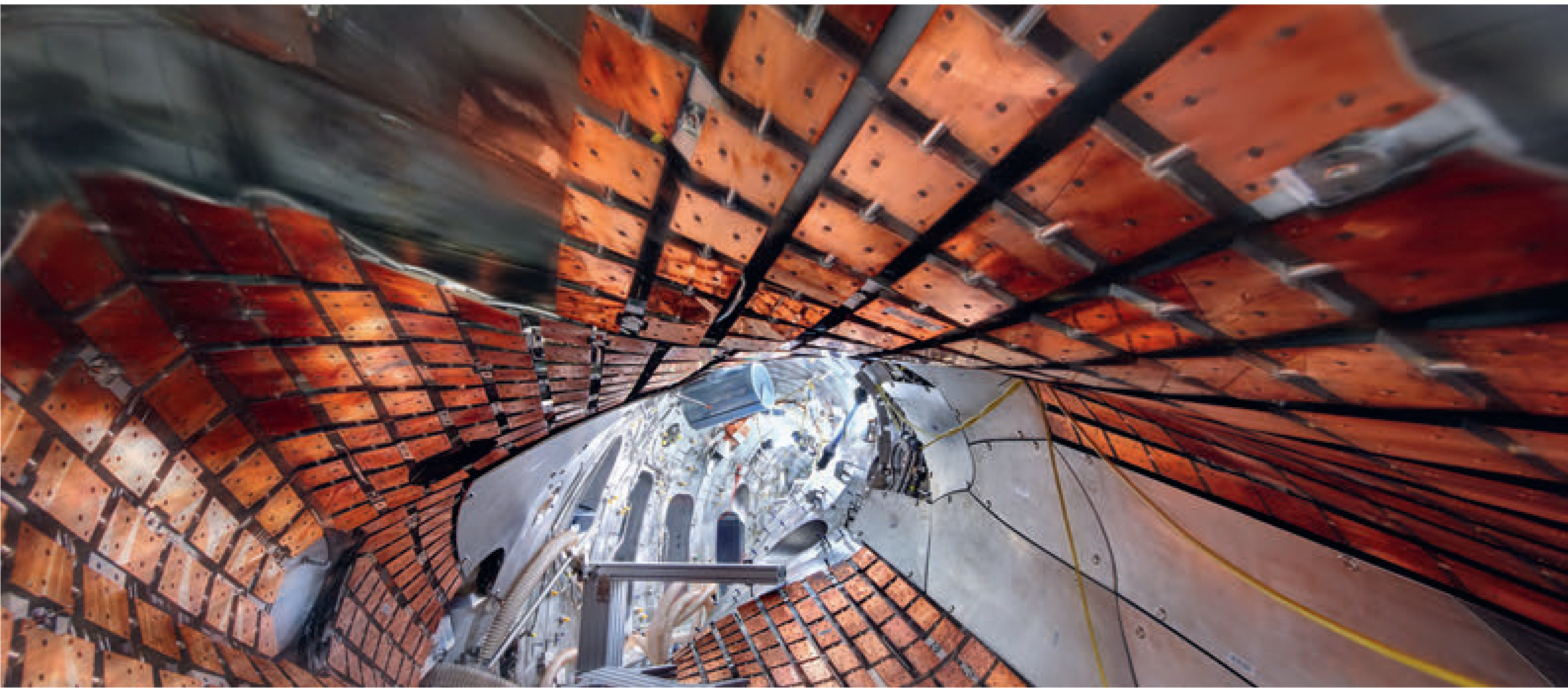
Max-Planck-Institut für Plasmaphysik

Annual Report 2013



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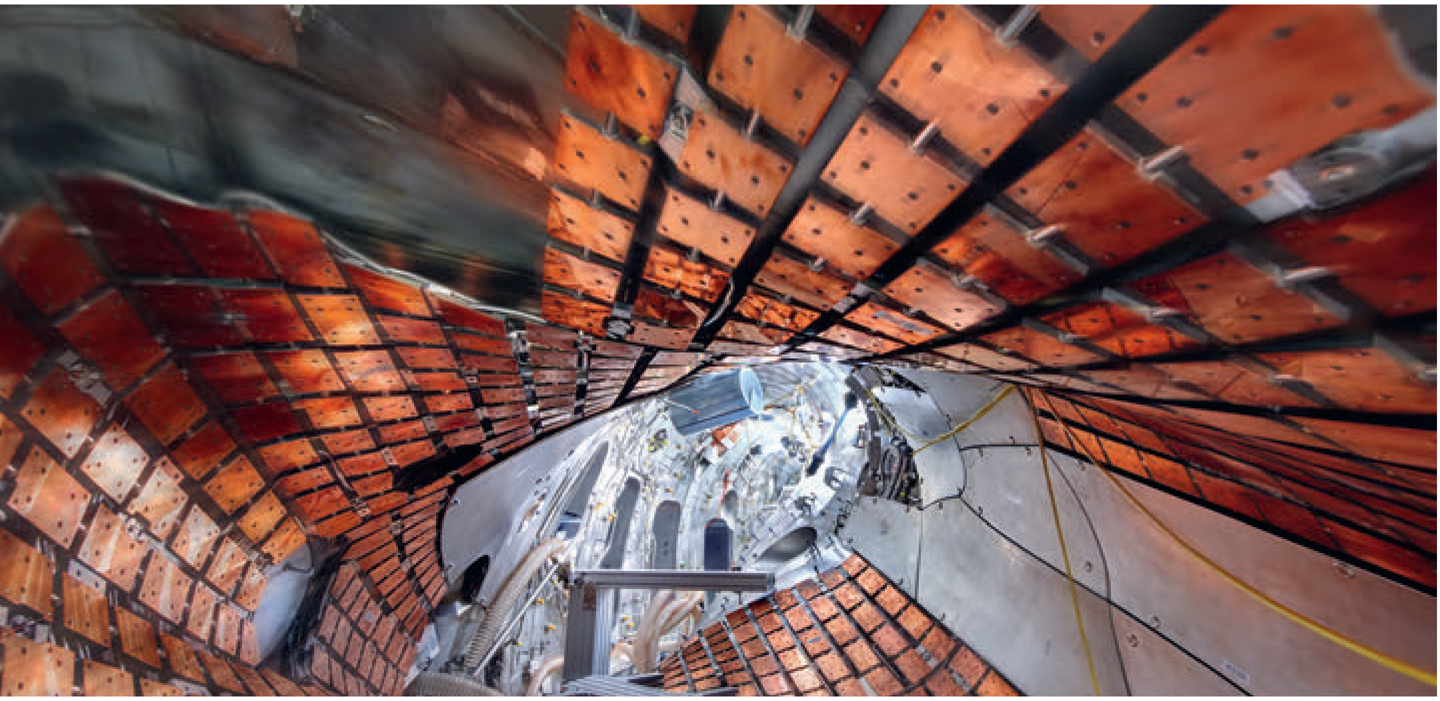

Photo: Bernhard Ludewig

One of the final stages of assembly at Wendelstein 7-X: the plasma vessel components

Max-Planck-Institut
für Plasmaphysik

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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

In Greifswald, the assembly of IPP's superconducting stellarator Wendelstein 7-X has reached the home stretch. Once the last weld seam on the module connections was closed in June 2013, the focus of the assembly work was on the completion of the in-vessel components, the current leads and the peripheral installations. The often arduous installation of in-vessel components is slowly but steadily progressing, and the final assembly of the last four current lead pairs is nearing completion. Meanwhile, space in the torus hall is becoming a scarce and precious commodity, since the remaining steel structures and both ECRH towers are now in place. The preparation for the next big work package, the commissioning of the machine, has also gained considerable momentum; first commissioning works are scheduled for the second quarter of 2014. The very fruitful national and international collaborations continue to be an important asset of the project. Karlsruhe Institute of Technology remains an important partner in the development of plasma microwave heating. Forschungszentrum Jülich is developing numerous plasma diagnostic tools and intends to make a significant contribution to the physics programme. The five trim coils for controlling the magnetic field configuration on the plasma boundary, contributed in kind by the Princeton Plasma Physics Laboratory, have been installed.

Work on the ASDEX Upgrade tokamak at IPP's Garching site continues its strong focus on clarifying fusion plasma physics relating to the operation and scientific exploitation of ITER. A series of experiments conducted in 2013 showed that the ITER operational point envisaged might not be readily accessible with a metal wall since confinement tends to be degraded relatively to the ITER prediction, and recipes for ELM mitigation, i.e. pellet triggering and RMP suppression, have typically been developed for higher edge safety factor and are not readily transferable. This is in line with findings from JET, where scientists from the ASDEX Upgrade team are contributing significantly to the progress, which encounters similar restrictions when operating with full-metal wall. However, work on ASDEX Upgrade suggests that the margin for ITER reaching its Q=10 goal can be significantly enhanced by drawing benefit from improved confinement at higher normalized plasma pressure and the possibility of operating at higher normalized plasma density. On the other hand, studies conducted in He plasmas to mimic the non-nuclear operation of ITER boost confidence that these can serve the goal of commissioning the machine in a relevant operational regime.

