global scientific energy debate and facilitate the dissemination of fusion technology as a future energy option amongst stakeholders.

PACT

The EU FP7 Project Pathways for Carbon Transition (PACT) finished in September 2011. The aim of the project was to shape what a sustainable society would look like and how we could reach it within the next 50 years. Within the project the IPP was involved in work package one, which dealt with post carbon cities and land use. All reports are available by this time. The reports comprise topics like technologies, lifestyles, goods and services but also societal dynamics, risk and government or young people's human capital. One focus of the project was to model pathways for a post carbon world. Finally three scenarios are presented for assessing post carbon transition.

The Future Energy Infrastructure in Salzburg

The project lead to reliable results for the energy infrastructure in Salzburg. The first challenge was to set up a good physical description of the building stock. Working on single objects the energy models can be set up in a high geographical resolution. The localization of the heat demand dependent on refurbishment and energy prices was therefore possible. On that base optimal supply structures were analysed comparing district heating expansion with heat pumps and solar-based technologies. Furthermore the influence of a specific climate in a city on the energy system structures is considered as well as the impact of global climate changes relying on macro scale climate models.

Calculating Heat Demand from Municipal Data Sources

The subject of this project is a much more precise estimation of the municipal heat demand. The investigation area is the city of Oldenburg in Niedersachsen. The calculation of the heat demand bases upon a special designed geo-database where all data is consolidated. Therefore a fixed heat demand calculation method for the whole municipality with a high spatial resolution can be applied on a very flexible designed data input. The data was collected exclusively from municipal and administrative sources. For example one piece of information was the decisive parameter "year of construction" of buildings where information could be improved from 0 % to 80 % of the building stock.

Scientific Staff

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Electron Spectroscopy

Head: Dr. Uwe Hergenhahn

The electron spectroscopy group at IPP carries out an internationally recognized research programme on excited state dynamics of ionized systems. The focus of its work lies on autoionization processes driven by long-range Coulombic interactions (‘Interatomic or Intermolecular Coulombic Decay, ICD’); a field, which has been pioneered by experiments of the group. Besides this, the group actively develops new concepts for electron-electron coincidence detection.

Electron Spectroscopy

The spectroscopic detection of free electrons, and of their kinetic energies and velocity vector components, is an important technique with applications ranging from plasma physics via basic atomic physics to materials science. In the IPP electron spectroscopy group we use synchrotron radiation to produce free electrons by photoionization, and study them spectroscopically in order to learn about the excited state dynamics in dilute, ionized gases. Autoionization processes in weakly bonded complexes (ICD and related processes) have again been the subject of several studies, e.g. on the competition between energy transfer and charge transfer in the autoionization of mixed, ionized ArXe clusters. Aiming more at electronic structure than at dynamics, we have also continued to study band dispersion in rare gas clusters. In these experiments, clusters are produced in a supersonic jet expansion. Photoelectrons and electrons from autoionization can be probed with high efficiency and good to moderate energy resolution in a magnetic bottle electron spectrometer, as described in the Annual Report 2009.

Another important field of our activities is the development of new experimental techniques in electron spectroscopy. Our project on electron-electron coincidence detection with high-energy resolution, started in 2004, has resulted in spectroscopic studies of molecular Auger decay in unprecedented detail. In 2011 we have commissioned the apparatus for the next generation of such experiments.

Band Structure in Rare Gas Clusters

One of the main motivations for the study of clusters is the search for the onset of bulk properties: How many atoms or molecules do we need to combine in order to make a small piece of condensed matter? Indeed, this question has been asked many times – and in part answered: It depends on which specific properties of the clusters are employed to pinpoint the cross-over (or smooth transition) from molecular to bulk systems, for example, the geometrical structure as seen in electron diffraction or EXAFS, the energy positions and structure of the optical absorption by excitons or the change in ionization potential. None of these results are incorrect, but one may ask, which property is really best suited to test whether a certain cluster is ‘bulk-like’. Some of the aforementioned experiments have investigated cluster formation itself and size confinement, while others have probed the structure of the aggregates, or at least their ‘local’ geometry. Arguably, no experiment so far has had the power to determine, at which size a certain cluster develops properties that are characteristic only of the ordered crystal lattice of the bulk solid.

In very recent experiments by the IPP electron spectroscopy group strong evidence was found for the dispersion of electronic bands in a cluster, which pinpoints the transition from molecular-like behaviour. The first result was obtained for relatively large Ar clusters ($\langle N \rangle$=1670) in the valence band photoemission spectrum (M. Förstel *et al.*, Physical Review B **82**, 125450 (2010)). In a photon energy range some two to three eV above threshold the spectrum is dominated by a prominent feature, which concomitantly undergoes strong changes in apparent binding energy (ca. 0.7 eV).

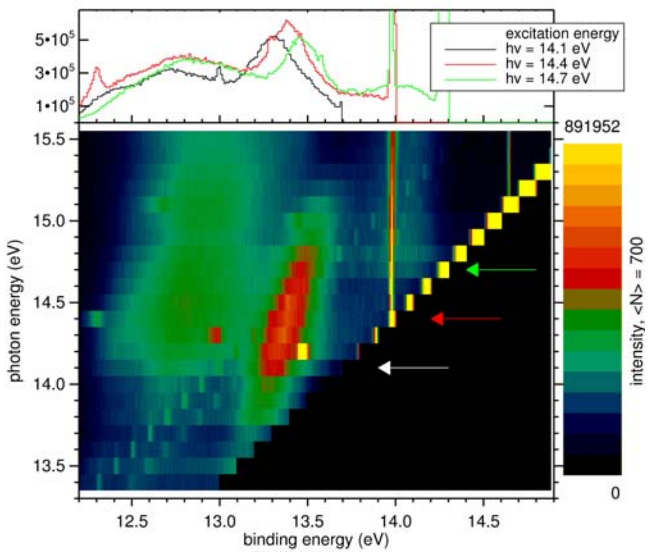

Figure 1: Valence photoelectron spectra of free Kr clusters with a mean size $\langle N \rangle$ of 700 atoms. Three spectra for selected photon energies are shown in the top panel, and from a series of such spectra the colour-coded map in the bottom panel has been compiled. The main point of interest is the intense feature showing up at photon energies between 14 and 15 eV, and binding energies between 13.1 and 13.6 eV. This change of apparent binding energy as a function of photon energy is interpreted as a signature of valence band dispersion, seen for the first time in free clusters. Recording numerous data sets for free Ar and Kr clusters we have been able to give a lower value of the mean size for the onset of electronic band dispersion in each case. The sharp features at 14.0 and 14.7 eV binding energy in the spectra shown result from photoionization of uncondensed Kr atoms, which are always present in our cluster jet. The diagonal line of high apparent intensity results from an artefact of the time-to-energy conversion in the electron time-of-flight data. Artefacts due to second order radiation from the synchrotron beamline are seen at photon energies 14.1, 14.2 and 14.3 eV.

The absolute value of the excitation energy and the degree of dispersion are qualitatively in agreement with a transition from the lowest 3p-derived band to an unoccupied band in the calculated band structure of crystalline bulk Ar. Experimental data on bulk condensed Ar films also corroborate this interpretation.

It is most interesting to determine the cluster size above, which this presumed band formation takes place. Unfortunately, for neutral clusters current experimental methods allow only the mean size ⟨*N*⟩ of a broad distribution of sizes to be selected. Moreover, estimates for ⟨*N*⟩ vary dependent on the method that is used. Nevertheless, a series of data was recorded for cluster jets with different values of ⟨*N*⟩, and weighing all evidence the onset for the recognisability of the dispersing feature could be placed between *N*=100 and *N*=230.

In 2011, with the aim of generalizing these results to other systems, we have measured photoelectron spectra of free Kr clusters of various mean sizes ⟨*N*⟩. A typical result is shown in figure 1. Very similar to the Ar case, we observe a strong feature near to the photoionization threshold, which dominates the valence band spectra of larger clusters, and which shows a dispersion of ca. 0.25 eV in binding energy. The feature is already observed for cluster beams with ⟨*N*⟩=100. Two words of caution about these statements are in order: 1. It is known from mass spectroscopy that cluster beams formed by supersonic expansion have a broad size distribution and 2. Cluster sizes given for the Kr results are based on an empirical relation between expansion parameters and size, which is of an approximate nature only. Work is under way to determine more accurately the mean cluster size with another method, namely, from the bulk and surface components observed in core level photoelectron spectra.

Electron-electron Coincidence: The "Next Generation"

Ionization of all but the lowest electron energy levels of matter produces excited states, very often leading to multiple ionization by subsequent radiationless decay, e.g. Auger decay. Auger spectra thus carry information on the final state energies, often hardly accessible by other means, and possibly also on the nuclear dynamics of the intermediate state. Much more concise information can be retrieved when the Auger spectra are filtered by recording the energy of the primary photoelectron in coincidence. We have established high-energy resolution photoelectron-Auger electron coincidence measurements of small molecules in the last few years. In 2011, together with groups from Helmholtz-Zentrum Berlin and Uppsala University, we have carried out first experiments with a 'next generation' set-up for these experiments. We stick to the combination of a time-of-flight electron energy analyser with a conventional hemispherical spectrometer, but have replaced our home-built analysers with a large, commercial instrument ('Scienta ArTOF'). First experiments on methane ions demonstrate the potential for improving the energy resolution further (figure 2). With the current set-up, it will certainly be possible to resolve vibrational structure in many metastable dications, and even breaking through the barrier of lifetime broadening of the decaying primary photoelectron lines becomes a distinct possibility.

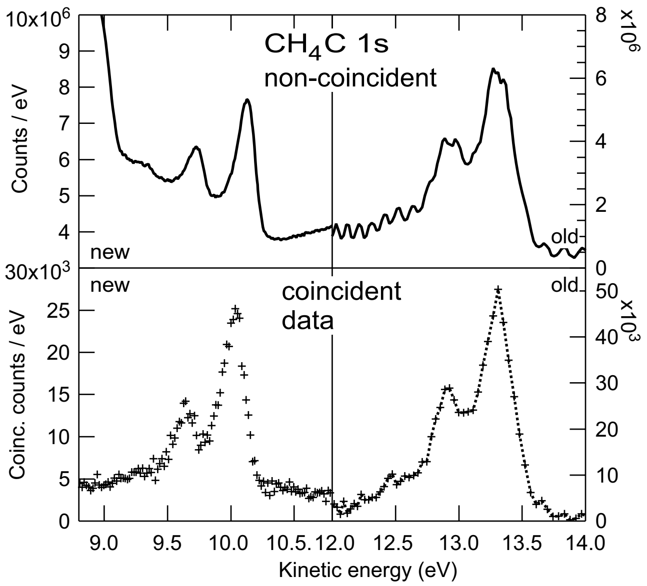

Figure 2: Non-coincident inner shell photoelectron spectrum of methane (top panels) and spectra of inner shell photoelectrons, for which the Auger electron has been recorded in coincidence (bottom panels). The two sharp lines correspond to production of an ion in its ground state and in its first vibrationally excited state. Data recorded with the old set-up (right) are compared with those using an ArTOF analyser for photoelectron detection (left). Coincidence count rates are comparable, but total acquisition time has been lower for the new data.