As preparation for the study of fast-particle physics on ITER, closely related to the goal of dominant self-heating, the set of diagnostics for the fast ion distribution function was further extended on ASDEX Upgrade, and the measurements allow quantitative comparison with theory. For example, slowing-down of fast particles was found to be comparable to neoclassical predictions as long as no MHD activity is present; the latter was shown to lead to significant enhancement of the radial transport of the fast particles as they slow down.

An extensive set of reflectometry diagnostics was installed on ASDEX Upgrade in order to enhance the capabilities for turbulence and transport studies, together with EU partners. Core fluctuation measurements are closely compared with gyro-kinetic GENE simulations to study transitions between different regimes of turbulence. Transport studies at the plasma edge further support the importance of neoclassical theory in determining the radial electric field and current diffusion. As possible ELM trigger, neoclassical tearing modes were identified which couple to ballooning modes to drive them unstable. A finite-ion-temperature model for blob propagation was developed and successfully compared with measured blob sizes and radial velocities. Simulations improved in reproducing key observations related to divertor detachment. The strong radiation from the X-point region as a consequence of nitrogen seeding is reproduced. The code package for simulating impurity migration was advanced and basic atomic data for nitrogen-tungsten surface interaction obtained from laboratory experiments will be used to analyse nitrogen migration studies conducted in 2013 on ASDEX Upgrade and JET. Hydrogen retention in tungsten was shown to depend strongly on the degree of damage. Retention appreciably increases in damaged regions and saturates at intermediate damage levels. Benign behaviour of pre-melted tungsten tiles in high-power discharges was found. A steel programme using EUROFER components on ASDEX Upgrade, accompanied by laboratory experiments, was initiated.

The ITER-like wall exploitation on JET continued for a few months in 2013, yielding one of its most significant results. Successful operation in general and, in particular, the specific experiment in which operation was successfully demonstrated after deliberate production of a shallow layer of molten tungsten, together paved the way towards a positive recommendation of the ITER Advisory Committee to begin with a full-tungsten divertor in ITER. This decision was approved by the ITER Council at the end of November and will allow optimal preparation of early ITER operations with a substantial reduction of the investment costs.

Efforts by the ITER cooperation project at IPP continued with major contributions to the development of heating systems, diagnostics and plasma control as well as theoretical investigations. The ELISE test facility successfully investigated basic operation parameters and then started operation in caesium, achieving high current densities at relevant parameters. The contributions to the consortium for the development of the ITER ICRF antenna and to the consortium for the ECRH upper launcher continue. For the latter a performance analysis demonstrated crucial operation parameters. Within the Framework Partnership Agreement for the ITER diagnostics pressure gauge work started with detailed project planning and system analysis. The agreement on the development of the ITER bolometer diagnostic was finally awarded to the ITERBolo consortium, headed by IPP. Meanwhile, R&D efforts as part of a nationally funded project have been successfully concluded. For the development of the plasma control system simulation platform for ITER, a prototype of the main components was successfully demonstrated at ITER. Furthermore, IPP finalised a study of the effects of ELMs on ITER performance and demonstrated that tungsten erosion from the target under ITER-controlled ELM conditions presents very little danger to the plasma.

Work at our theoretical divisions supports the experimental activities and paves new ways in fundamental plasma physics. In 2013, a substantial computational effort helped to clarify the “shortfall mystery” in tokamak transport theory. For several years, it has appeared that the best theoretical models available are unable to explain the transport observed in the edge region of L-mode plasmas, triggering a worldwide debate on the applicability of these models. However, the latest, very extensive, computer simulations at IPP now suggest that there is in fact no transport shortfall, and that the observations can indeed be explained by gyrokinetic theory. This is reassuring and creates confidence that extrapolations to ITER are reliable. In the field of transport theory, we have also established that some of the most important microinstabilities driving plasma turbulence can be fundamentally different in stellarators to those in tokamaks, and that they can be suppressed by appropriately tailoring the magnetic geometry.

On behalf of the Directorate and the Board of Scientific Directors I thank all friends and colleagues for their excellent cooperation and continuous support.

Scientific Director Sibylle Günter

Content

Tokamak Research

ASDEX Upgrade

Head: Prof. Dr. Arne Kallenbach

The ASDEX Upgrade experimental program is devoted to the preparation and improvement of ITER operation, enabling research for basic physics understanding and the design of a future DEMO prototype fusion reactor. After successful plasma operation up to end of April 2013, a machine vent was undertaken for the installation of major upgrades, including the massive tungsten divertor III, a large divertor manipulator DIM-II, two toroidal rings of ferromagnetic P92 steel on the inner wall and several new diagnostics.

1 Overview

ASDEX Upgrade (AUG) operation was conducted until the end of April 2013 with 766 useful plasma discharges, followed by a major vent, which was completed at the end of the year. The major task of the vent was the installation of the massive tungsten divertor III. In parallel, a number of new and important physics results could be obtained from evaluation of the 2012/13 experimental campaign data. Preparation of the 2014 operation was done in close collaboration with the emerging EUROfusion consortium, which brought many changes to the structure and procedures for the 2014 campaign.

1.1 Major Physics Results

Investigations of the pedestal structure continued to be a major thrust of the experimental work. Previous analysis of the electric field in the H-mode transport barrier, which found largely neoclassical behaviour, could be further corroborated. The new high-field side CXRS diagnostic revealed an in-out asymmetry of impurity densities with higher densities on the high field side by up to a factor of 3. Filamentary transport emerging from the separatrix region was investigated with different probes, gas puff imaging, reflectometry, and Li beam spectroscopy. The ion temperature in the filaments appeared as an important parameter for its propagation in the scrape-off layer, as well as for the sputtering of tungsten on low field side limiters.

The changes of filament dynamics for high density L-modes could be attributed to their electric disconnection from the divertor target. This mechanism is supposed to be also important for the dynamics of the H-mode density limit, where the H→L back-transition is accompanied by a drastic increase of radial transport and degradation of the radial electric field in the vanishing edge transport barrier. Further inside the plasma, fluctuation measurements with the improved Doppler reflectometer diagnostic allowed direct comparisons with turbulence codes.

Complete divertor detachment along the outer target could be obtained with nitrogen seeding. This is accompanied by an abrupt increase of the pedestal top density by about 15 %. A similar density rise is observed during partial detachment (a few cm from the separatrix into the SOL), which is obtained by combined nitrogen and argon or krypton seeding even under high power conditions of 20 MW heating. A change in plasma fuelling due to a change of divertor plasma conditions is suspected responsible for the density rise, but its reproduction by edge modeling failed so far. Nevertheless, this scenario is regarded as very attractive for a future DEMO reactor.

Two different plasma scenarios representing ITER baseline operation have been further developed at I_p=1.1 MA and B_t=1.8 T with central ECRH in X3 mode and 1.2 MA and 2 T with central ICRH, respectively. These scenarios are challenging for AUG since only a low (central) heating power is allowed due to low β and low $P_{heat}/P_{L\rightarrow H}$ constraints imposed by ITER similarity, resulting in conditions prone to central tungsten accumulation for AUG parameters. Stationary discharges could indeed be obtained, albeit with very large ELMs expelling 20 % of the stored energy. Initial attempts to mitigate these ELMs by magnetic perturbations (MP), pellets and nitrogen seeding were not successful.

New insights could be gained from comparison with excellent pedestal measurements on JET, in particular for parameters around the ITER baseline scenario and during nitrogen seeding. Both AUG and JET show beneficial effects of higher β and nitrogen seeding on confinement, while the high ITER-like shaping causes in particular large ELMs.

Experimental work on ELM mitigation concentrated on the search for ELM suppression at low collisionality, investigations on the role of MP field penetration for different resonance conditions and electron fluid speeds, and the lag time for ELM triggering by pellets. So far, the high density H-mode remains a robust scenario where ELM mitigation can be achieved in AUG. The important question, whether this is due to its high collisionality, its high Greenwald fraction or another unidentified parameter remaines open.

The experimental techniques for stabilization of neoclassical tearing modes (NTM) could be further improved and solidified, allowing for consecutive stabilization of a (3,2) and a (2,1) mode in a single discharge. An open problem remains the exact localization of the mode by equilibrium reconstruction. Still, an empirical offset has to be used for matching of ECR deposition and mode location.

A breakthrough could be obtained with the Collective Thomson Scattering (CTS) diagnostic, which is operated by colleagues from the Danish DTU in close collaboration with the AUG ECRH group. By operating two CTS receivers simultaneously, spurious signals could be removed from the measurements, which so far prohibited a quantitative analysis of the ion distribution function. With the new set-up, good agreement with the CXRS diagnostic could be demonstrated.