Interatomic and Intermolecular Coulombic Decay

The experimental investigation of ICD has also continued at a high pace. In particular, greatly improved data sets for ArXe mixed rare gas clusters have been recorded, since here competition between autoionization mediated by energy transfer and autoionization by charge transfer is expected. The IPP group is one node in a proposal for a research network (*Forschergruppe*) on ICD recently submitted to the *Deutsche Forschungsgemeinschaft* (German Research Foundation).

Scientific Staff

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Astrophysics and Laboratory Plasma Studies (ALPS)

Heads: Prof. Dr. Günther Hasinger, Dr. Mara Salvato

The "Astrophysics and Laboratory Plasma Studies" (ALPS) was established in September 2009. Half of the group is currently developing X-ray detectors conventionally used in X-ray space astronomy for plasma diagnostics while the other half is occupied in studying the properties of galaxies hosting an Active Galactic Nuclei (AGN), one of the most powerful sources of X-ray emission in the Universe. Our work is done in close collaboration with the HLL and MPE.

Laboratory Experiments

X-ray Signal Reconstruction

We are developing a new Hard-X-ray detector, designed to combine X-ray spectrometry and millisecond time resolution with the imaging capabilities of a pinhole camera. The sensor uses a single cylindrical CsI(Tl) scintillator crystal (O=8.7 mm, height=5 mm) to detect X-rays. The optical light produced in the scintillator is read out by 7 hexagonal Silicon Drift Detectors (SDD) with a outer diameter of 3.3 mm on a single chip produced by the companies PNSensor and PNDetector.

In this design, the amplitudes of the signal is used to a) measure the energy of the incoming X-ray and b) detected the point of interaction of the photon inside the scintillator. The spatial information is then used to calculate the origin of the radiation and this allows imaging just like a pinhole-camera. However, the reconstruction of all these parameters involves special requirements on hardware and deep understanding of how the signal out of the 7 SDDs is generated. For this purpose we simulated different physical processes taking place in the detector and tried to recover the initial input values. Finally we succeeded in developing a method of reconstructing the point of interaction (figure 1) in three dimensions.

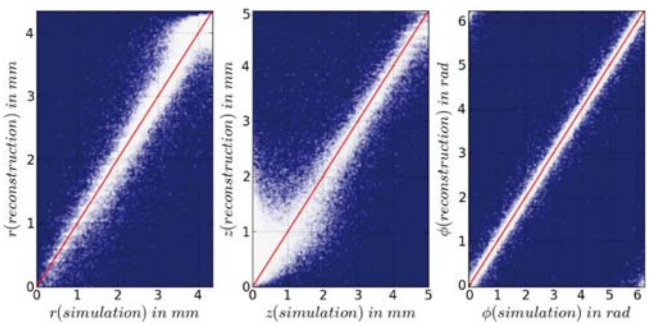

Figure 1: Reconstruction of the signal from simulations.

The most difficult of the three dimensions, i.e. the distance between interaction and the silicon surface, could be computed with an accuracy better than 1 mm for most of the scintillator volume. Assuming a pinhole 100 mm in front of the detector, projection of the X-ray to the surface of the scintillator yields a spatial resolution of 0.44 mm (FWHM) where each of the SDDs has an outer diameter of 3.3 mm and the scintillator a diameter of 8.7 mm. This means events can be resolved almost a factor of 10 better than the size of the SDD.

Right now, these numbers are only based on simulations as the detector hardware is not completely finished yet. Currently the last of the mechanical pieces and a specialized data acquisition system are under construction at the IPP workshops. First measurements will take place beginning of 2012 when the hardware setup is completed at the WEGA instrument.

ECRH Physics at Hard X-ray Regime: ALPS HXR Diagnostics

Another interest of the group is the study of highly energetic (suprathermal) electron tails during the electron cyclotron resonance heating at AUG. The best energy range for the investigation of the ECRH physics in this context lays between the atomic X-ray energies and the nuclear origin gamma energies i.e. 20 keV to 2 MeV. For this purpose, a hard X-ray diagnostics system has been recently installed at ASDEX Upgrade and is functional since the last (2011) campaign. The diagnostics is based on the Silicon Drift type Detector (SDD) coupled to a CsI(Tl) scintillator. The SDD is 6 mm in diameter and 450 micron thick. The cylindrical shaped scintillator sits on the top, and has diameter of 5 mm and height 5 mm. The plasma discharges with dominant ECRH/ECCD are of interest for us.

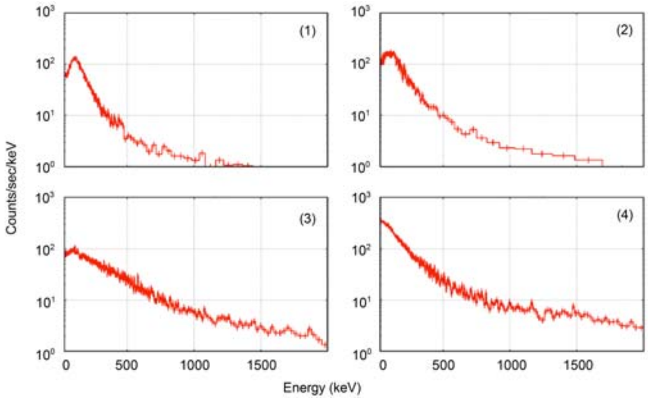

Figure 2. The Hard X-ray spectra recorded during the discharge #27227, in four time bins (1-4), roughly 500 msec each. Spectrum (3) shows the extended energetic tail formation as a response to the onset of ECRH.

The resonance heating of the electrons is a process of transfer of energy from waves to the particles. When the waves impart the momentum in a specific direction, the electrons can gain extremely high energies and can drive a significant current. Figure 2 shows the hard X-ray spectra recorded during the discharge #27227 and the evolution of the spectrum over four time bins (tagged 1-4). The spectra 1-2 are recorded before turning ON the ECRH and spectra 3-4 are recorded during the ECRH turned ON. The flattened spectrum 3, implies the building up of the high energy tail as a response to the onset of the ECRH. In the last spectrum the plasma core temperature is seen to undergo a sudden drop i.e. also visible in the increased counts towards lower energies. At the same time the energetic electron tail starts decaying. Given the total applied ECRH power of 1 MW, the extent of the energetic tail is quite surprising. We plan to continue to study the properties of the suprathermal tail during ECRH through the proposed dedicated discharges in the coming campaign. Simultaneously, measurements at the PIGE instrument are undergoing with the purpose to better calibrate our instrumentation.

Astrophysics

Multi-wavelength Spectroscopy and Modelling of (Photo)ionized Plasma in AGN

Emission and absorption lines from ionized gas represent important diagnostics of the physical conditions in the inner regions of Active Galactic Nuclei (AGN), and in the immediate vicinity of the supermassive black holes (SMBHs) at their centers. In the plasma surrounding SMBHs, the physical conditions are extreme, and they allow us to probe rare physical processes and the conditions of matter under very strong gravity.

We have an ongoing monitoring program to identify bright AGN with strong imprints of ionized matter in their (low-state) X-ray spectra, including multi-wavelength follow-up spectroscopy and modelling of the ionized gas based on dedicated photoionization codes. We find that the X-ray spectra of the observed AGN are well described by emission from the accretion disk and highly ionized gas superposed in absorption, of high column density. In one case, the X-ray properties are so extreme, that we likely see emission of gas close to the SMBH's event horizon (D. Grupe, S. Komossa, L. Gallo et al., The Astrophysical Journal (2012), submitted).

Ultra Hard X-ray AGN Luminosity Function

Determining the luminosity function of active galactic nuclei (AGN) plays an important role in mapping the growth of supermassive black holes located at the centers of most massive galaxies, while at the same time is a key ingredient in shedding light on the coevolution of the AGN and their host galaxies. For the first time we are able to compile a sizable sample of 500 AGN detected in the 5-10 keV with the goal of determining the luminosity function of AGN in this particular energy band. The benefit of the 5-10 keV band lies in the fact that even for high hydrogen column densities NH~$10^{23}cm^{-2}$, the 5-10 keV remains largely unaffected by photoelectric absorption. Our results show that in the early Universe, high luminosity AGN where more abundant than today, while the present epoch is dominated by low luminosity sources (S. Fotopoulou et al., 2012, in preparation).

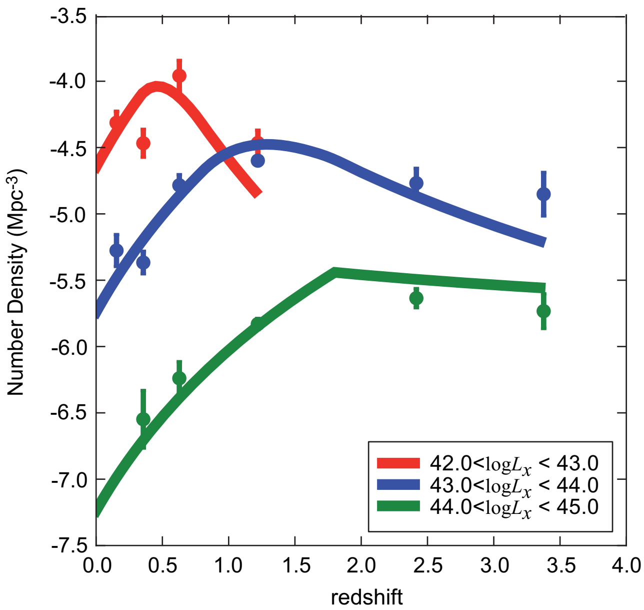

Figure 3:Number density of AGN as a function of redshift for different luminosity ranges. More luminous AGN were more abundant in the early Universe than today.

Occupation of X-ray Selected Galaxy Groups by X-ray AGN

The theoretical understanding of the AGN distribution in the Universe has been greatly enhanced through the halo occupation distribution (HOD) modelling. The power of the HOD is the capability to transform data on clustering into a physical relation between AGN and dark matter halos (DMHs) at the level of individual halos.

By using this framework we can constrain the typical DMH mass, in which AGN reside and the distribution of AGN within halos as a function of the DMH mass. These measurements led us to a more comprehensive view of what kind of environment is more likely to host AGN and address, which physical processes are triggering AGN activity.

Due to the low number density of AGN, there have been few results in the literature studying the shape of the HOD. In this work, we directly count the number of AGN within DMHs as a function of the halo mass (HOD), by using a sample of X-ray selected AGN and galaxy groups in the COSMOS field at redshift <1. Our results suggest that the fraction of AGN increases with the DMH mass. In particular the fraction of central AGN in DMHs is neither a constant nor an negligible contribution at $M_h>10^{13}$ M_{SUN}, as found in previous works (V. Allevato et al., 2012, in preparation).

Scientific Staff

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University Contributions to IPP Programme

Cooperation with Universities

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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

Fusion research and engineering are collaborative and international long-term endeavours. For that reason IPP is interested in sparking national and international students' interest in high-energy plasma physics and other fusion-relevant fields like plasma-material interaction. Teaching plasma physics at various universities has therefore a long tradition at IPP. In 2011, 27 members of IPP taught at universities or universities of applied sciences: Many members of the IPP staff are Honorary Professors, Adjunct Professors or Guest Lecturers at various universities and give lectures on theoretical and experimental plasma physics, fusion research, data analysis and materials science. Table 1 gives an overview. The teaching programme has been highly successful over the years and many students who first came into contact with plasma physics through lectures given by IPP staff have later done thesis work and even taken up a career in the fusion research.

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 2011 for the 26th time at Greifswald. Most of the participants were from Europe but the number of participants from abroad is steadily increasing. 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 four years ago. At present institutions in Germany, Italy (EURATOM Association Consorzio RFX Padova and the University of Padua), and Portugal (EURATOM Association IST) are supporting this programme.

University	Members of IPP staff
University of Greifswald	Dr. Hans-Stephan Bosch Dr. Andreas Dinklage Prof. Olaf Grulke Prof. Per Helander Prof. Thomas Klinger Dr. Heinrich Laqua
Technical University of Berlin	Prof. Dr. Robert Wolf
Technical University of Munich	Prof. Sibylle Günter Dr. Klaus Hallatschek Prof. Thomas Hamacher Prof. Günther Hasinger Dr. Philipp Lauber
University of Munich	Dr. Thomas Pütterich Dr. Jörg Stober Prof. Hartmut Zohm
University of Augsburg	Prof. Ursel Fantz
University of Ulm	Dr. Frank Jenko Dr. Emanuele Poli Dr. Jeong-Ha You
Technical University of Graz	Dr. Udo v. Toussaint
University of Tübingen	Dr. Rudolf Neu
University of Bayreuth	Dr. Wolf-Christian Müller-Nutzinger Dr. Wolfgang Suttrop
University of Gent	Prof. Jean-Marie Noterdaeme
University of Stuttgart	Prof. Ulrich Stroth

Table 1: IPP staff who taught courses at universities in 2011.

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 In the year 2011 a total of 57 postgraduates were supervised, 14 of them successfully completing their theses.

Joint Appointments, Grown and Growing Cooperation

IPP cooperates closely with several universities in the form of joint appointments. By the end of 2011 there was a W3 appointment at the Ernst-Moritz-Arndt University of Prof. Sunn-Pedersen in the field of experimental plasma physics.

An further W2-appointment in the field of plasma astrophysic at the Technical University of Berlin is expected to take place in 2012.

To intensify the cooperation, the Technical University of Munich and IPP agreed upon three joint professorships in various fusion-relevant research fields, i.e. plasma edge and divertor physics, plasma-wall interactions, and numerical methods in plasma physics. Two joint W3 appointments are expected in 2012.

A further example of the close cooperation with universities is the development of a negative-ion source for the neutral-beam injection – selected as reference source for ITER – in cooperation with University of Augsburg. 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 Helmholtz Graduate School for Plasma Physics (HEPP), started in October 2011, which is a graduate school for doctoral candidates at the Max-Planck-Institute for Plasma Physics (IPP) and their partner universities the Technical University of Munich (TUM) and the Ernst-Moritz-Arndt University of Greifswald (EMAU). Associated partners are the Leibniz Institute for Plasma Science and Technology (IPN) in Greifswald and the Leibniz Computational Center (LRZ) in Garching. HEPP aims to provide a coherent framework at IPP and the participating universities for qualifying a new generation of internationally competitive doctoral candidates in the field of plasma physics, fusion research, computational physics and surface science,
- the International Max Planck Research School on Bounded Plasmas at Greifswald in cooperation with Greifswald University (which ended after 6 years in 2011),
- 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:

- the European Research Council (ERC) has awarded a starting grant of 1.45 million euros over five years in support of the research on plasma turbulence headed by Professor Dr. Frank Jenko at the Max Planck Institute of Plasma Physics (IPP) in Garching,
- European Young Investigator Award Group, Zonal Flows, headed by Dr. Klaus Hallatschek,
- Helmholtz Russia Joint Research Group, Hydrogen Behaviour in Advanced and radiation damaged materials for fusion applications, headed by Dr. Matej Mayer as Helmholtz Principle Investigator and Dr. Alexander V. Spitsyn, RSC Kurtschatov 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.

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. IPP is also one of the eight partners of the newly formed International Doctoral College in Fusion Science and Engineering, which has been approved under the auspices of Erasmus Mundus, the European programme to promote training schemes. The doctoral college, which has started in October 2011 is being supported with about five million euros and provides 40 doctoral scholarships for work in the field of fusion research.

University of Augsburg
Lehrstuhl für Experimentelle Plasmaphysik

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

The research at the University of Augsburg is concentrated on diagnostics of low temperature plasmas, on investigations of the plasma chemistry in molecular plasmas and on plasma surface interaction. For that purpose several different low pressure plasma experiments are available. Focus is laid on developments for negative hydrogen ion sources, which are carried out in close collaboration with the Technology Division of IPP.

Developments for Negative Hydrogen Ion Sources

Helicon discharges in hydrogen are investigated as an alternative concept for plasma generation by the inductive rf-coupling as used in the IPP prototype ion source for the ITER neutral beam systems. The helicon concept promises higher rf-power efficiency as well as higher atomic hydrogen and positive hydrogen ion densities at the required low pressure. In a first step the discharges are generated with an rf-frequency of 13.56 MHz in a quartz tube with 10 cm diameter and 40 cm length utilizing the m=1 helicon mode with a Nagoya type III antenna and Helmholtz coils with an axial magnetic field up to 15 mT. As already reported (Annual Report 2010), an axially averaged ratio of atoms to molecules of about 5-10 % is achieved, increasing with the magnetic field strength. In deuterium, a higher dissociation is observed; the ratio varies from 7-17 %. In addition, a peak appears at low magnetic field strengths, which is known as the typical low-field peak of a helicon discharge. Figure 1 shows the increase of the atomic to molecular density ratio at the low-field peak in the accessible power range. As indicated, the typical value of the IPP source at the test facility BATMAN is achieved at a remarkably reduced power level. However, direct scaling requires a change to the same plasma volume, in particular by changing the aspect ratio, as well as an adoption of the lower rf-frequency; both steps are in preparation.

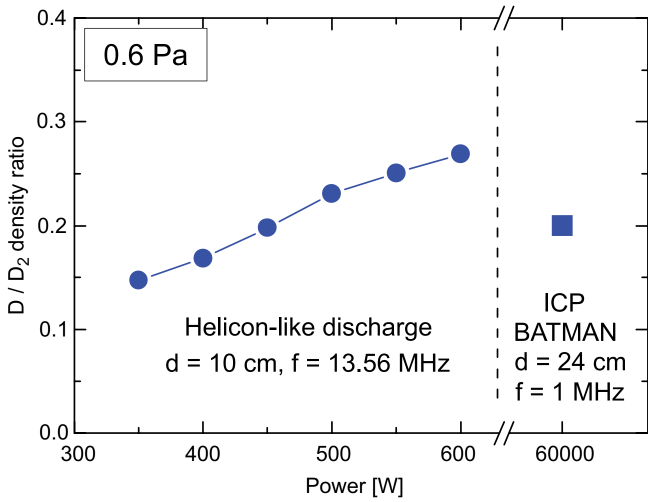

Figure 1: Atomic to molecular deuterium density ratio at the low-field peak of a Helicon-like discharge (ICP with magnetic field) compared to the respective ratio in the IPP prototype source at BATMAN. In both cases the ratios are determined by emission spectroscopy using an axial line of sight.

In ion sources for ITER the formation of negative hydrogen ions is based on the effective conversion of atoms and positive ions at the caesium layer on the plasma grid surface. Since the source performance depends on the very complex caesium dynamics in the source, alternative mechanisms or materials are highly desirable. The ECR plasma experiment used for these investigations is equipped with an electrostatic grid to cool the electrons and thus minimize the destruction of negative ions. At the standard parameters (1 Pa, 400 W) the electron temperature decreases from roughly 3 eV to 1 eV, the electron density is reduced by a factor of 4 to a value of 4×10^{16} m^{-3} and the atomic to molecular hydrogen density ratio is 1.5 %. In this source a ratio of negative ions to electrons of about 16 % has been achieved by volume formation, i.e. the dissociative attachment of hydrogen molecules (Annual Report 2010). After introducing a tungsten surface the negative ion ratio shows a dependence on the distance to the surface and increases almost by a factor of two as shown in figure 2. Further surface materials will be tested next as well as the influence of the surface temperature and biasing the surface.

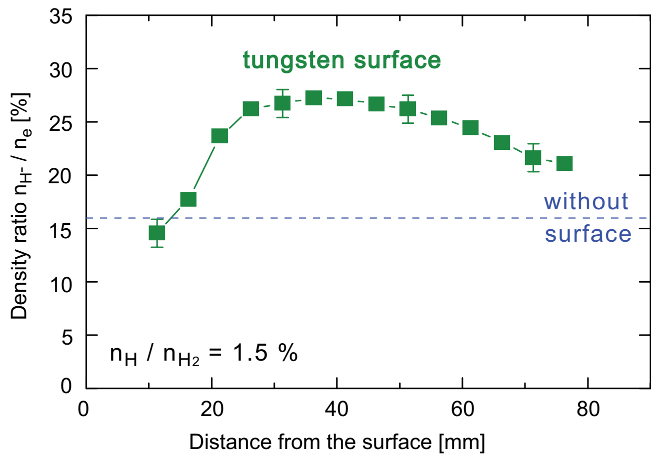

Figure 2: Density ratio of negative hydrogen ions to electrons as measured by laser detachment above a tungsten surface in an ECR discharge at 1 Pa pressure and 400 W microwave power.