1.2 Machine Enhancements

A number of major enhancement were installed between May and December 2013. The largest item is the massive tungsten divertor III, which allows higher surface temperatures compared to the previous tungsten coatings and more ITER/ DEMO relevant operation and fuel retention studies. Integrated is the new large scale divertor manipulator DIM-II for the test of new materials and components and surface diagnostics. For maintaining flexible pumping capabilities for high recycling as well as low collisionality operation, a switchable valve has been inserted into the helium circuit of the cryo pump. This allows a reduction of the effective cryo pumping speed to 1/3, relative to the slightly improved pumping of the new divertor III. Two toroidal rows of ferritic P92 steel have been mounted above and below the midplane on the high field side heat shield. P92 is similar to EUROFER, which is supposed to be used in a future DEMO reactor. Its capabilities as plasma facing material will be tested in AUG regarding its sputtering behaviour and the perturbation of the magnetic field and probe measurements. The latter effects were incorporated into the magnetic equilibrium reconstruction codes for prediction and analysis in the upcoming campaign. Preparation work has been performed for the installation of two new 3-strap ICRF antennas foreseen for end of 2014. The current antenna supplies have been re-configured to allow individual powering of different antenna straps. AC power supplies add new properties to the MP-coils system allowing rotating magnetic perturbations.
The enhancement work is completed by the installation of a number of new diagnostics, such as a high resolution CXRS system, a new poloidal correlation reflectometer and a fast helium beam, which have been relocated from the TEXTOR tokamak, a fast-swept reflectometer loaned from Tore Supra by CEA collaborators, a second ECE imaging system supplied by Dutch collaborators, and upgrades to the DCN interferometer allowing density measurements on the magnetic axis and a polarimeter channel for improvement of the equilibrium reconstruction and possibly a better detection and correction of interferometer fringe jumps.

1.3 Preparation of the 2014 Experimental Campaign

A major change concerns the European participation in the AUG program for 2014. With the conclusion of EFDA and the EURATOM baseline support, AUG operation will be partly conducted under the medium size tokamak (MST1) programme of the emerging EUROfusion Consortium. Under this new umbrella, 40 of about 80 experiment days are planned for 2014. In autumn 2013, several joint planning meetings took place for the set-up of the combined IPP-Consortium 2014 experimental programme. In addition, resources from IPP and Europe were allocated to the execution of experimental tasks in line with the EU Roadmap and Horizon 2020. Parallel to this, work on the IPP infrastructure was started to allow hosting of more than 200 guest scientists over the 2014 experimental campaign.

2 Intermittent Transport in the SOL

The intensity of the interaction between the main plasma and material components in both the divertor and main chamber is mostly determined by the transport properties in the scrape-off layer (SOL). Transport in the SOL is turbulent and, departing from the separatrix, an increasing fraction of it is carried by intermittent events called plasma filaments or blobs. For the design of plasma-facing components in future devices predictive capabilities of blob-related transport is needed and thus the understanding of the processes leading to blob generation and blob propagation must be improved. Existing analytic models describing the dynamics of blobs assume cold ions. In response to measurements on AUG, which revealed ion temperatures close to the limiters of up to 100 eV, a new analytic model for finite ion temperature has been derived from the full drift-interchange-Alfvén fluid equations. The general expression obtained reduces to the standard blob models for the cold-ion case. The finite ion temperature enhances the interchange drive, which is responsible for the radial propagation of the blob, and leads to polarization currents altering the blob's vorticity. It thus affects the dynamics of the blob and modifies the scaling laws for the blob velocity v_b as a function of blob size.