For monitoring the caesium density in the plasma and in the vacuum phase of the IPP test facilities, the developed laser absorption system is routinely in operation now. In a planar ICP plasma source basic experiments on the caesium dynamics are carried out using white-light absorption and emission spectroscopy, a surface ionization detector and a mass spectrometer.

Together with the newly installed temperature control system for the cooling water the influence of the wall temperature (20 °C up to 65 °C, covering the same range as in the ion sources), on the caesium amount in the source is investigated systematically. The combined measurements show that the volume average density of caesium in the vacuum chamber is – in contrast to the expected behaviour – drastically reduced by increasing the wall temperature, which can be explained by the release of water from the walls reacting subsequently with the evaporated caesium. This demonstrates once more the sensitivity of caesium on small amounts of impurities resulting in deactivation of the caesium layers. Systematic measurements of the subsequent degradation of the work function will follow.

Low Temperature Plasmas

For the quantitative diagnostic of plasma parameters from optical emission spectroscopy collisional radiative (CR) models are constructed, tested and steadily improved. Besides CR models for helium and argon, models for atomic and molecular hydrogen are available now. Recently, a CR model for molecular nitrogen has been established and benchmarked in low pressure arc discharges in nitrogen. In the mbar pressure range heavy particle collisions play an important role for the population balance. In particular, the collision induced transitions between the metastable $A^3\Sigma_u^+$ state and the $B^3\Pi_g$ state turned out to be relevant to match the emission from the 1st positive system of nitrogen ($B^3\Pi_g \rightarrow A^3\Sigma_u^+$) with the measurements. In mixtures with other gases, however, it is not clear from the literature whether nitrogen only or all neutral particles have to be considered as collision partners. Therefore nitrogen mixtures with argon have been investigated as well. In the CR model two cases have been checked: case I with $M=N_2$ and case II with $M=N_2+Ar$ for the reaction $N_2(A)+M \leftrightarrow N_2(B)+M$. Figure 3 clearly shows that always both species have to be considered to reproduce the measured radiation of the 1st positive system for all nitrogen concentrations whereas the 2nd positive system ($C^3\Pi_u \rightarrow B^3\Pi_g$) is independent of this process. For the latter, however, the excitation transfer from metastable argon particles to the excited $C^3\Pi_u$ state of nitrogen has to be taken into account, which in turn requires a coupling of the CR model for argon with the one for nitrogen.

Planar ICP discharges in rare gases are used to identify suitable emission lines of neon and krypton for electron temperature diagnostics provided the electron density is known. The plasma parameters are measured by a Langmuir probe. Spatially resolved measurements allow for consideration of their profiles along the line of sight. A residual gas analyser is used to take the demixing of a specified gas mixture into account. Argon and helium, for which CR models exist, are added to get a consistent picture from optical emission spectroscopy. In those cases, the argon line at 750 nm and the helium line at 728 nm have been established as standard lines for electron temperature diagnostics. Since for neon and krypton such models are missing, emission lines have to be selected, for which ground state excitation dominates such that the simplified corona model can be applied. Regarding neon, the emission lines at 540 nm and 585 nm are identified as being suitable for diagnostics; in case of krypton the emission lines at 758 nm and 768 nm can be used. Other neon and krypton lines are clearly influenced by excitation from the metastable particles resulting in remarkably higher radiation than predicted by the corona model. The results, however, indicate that a non-Maxwellian EEDF has to be used for the analysis.

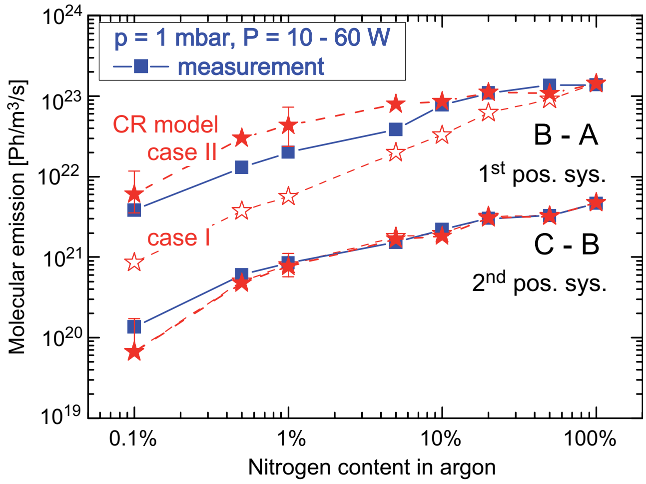

Figure 3: Intensity of the 1st and 2nd positive system of molecular nitrogen: measurements (squares) compared to predictions from the CR model including heavy particle collisions using as collision partner N_2 (case I, open stars) or N_2 and Ar (case II, full stars).

Diploma and PhD Theses

S. Briefi: Spectroscopic Investigation of Indium Halides as Substitutes of Mercury in Low Pressure Discharges for Lighting Applications. (PhD Thesis)

T. Maier: Laser-Photodetachment zur Quantifizierung der Volumenproduktion negativer Wasserstoffionen im ECR-Plasma. (Diploma Thesis)

F. Vogel: Vergleich der Strahlungscharakteristik von Stickstoff in Niederdruck-Bogenentladungen mit verschiedenen Hintergrundgasen. (Diploma Thesis)

Scientific Staff

U. Fantz, S. Briefi, W. Böhm, D. Ertle, R. Friedl, S. Kalafat, U. Kurutz, T. Maier, F. Vogel.

University of Bayreuth
Lehrstuhl für Theoretische Physik V

Head: Prof. Dr. Arthur G. Peeters

In the frame of the collaboration between IPP and the University of Bayreuth, research projects on nonlinear dynamics and computational physics are carried out. They include the study of neoclassical and turbulent dynamics of magnetic islands, of the influence of the centrifugal force on plasma turbulence, of electromagnetic effects within the global plasma description and of toroidal momentum transport.

Cooperation

With the opening (2010) of a new Chair for theoretical plasma physics, supported by the University of Bayreuth, the 'Volkswagen-Stiftung' and the IPP, the University and the IPP continue and strengthen their long term collaboration, in particular in the areas of nonlinear dynamics and computational physics. In 2011 this collaboration resulted in seven publications with shared co-authorship. Many of the research projects use the state of the art nonlinear gyro-kinetic code GKW, which is developed by scientists in both Bayreuth as well as IPP. Two examples are discussed in some detail below.

Island Dynamics

Magnetic islands are known to limit the performance of the plasma in tokamak devices. Neoclassical processes play a fundamental role in their dynamics. In particular, the early phase of the island evolution is poorly understood, among other things because analytic calculations become difficult in the limit of small island widths (of the order of the thermal ion banana width). Numerical gyrokinetic simulations have been employed to investigate this issue, retaining finite-orbit effects and including a self-consistent determination of the electrostatic potential in the island region via the Poisson equation. An adiabatic response of the trapped ions is found to lead to a significant smoothing of the electrostatic potential across the island separatrix as compared to analytic predictions used to interpret experimental results. In particular, the neoclassical polarization current often invoked as a key ingredient for the stability of small islands falls below detectability. The classical polarization current is also strongly reduced, as shown in figure 1.

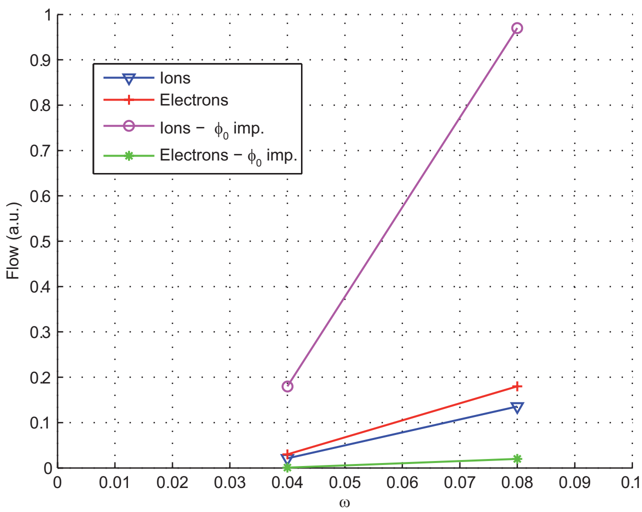

Figure 1: Classical polarization flows for ion and electrons from gyrokinetic simulations (GKW) with imposed analytic potential φ_0 and with self consistent potential.

High Mach Number

Heavy impurities have toroidal rotations, which can exceed their thermal velocity in tokamaks. Therefore, the impact of centrifugal effects is an important element in the research on turbulent impurity transport. This has been investigated with numerical simulations with GKW. The gyrokinetic model has been extended to include the radial variation of the background plasma toroidal velocity, which has enabled consistent two dimensional reconstructions of the predicted impurity density distribution, shown in figure 2. The impact of centrifugal effects on the predicted peaking depends on the size of the Mach number, on the radial gradient of the toroidal velocity and on the local aspect ratio. For sufficiently small values of the toroidal velocity gradient, centrifugal effects reduce the gradient of the low field side impurity density profile, whereas for sufficiently large values the gradient of the impurity density is increased. Present research is dedicated to the identification of signatures of the impact of centrifugal effects on turbulent impurity transport in the experimental observations.

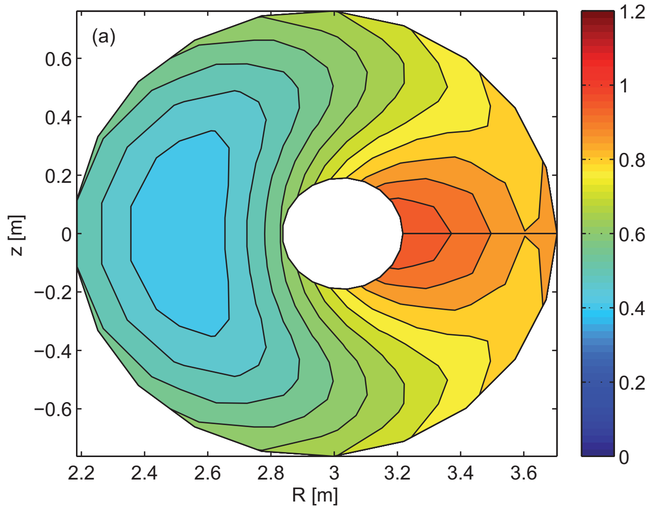

Figure 2: Poloidal cross section of the predicted two dimensional density distribution of chromium for typical conditions of a H-mode plasma with neutral beam injection heating. This result is obtained imposing the condition of the flux surface averaged turbulent chromium flux computed by GKW to be equal to zero. The centrifugal trapping effect at the low field side is clearly visible.

Scientific Staff

C. Angioni, A. Bottino, F. J. Casson, T. Hein, W. A. Hornsby, W.-C. Müller, E. Poli, B. D. Scott, M. Siccino.

Ernst-Moritz-Arndt University of Greifswald

IMPRS "Bounded Plasmas"

The education within the framework of the "IMPRS on Bounded Plasmas", which ended 2011, was for long time the key element of the cooperation with the Ernst-Moritz-Arndt University Greifswald. Since 2011, the new "International Helmholtz Graduate School for Plasma Physics" took over this important role. Another scientific collaboration is performed in the field of plasma propulsion, where dedicated particle-in-cell simulations are performed.

Head: Prof. Dr. Thomas Klinger

The International Max-Planck Research School "Bounded Plasmas" jointly run by IPP, the Institute of Physics of the Ernst-Moritz-Arndt University Greifswald, and the Institute for Low-Temperature Plasma Physics, Greifswald ended after the maximum allowed allowance period of 10 years in May 2011. The very successful program combined uniquely the expertise of the contributing institutions on basic plasma research, plasma technology, and fusion science to foster a structured Ph.D. student education. Additional expertise was provided in the framework of guest lectures by external lecturers on dedicated topics of plasma physics and soft skills. More than 50 guest lectures were organized. The school had typically 25-30 students per year as regular members with a total number of members over the entire period of 86, well balanced among the institutions. The international character of the school is expressed by a total number of foreign students of nearly 50 %. The excellent education and research environment lead to an average time for the Ph.D. projects of 3.2 years, which is well below the German university average.

International Helmholtz Graduate School for Plasma Physics

Speakers: Prof. Dr. Frank Jenko, Prof. Dr. Thomas Klinger

As a successor program the "International Helmholtz Graduate School for Plasma Physics" started in October 2011 with a considerably broadened scope. Its mission is to provide a structured Ph.D education and to provide an interdisciplinary research environment. Partner institutions are IPP Greifswald and Garching, the Ernst-Moritz-Arndt University Greifswald and the Technical University Munich, including the Leibniz Computational Center Munich and the Institute for low-temperature Plasma Physics Greifswald as associated partners. A key aspect of the program is the exchange of lecturers to provide a homogenous research portfolio across the institutions supplemented by external guest lecturers. A regular graduate seminar and yearly graduate colloquium has been already established to encourage know-how transfer among the Ph.D. students. By end of 2011 in total 56 students were members of the school.

Particle Modelling of Plasma Thrusters

Head: Prof. Dr. Ralf Schneider

Within the DLR project 50RS0804 particle-in-cell models, originally developed for fusion applications, are applied to ion propulsion systems in collaboration with Prof. Dr. Ralf Schneider at the Ernst-Moritz-Arndt University in Greifswald. Ion propulsion gets more and more attractive for satellites due to the larger exit velocity compared with chemical propulsion allowing weight reductions of some 100 kg. Developments of ion propulsion systems are dominated by empirical testing of prototypes. Advances in the physics models for plasmas in contact with walls and in computing create new chances for numerical optimization and cost reduction by a smaller number of prototypes. The interaction of the plasma with the walls and its influence on the performance as well as fluctuation-induced transport processes are key elements for a better physics understanding, as also in fusion plasmas.

A 3-dimensional Particle-in-Cell code with Monte Carlo Collisions (PIC MCC) was applied to simulate the operation of the PPPL 100 W cylindrical Hall thruster (CHT). The CHT has a reduced ratio of the channel surface area to volume which is limiting electron transport and ion losses.

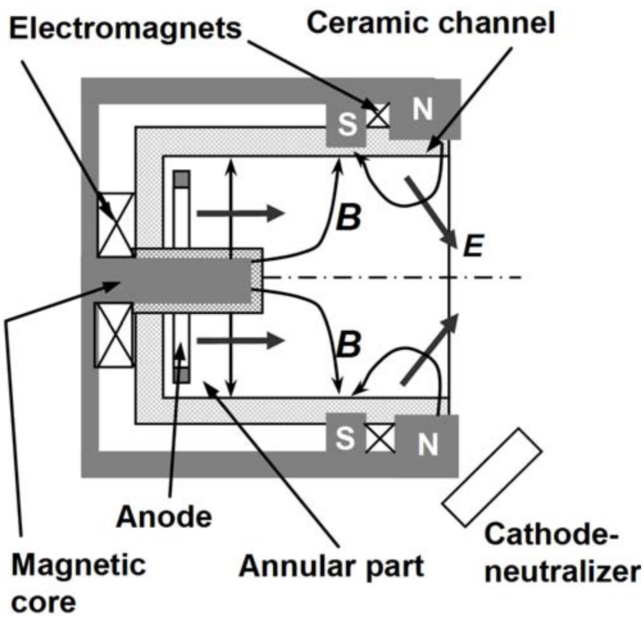

Figure 1. Schematic of a cylindrical Hall thruster.

Figure 1 illustrates the principle of operation of the cylindrical thruster. A cylindrical Hall thruster consists of a cylindrical ceramic channel, a ring-shaped anode, which serves also as a gas distributor, a magnetic core and magnetized sources. The magnetic field lines intersect the ceramic channel walls.

The electron drifts are closed, with the magnetic field lines forming equipotential surfaces, with $E = -v_e \times B$, where E is the electric field and v_e is the electron drift velocity. The radial component of the magnetic field crossed with the azimuthal electron current produces the thrust. However, the electrons are not confined to an axial position; rather they bounce over an axial region, impeded from entering the annular part of the channel because of magnetic mirroring. Two magnetized sources, electromagnetic coils with opposite currents, can produce a cusp-like magnetic field in the channel, with a strong radial component. To maintain ionizing collisions, the anode (gas inlet) is placed in the short annular part of the channel. The length of the annular part of the channel is designed to minimize the ionization mean free path, thus localizing the ionization of the working gas at the boundary of the annular and cylindrical regions. Hence, most of the voltage drop occurs in the cylindrical region that has large volume-to-surface ratio.

In the simulation a spoke moving with the velocity of about 0.8 cm/µs was observed. The initial position of the spoke was found to be strongly correlated with the cathode placement. The simulation has shown that the depletion of neutral gas can lead to azimuthal asymmetry of the discharge and possibly to the spoke phenomenon.

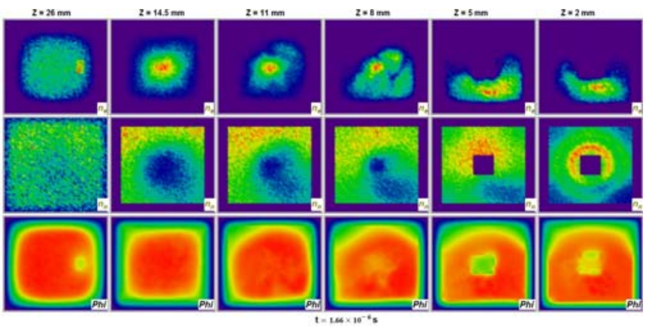

Figure 2. Snapshot of the plasma parameters at $t = 1.691 \cdot 10^{-6}$ s taken at six lateral cross-sections. Top row – plasma density, middle row – neutral density, bottom row – plasma potential. All values are given in relative units: reds correspond to the maximum value, blues to the minimum.

In figure 2 at $t = 1.691 \cdot 10^{-6}$ s it becomes clearly visible in the simulations that the spoke causes azimuthal asymmetry in the neutral density profile along the thruster channel, depleting the neutrals due to electron-impact ionization. The depletion of the neutral density at the spoke position reaches ~80 % at Z=11 mm. This is also where the electron density reaches its maximum $N_{e\,max} = 2.4 \cdot 10^{12}$ cm^{-3} along the thruster channel. The rapid ionization in the spoke indicates that a strong electric field is present, heating the electrons. Indeed, the electric field oscillations with frequency f≈10 MHz, wavelength λ≈4 and the amplitude up to 100 V/cm both in the axial and azimuthal directions are observed in the simulation. These fluctuations are responsible for the electron heating and cross-field transport in the simulation. The electron current through the spoke in the simulation was $I_e \approx 0.55$ A, which is at least by two orders of magnitude larger than current provided by "classic" diffusion due to collisions with neutrals; and no near-wall conductivity is accounted in the model as the secondary electron emission is neglected. The measurements of the electron current flowing through the spoke[20,21] have shown that approximately 50 % of the total current is conducted by the spoke.

The clarification of the phenomena underlying the spoke formation and the dynamics as well as electron transport inside the spoke will be the goal of our further research.

Technical University of Munich
Lehrstuhl für Messsystem- und Sensortechnik

Head: Prof. Dr.-Ing. Dr. h.c. Alexander W. Koch

Introduction

There has been a continuous cooperation of IPP and TUM, Institute for Measurement Systems and Sensor Technology in the past. Next to thermography, thin film and speckle interferometry has been a field of research. Since last year, the focus of the collaboration was extended towards the ITER Bolometry Group. The objective of this cooperation is the development of an automated method to measure the geometric function of the lines of sight of diagnostics.

The measurement and evaluation of the plasma parameters in ASDEX Upgrade is done by numerous diagnostic systems. It is crucial to know accurately the position, orientation and geometric properties of the various components of the corresponding sensors and detectors. Some of them need for a successful reconstruction of plasma parameters to take the finite sizes of detectors and apertures and the resulting non ideal measurements into account [3,4]. For example, in order to derive the local emission profile of the plasma radiation in a fusion device using the line-integrated measurements of the bolometer diagnostic, tomographic reconstruction methods have to be applied to the measurements from large numbers of different lines of sight [2]. Moreover bolometry diagnostics in future fusion research facilities like ITER are facing new challenges, e.g. that the viewing cones have to pass through narrow gaps between components for shielding. The lines of sight might then not be defined by the diagnostic itself but by other components [3].

Objective

Our approach is the development of an automated procedure of the measurement of the geometric properties of diagnostics in ASDEX Upgrade. Current experiments were done with prototypes manufactured as part of the development for the ITER bolometer diagnostic (see chapter 5) and the basic feasibility was already shown in the development of a laboratory assembly [1]. A research lightweight robot from KUKA was used to position an intense light source in the three-dimensional space oriented towards the diagnostic. Simultaneously the generated signal was measured and correlated with the actual robot coordinates. Figure 1 shows the measurement principle.