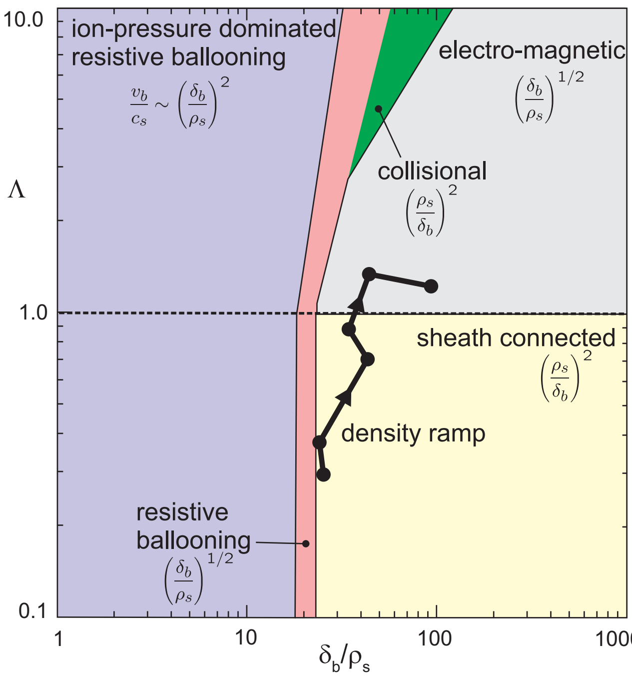

Figure 1: Limiting regimes for the finite-T_i blob model as a function of collisionality Λ and blob size δ_b/ρ_s with the corresponding scaling dependences and a trace (solid line) of parameters estimated during a density-ramp discussed below.

Figure 1 shows the different blob regimes as a function of the normalized blob size δ_b/ρ_s and collisionality Λ, which determines the connection of the blob through the sheath with the wall.

ρ_s is the drift scale. Above a value of Λ=1 the plasma of the blob disconnects due to high parallel resistivity from the sheath and an amplification of the blob velocity is predicted. The blob properties have been measured by Langmuir probes, Li-beam emission spectroscopy and with a fast camera using the gas-puff-imaging technique. Figure 2 compares the measured blob size a with predictions a* for the cold (triangles) and warm (diamonds) ion cases. As observed in other experiments, the measured blob sizes exceed the model estimates for the most stable blob size for cold ions in average by more than a factor of two. The measured blob sizes agree, however, with the prediction of the model taking the effects of warm ions into account. The result is also in excellent agreement with analyses of two-dimensional gas-puff imaging data captured with a high-speed camera. This is a strong indication that finite-ion-temperature effects play a significant role in the blob dynamics and hence for the transport in the SOL. These and similar investigations have been carried out on L-mode discharges and between ELMs of H-mode discharges; the ELM filaments, which are expected to behave similarly, will be addressed in the next experimental campaign. By analysing high-speed camera data it was found that the detection rates of blobs are similar during L- and H-mode phases, indicating that there is no drastic change in the blob generation mechanism and the blob dynamics.

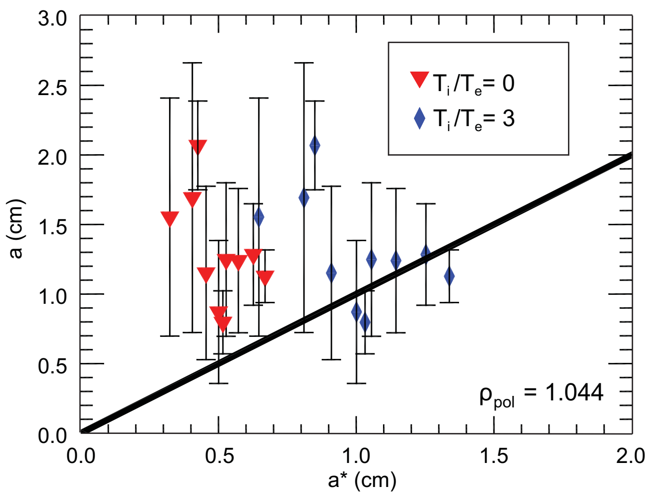

Figure 2: Characteristic blob size from the Li-beam diagnostic compared with cold and warm-ion models. Data are from conditional averaging at ρ_{pol} = 1.044.

The scaling of the radial blob velocity with blob size as obtained from experiment was compared to different models. It is remarkable that all blobs have almost the same size of about 1 cm while the velocity normalized to the sound speed decreases with increasing blob size. This rules out inertial models, which predict the opposite trend and also overestimate the velocity by a factor of 10. These experiments were carried out at low plasma densities where the SOL is almost collisionless and the model of the sheath-connected regime should apply.

The absolute values from both the warm ion and the cold-ion model agree well with the measurements but a better agreement with the warm ion model is found.

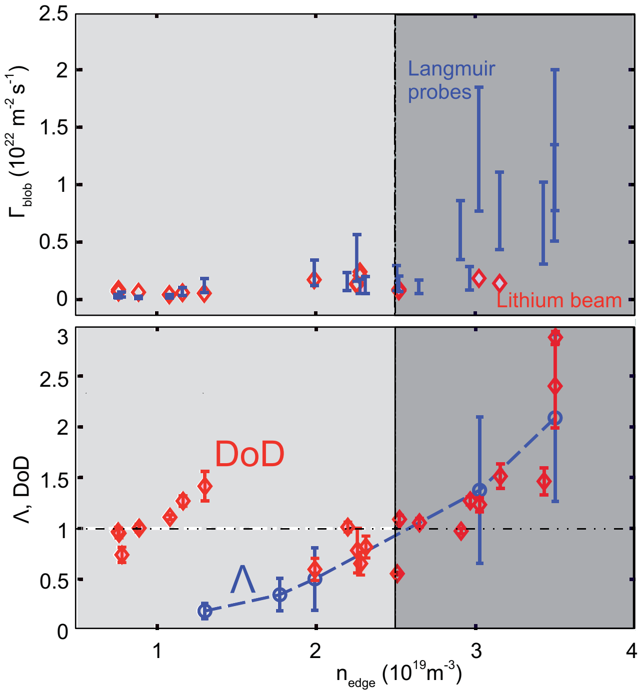

Figure 3: n_{edge}-scan: the blob transport Γ, collisionality Λ and the degree of detachment (DoD) rise at higher densities. For Λ > 1 the blob transport increases significantly.

It has been observed previously that with increasing density a transition in SOL transport can occur, manifesting itself in the development of a shoulder in the radial density profile. In figure 3, the high-density transition is outlined. The blob-related particle transport Γ was estimated from the radial velocity and the densities of the blob, as obtained from conditional correlation analysis of signals from two radially separated Langmuir probes. Plotted as a function of the line-integrated edge plasma density, the estimated transport increases strongly when the density crosses a value of about $2.5 \cdot 10^{19}$ m^{-3}. The quantitative agreement between the estimates from the Langmuir probes (blue lines) with those from the Li-beam (red diamonds) is remarkable.
The lower part of figure 3 establishes a link of the transition in transport to the collisionality parameter Λ (blue circles) entering the blob model from above and to the degree of outer divertor detachment (DoD; red diamonds), which is estimated from the ratio of the measured particle flux on the outer target plates to the prediction of a simple two-point model. At edge densities <$2.5 \cdot 10^{19}$ m^{-3}, the divertor remains attached and the transport increases only weakly with density; the collisionality is low (Λ<1), blobs are in the sheath connected regime and parallel losses are dominant.

At higher densities >2.5·10^{19} m^{-3}, collisions become dominant (Λ>1), the divertor begins to detach and an increase in both size and radial velocity of the blobs leads to a rapid growth in transport. In figure 1, a trace of the parameters during a density ramp is also plotted and a transition from the sheath-connected to the electromagnetic regime is indicated.

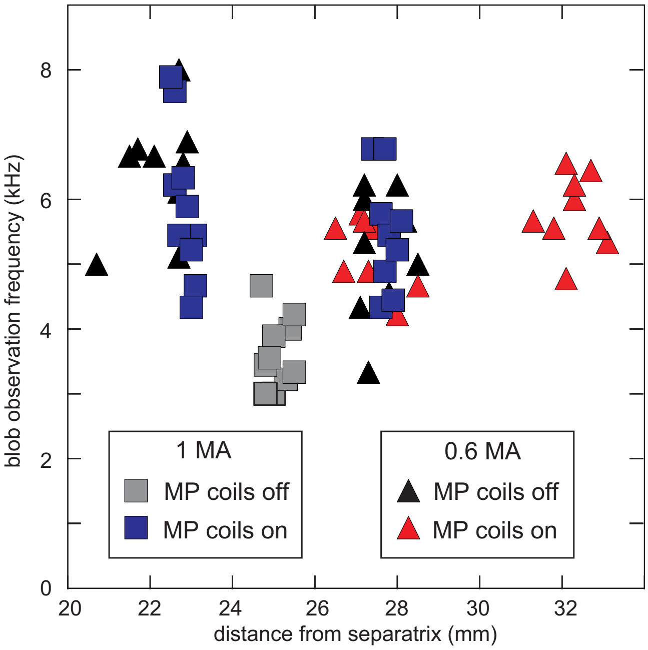

Figure 4: The frequency with which blobs are observed with Langmuir probes in the outer mid-plane as a function of the distance to the separatrix for discharges at two currents, with and without magnetic field perturbations (MP).