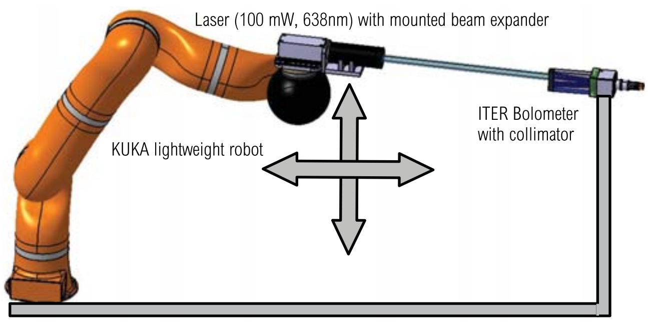

Figure 1: Schematic CAD drawing of laboratory assembly for the line of sight calibration.

A laser with high intensity is used as energy source to illuminate a bolometer assembly consisting of detector and collimator from many different angles in the poloidal and toroidal direction. The correlation between the response of the bolometer and the position-signals of the robot allows the calculation of the angular étendue. Figure 2 shows that the étendue of each channel is characterized by the construction parameters of the collimator like cover plate size (green), channel width (yellow), diameter and number of the integrated apertures (red). The automation allows to cover many points and to measure the viewing cone of each line-of-sight and above all, provides repeated measurements with a constant and reliable accuracy to achieve a comparable standard allowing binding statements.

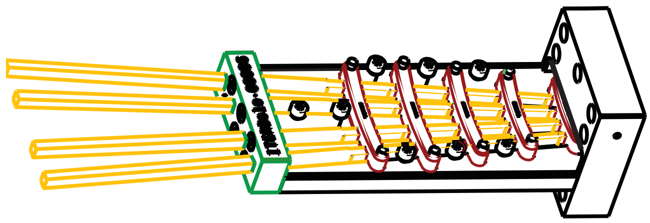

Figure 2: Lines of sight of a collimator for ITER bolometer: Apertures inside the collimator are limiting the radiation beam.

ITER Bolometer Development

In the following part two different measurement results from ITER prototype bolometers will be presented to give a first overview of the current capabilities of the test rig. The data acquisition was implemented using National Instruments LabVIEW and the control of the robot was programmed using the KUKA Robot Language (KRL) and via a Network Interface Library from ImagingLab Vision & Robotics.

Measurements with Different Collimator Configurations

In order to understand the causal relationship between the geometry of the sight lines and the configuration of the specific bolometer and to determine the reason for the stray light, which was discovered in previous measurements [1], tests with different assembly settings were done. Figure 3 shows the normed transmission functions of one single channel in the poloidal plane, i.e. representing a vertical movement of the light source from top to down, with four different configurations, respectively: The original collimator prototype, then two modified versions where parts of the channel borders have been removed and one with only three integrated apertures instead of five.

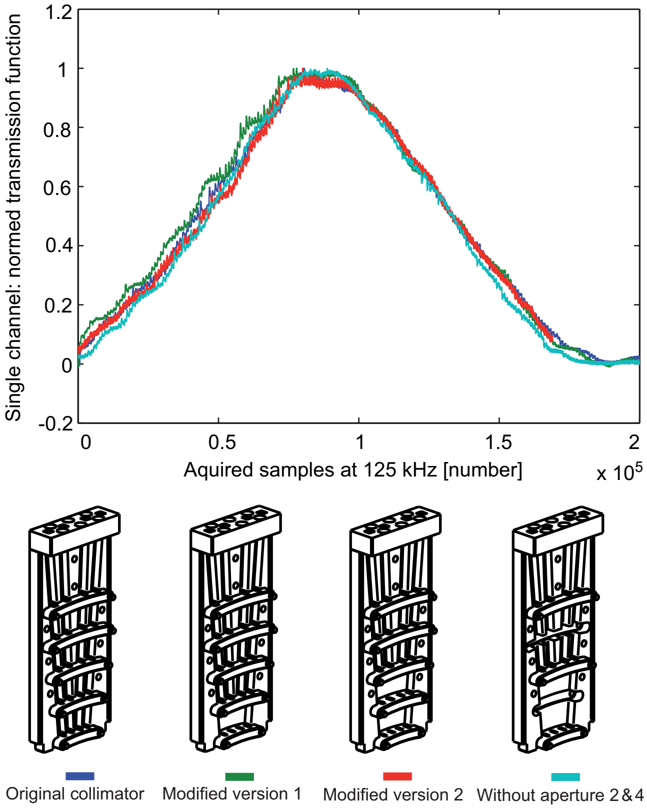

Figure 3: Measurements of the normed transmission function with the following collimator configurations.

The analysis shows that there is no significant difference in the signal characteristics. Hence we can limit the number of apertures and remove most of the channel borders for the next prototypes regarding the poloidal orientation. Removing certain parts of the collimator, reduces the manufacturing difficulty and gives furthermore a financial advantage.

Measurement of 3D Transmission Function

For a successful and more accurate tomographic reconstruction than up to the present, all lines of sight will have to be determined before reactor operation, to take the non ideal, respectively individual, channel properties into account. Applying data fusion, the performance of the system can be increased.

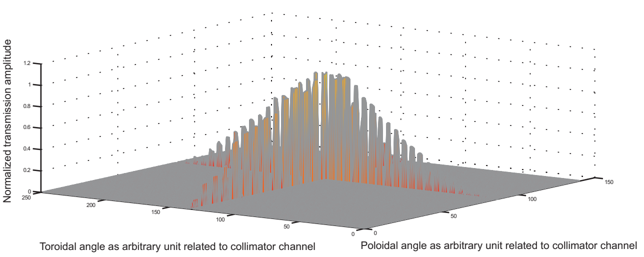

Figure 4: Three-dimensional reconstruction of the signal response in amplitude and angle.

This can be done in a high-resolution three-dimensional manner. Figure 4 shows (3D) reconstruction of a single channel (4). However, the automation is not fully complete and shows only two superposed measurements.

Outlook

To provide reliable conclusions from the measurements all uncertainties have to be investigated and integrated in the data analysis. Following improvements will be under examination:

- The time synchronization of robot movement, measurement and sensor stimulation (e.g. laser triggering) has to be implemented.
- Full automation will be necessary to provide measurements with higher resolution and exclude human handling errors during the calibration procedure.
- A calibration procedure for the alignment of the laser beam in relation to the robot coordinate systems has to be implemented to guarantee an overall effective accuracy. Procedures will have to be implemented using a precise metrology system (e.g. FaroArm).
- Gaussian distribution of the laser power should be examined for the final data analysis, especially for studies at the border of lines of sight. In any case it has to be checked depending on the entrance slit size of the corresponding of the collimator. In any case it has to be checked depending on the entrance slit size of the corresponding collimator.

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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

Electron Bernstein waves (EBWs) provide a method to heat over-dense plasmas, which are inaccessible for O- or X-mode waves. They are electrostatic waves that need to be coupled to injected electromagnetic waves around the O-mode cutoff layer. Hence, the plasma density must exceed the cutoff density in order to allow EBWs to be generated. In 2010, the 8 GHz microwave heating system of TJ-K has been upgraded to higher power of 3 kW. In addition, the wavefronts of the injected microwave beam was matched to the plasma curvature by a numerically optimized lens. Both improvements together lead to an increase of the plasma density to values that allowed the excitation of EBWs, as was shown in experiments in 2011. The efficiency of the responsible mode conversion process depends on the injection angle of the microwave with respect to the background magnetic field. Since EBWs can drive significant toroidal net currents, the magnitude of driven current should also depend on the injection angle. An external Rogowski coil was used in TJ-K to obtain the toroidal current.

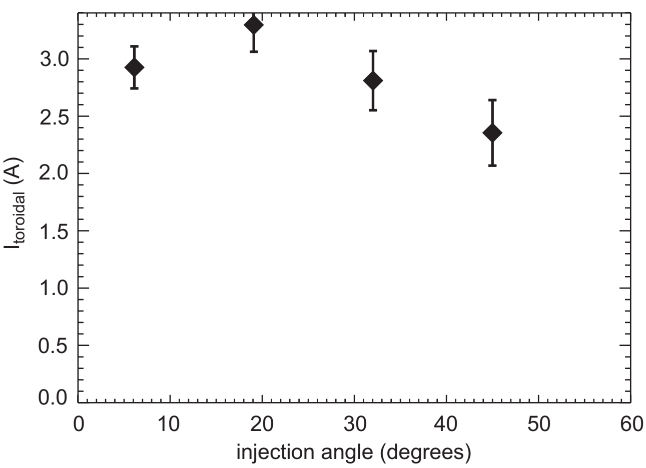

Figure 1: Toroidal net current as a function of the injection angle of the microwave beam with respect to the antenna axis.

As shown in figure 1, the expected dependence was verified in a scenario, where the electron cyclotron resonance (ECR) was close to the plasma centre. The current was found to flow in counter-B_0 direction and is thought to be driven by the Fisch-Boozer mechanism. The amount of the total energy in the plasma, obtained from an external diamagnetic loop, shows a similar behaviour as the toroidal current.

Furthermore, the upgraded heating system has made accessible a new plasma regime in TJ-K: EBW heating at high-harmonics of the ECR. It was possible to sustain a plasma discharge up to the 4th harmonic, where extremely low density fluctuation levels on the order of 3 % are found.

With the full-wave code IPF-FDMC, the potential of EBW heating for the Pegasus Toroidal Experiment (Madison, Wisconsin) has been investigated. The strongly elongated plasma in Pegasus can lead to vertical displacements of the plasma. To study the influence of such displacements on the conversion efficiency, the plasma has been shifted vertically by ±10 cm. The efficiency was found to be relatively stable against such displacement, which is due to the small value of the normalized density gradient length k_0L_n. With maximum efficiencies around 80 % the EBW scheme considered is an attractive candidate as an additional heating source at Pegasus.

Global Turbulence and Confinement Studies

Spontaneously driven large-scale potential perturbations were found in limited TJ-K plasmas and their zonal-flow (ZF) characteristics could be verified: They are radially localized ($k_r \neq 0$) and homogeneous on a flux surface ($k_\theta = k_\varphi = 0$). Flux-surface averaged potential fluctuations as well as the averaged turbulent Reynolds stress (RS) were extracted from 2D measurements and the role of differential RS as ZF drive could be demonstrated.

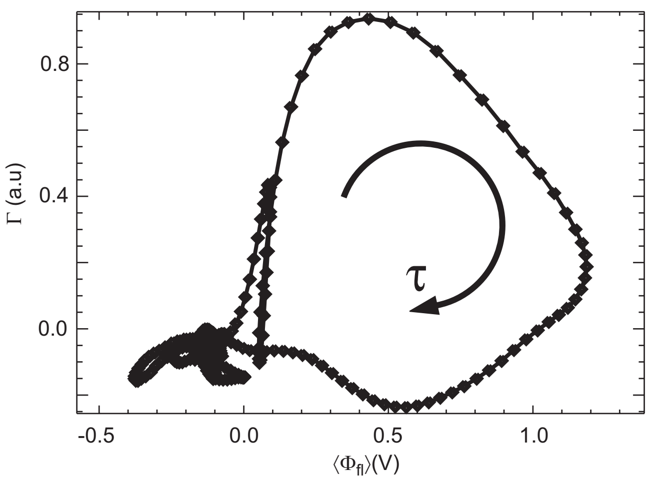

Figure 2: Trajectories in the phase space spanned by turbulent transport and the flux surface averaged potential.

The predator-prey limit cycle in the ZF/drift-wave system shows up in the phase space spanned by local turbulent transport and the flux-surface averaged potential as can be seen in figure 2. In the parameter range of TJ-K plasmas, zonal structures turned out to be less frequent with increasing collisional damping but more long-lived. The ZF amplitude did not show a clear dependency on the collisionality.
Intense fluctuation measurements were carried on with two 64-pin probe arrays at topologically different toroidal positions. In the dynamical behaviour of the flux-surface averaged turbulent transport, a similar correlation with the zonal potential is observed as in limited plasmas. Zonal structures appeared as a transient phenomenon, temporarily accompanied by a 30 % reduction in turbulent radial net transport. The measured parallel structure of dominant drift modes as resolved with reasonable toroidal resolution showed a complex pattern. This can be understood in terms of radially propagating drift modes, which are once perfectly aligned to an inner field line and then pass over regions with different field-line pitches. Hence, the observed pattern likely reflects the local variation of the rotational transform. A reduction in poloidal correlation length is observed in regions with strong local magnetic shear. Time-delay analyses reveal complex perpendicular and parallel structure-propagation patterns with a sign reversal in these regions, which will be addressed in more detail in 2012.
LIF measurements in Ar plasmas were continued in a variety of magnetic configurations and aided by MCC calculations to study toroidal ion flows. Concerning toroidal direction and order of magnitude, first calculations incorporating plasma-potential measurements show reasonable agreement of toroidal ion flows from LIF measurements with the toroidal projection of perpendicular $E \times B$ flows.

Reflectometry Simulations with IPF-FD3D and European Collaborations

Doppler reflectometry is an important diagnostic for density fluctuations and poloidal flows on fusion experiments. The 2D and 3D capable fullwave code IPF-FD3D is a finite difference time domain code that solves Maxwell's equations and the electron equations of motion in a cold plasma. The main research thrust in Doppler reflectometry is the investigation of the scattering efficiency of turbulent plasmas. In collaboration with ASDEX Upgrade and IPP Garching, the experimental situation for Doppler reflectometry measurements is being recreated in simulation.
An important aspect is the incorporation of plasma turbulence in the synthetic reflectometer. To this end, the turbulence code GENE is employed (in collaboration with T. Görler, IPP) to give a realistic estimate of the fluctuations under the conditions encountered in experiment. This way, a three-way comparison of the poloidal turbulent fluctuation spectra is possible, between the raw measured spectrum, the (known) simulated turbulence spectrum, and how they actually appear to the reflectometer. In the current status, the code can read the GENE density fluctuation output, and simulations runs are planned to start in January 2012.

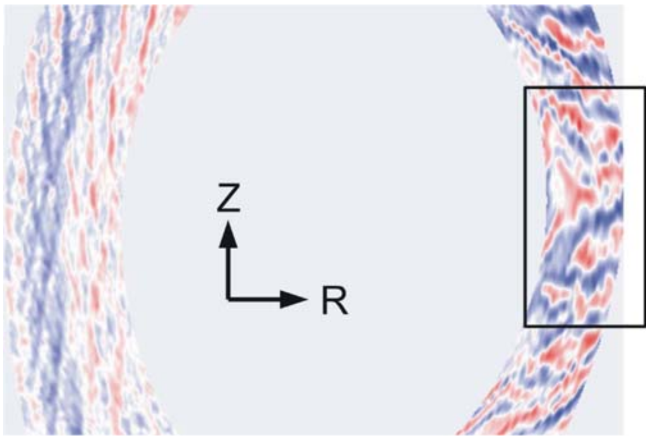

Figure 3: Plasma turbulence from the GENE code, converted to cylindrical coordinates [private communication by T. Görler]. The region of interest for reflectometry is marked by the box.

International activities have been continued under the European Reflectometry Code Consortium (ERCC) and EFDA-ITM umbrella. The ERCC has been founded for pooling reflectometry simulation know-how from European research institutions. There are several meetings, video conferences and code camps each year with participants from IPF, IPP, CEA, CIEMAT, LPMI (Nancy), FZJ, and IST (Lisbon) to discuss simulation techniques.
There are ongoing benchmarking efforts within the ERCC to prove the correctness of the codes that are in use within the ERCC. Comparisons between the codes used by ERCC members show some agreement and some disagreement, and it is currently being discussed how the different simulation methods used within the various codes effect these differences.
Activities within the Integrated Tokamak Modeling (ITM) task force under ID WP11-ITM-EDRG-ACT6 have been continued. The European 3D reflectometer code for use on ITER is now ported to the ITM computers. Integration with ITM data structures is nearly complete and first test runs in 3D have been completed. These activities will be continued under priority support from EFDA (European Fusion Development agreement).

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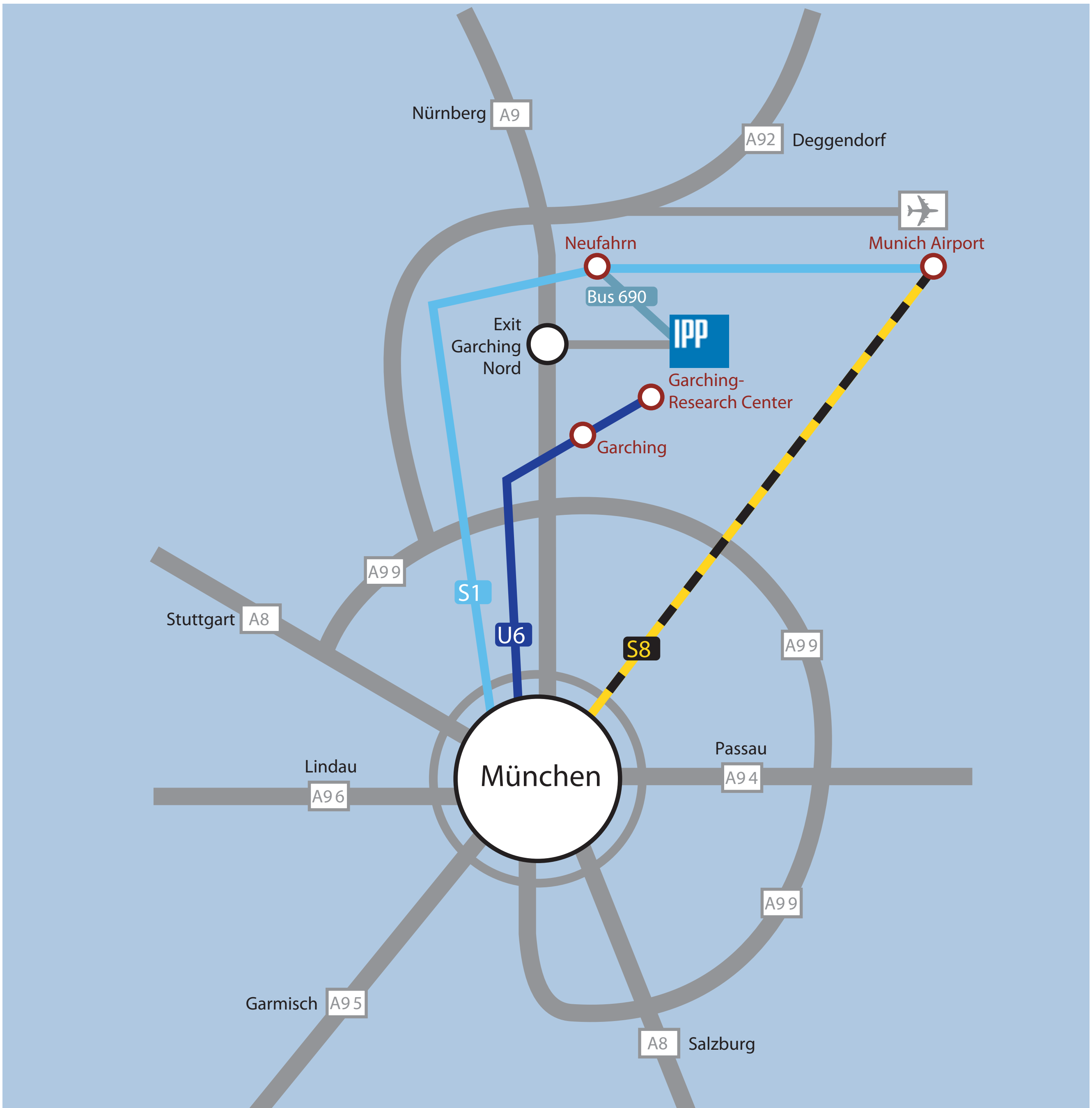
* *external authors*

\+ Lite Trainee

Appendix

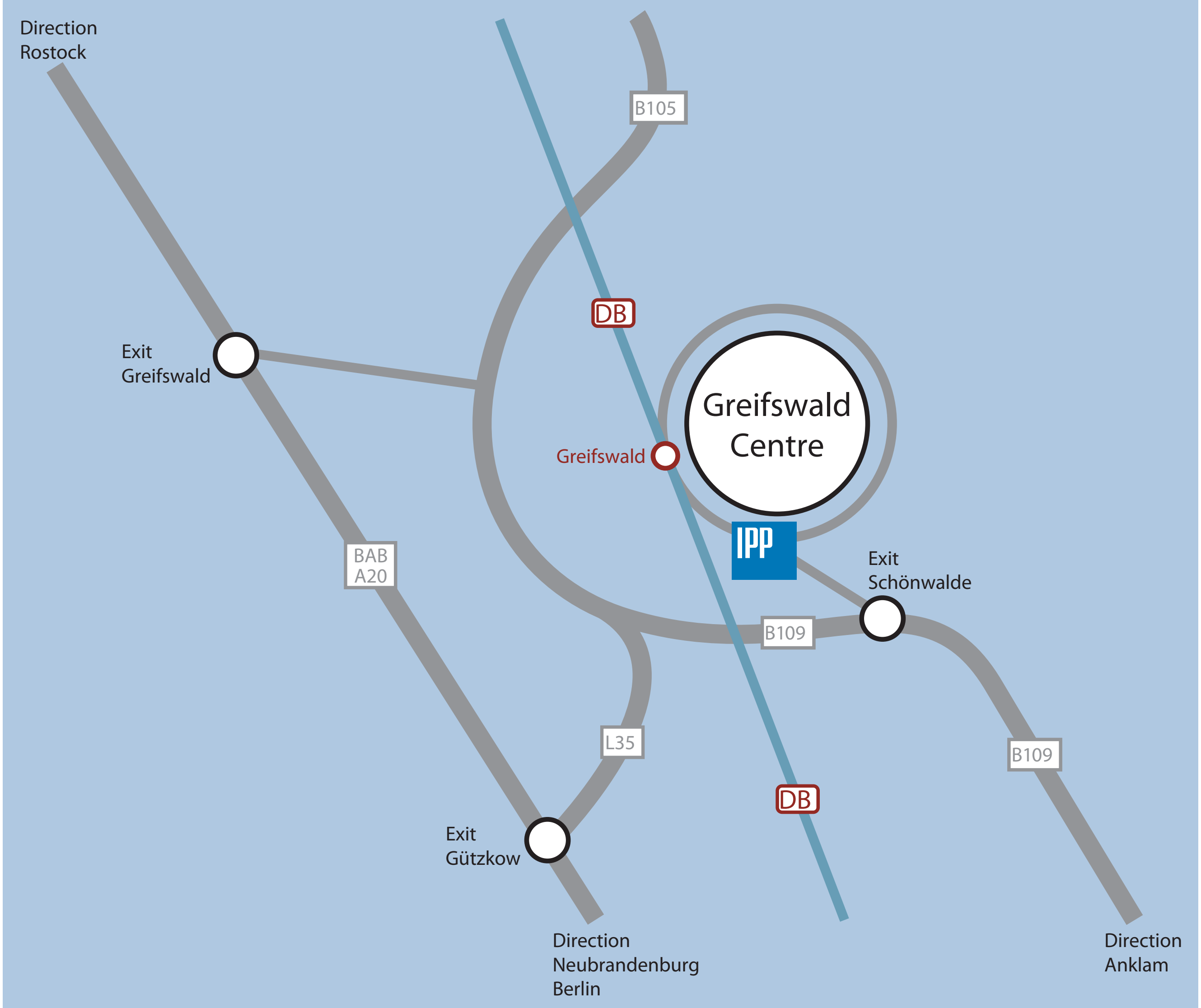
How to reach IPP in Garching



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.
(Note: The new Berlin Airport (BER) is scheduled to open on 3rd June 2012.
The Airport Express train (R9) will run between the main railway station (Berlin Hauptbahnhof) and BER airport. You can also use the specially identified regional train lines RE7 and RB14.)
Via Hamburg: from the airport to main Railway Station, by train to Greifswald main station.

By bus:
From Greifswald-Railway Station (ZOB) by bus No. 3 to the "Elisenpark" stop.

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

IPP in Figures

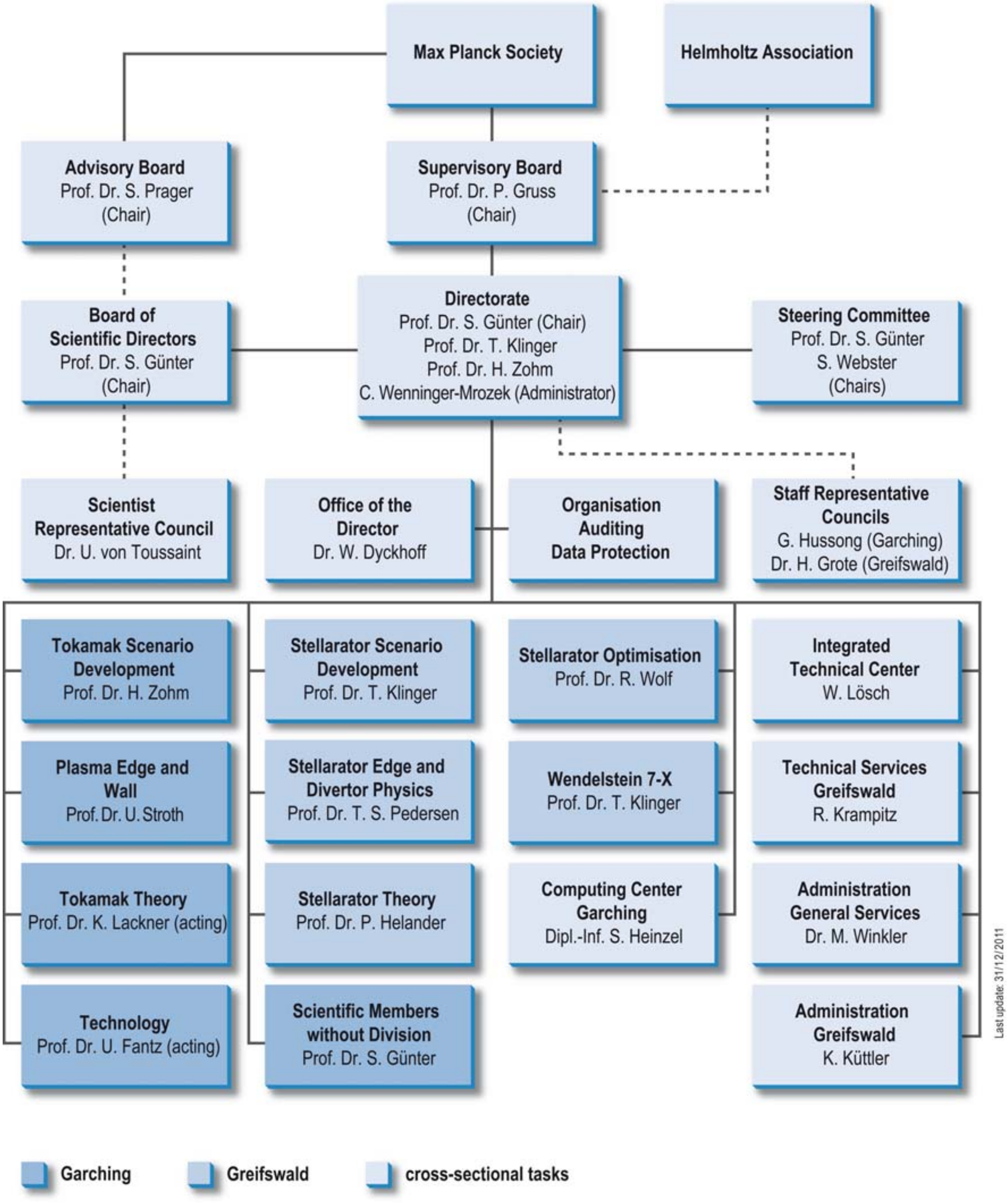
Funding

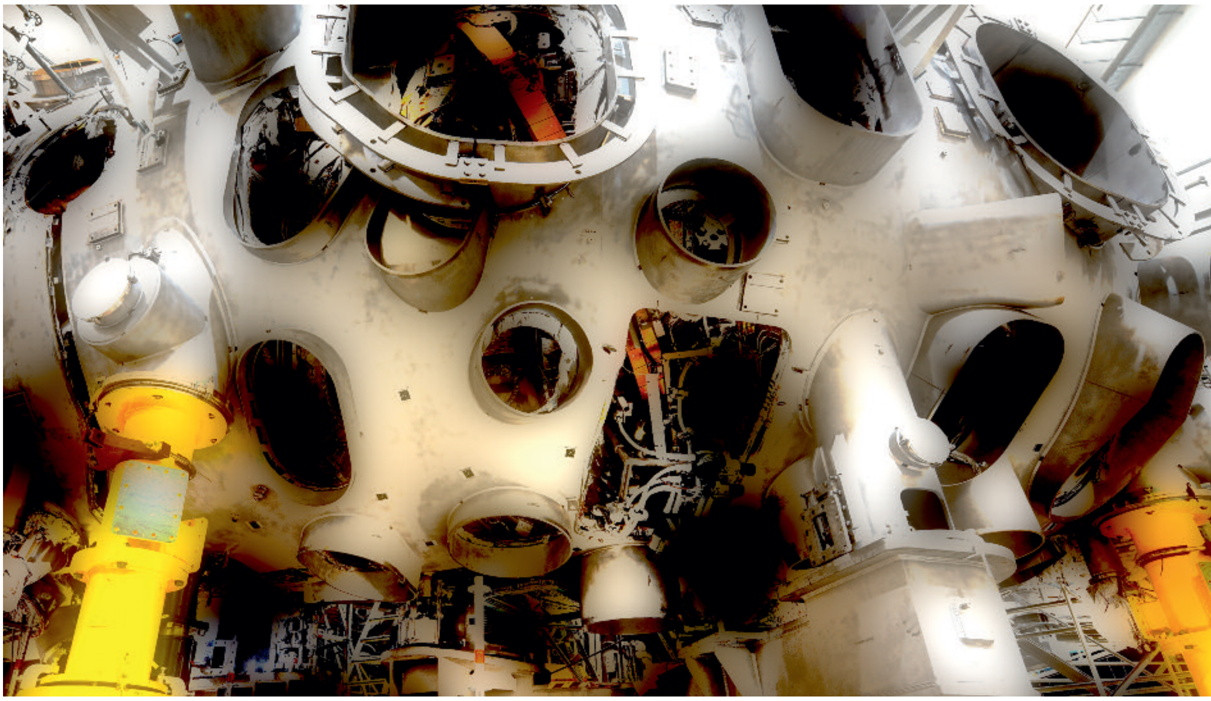
IPP received approx. 15 % of its total funding from EURATOM. The Federal Government funded 90 % of the national expenditure for fusion research, the states of Bavaria and Mecklenburg-West Pomerania provided the remaining 10 %. This came to total funding of approx. 106 million euros for the year 2011.

Scientific Staff

At the end of the year IPP had a total of 1143 members of staff, 429 of them worked at IPP's Greifswald site. The workforce comprised 285 researchers and scientists, 47 postgraduates and 39 postdocs. In addition, 15 guest researchers used the research infrastructure.

Organisational Structure





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