Since the transition in blob transport could be related to the degree of divertor detachment and since detachment is closely related to the density limit, one might argue that the transition happens at a certain fraction of the Greenwald density. A further indication that the Greenwald density is a relevant parameter for the transition is found in experiments with non-axisymmetric magnetic perturbations (MPs). An effect of the perturbations at low density is that plasma lobes appear in the divertor, which can be detected by thermography. They are accompanied by enhanced SOL transport and an increase in the blob appearance frequency by about 50 %, as shown figure 4 for discharges at a plasma current of 1 MA. The probe data were taken at a distance of 25 mm from the separatrix, with and without n=2 magnetic perturbations (grey and blue squares, respectively). When the current is reduced to 0.6 MA the same plasma density corresponds to a higher Greenwald fraction. The blob frequency, which is now at a higher level (red triangles), does not increase further when the MPs are switched on (black triangles). Also, the other effects of the magnetic perturbations, such as lobes in the divertor, do not occur. This could point to the influence of enhanced blob transport at higher Greenwald fractions, which would wash out the effect of the MP in the SOL.

3 Influence of Perturbation Fields on Plasma Performance and MHD

Recently, AUG has been equipped with 16 in-vessel saddle coils that are capable of producing non-axisymmetric magnetic perturbations (MP) with relative strength B~10^{-3} B_t, in either resonant (field-aligned) or non-resonant configurations. As reported, e.g. in the annual report 2011, both resonant and non-resonant MP can be effective in suppressing large type-I ELMs in favour of small, grassy ELMs with largely reduced peak divertor power load. Further studies have been performed to identify the plasma operational requirements for ELM mitigation. Almost independent of the perturbation configuration, small ELMs are obtained at a pedestal density of about 60 % of the Greenwald density n_{GW}, slightly below the transition to type-III ELMs. While the pedestal temperature can be well above that normally found with type-III ELMs, the edge parameter space of this type of perturbation field-induced ELM mitigation is narrow. The search for a full ELM suppression at low pedestal collisionality (as observed at DIII-D) has continued, however, only a reduction of type-I ELM losses by up to a factor of 3 has been found, and in no case full ELM suppression (see section 7). The perturbed magnetic field structure in the scrape-off layer is well observed as a splitting of the divertor strike zones, even in cases with strong field shielding in the plasma core. Application of the MP tends to cause a density increase at high plasma density, while at low plasma density or collisionality the density often decreases (‘pump out’ effect). The former case coincides with the existence of a poloidally localised high density area in the high field side scrape-off layer, which is intersected with the magnetic lobe structures caused by the magnetic perturbation. This new type of plasma fuelling mechanism is a topic of further study.

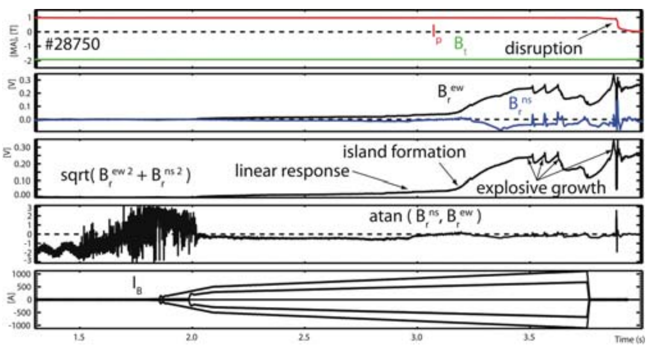

Figure 5: Time traces of an MP coil current ramp in L-mode at low n_e with linear response at low current, spontaneous mode growth (‘field penetration’) above a threshold and ultimately a disruption.

Significant effort has been spent to assess the effect of MP on plasma properties. The measured non-axisymmetric plasma boundary deformation is consistent with both the vacuum field approximation and NEMEC 3D equilibrium calculations –

resonant field amplification is not observed in H-mode in the probed range of normalised β_N up to 2.7. However, field penetration into the core plasma is clearly observed in Ohmic and L-mode plasmas with low densities and reduced toroidal field ($B_t \leq 2$ T) and takes the form of destabilised tearing modes that can eventually lead to a disruption (see figure 5). Threshold perturbation coil currents I_{MP} at island formation depend on the orientation of the n=1 MP. The position of the n=1 locked mode ϕ_{LM} is measured with the newly installed locked mode detector on the HFS. The coil currents $I_{MP} \cdot \phi_{LM}/n_e$ allow to deduce the orientation of the n=1 component of B_{int} (figure 6a). A histogram of a large set of natural disruptions shows a distribution of LM orientations for different scenarios (figure 6b). NBI heated discharges show a dominant maximum, which is tilted with respect to a local maximum generated by Ohmic disruptions. One plausible contribution to B_{int} could be identified as the dynamic feed-throughs of the shaping coils. Future experiments and analysis will provide further information on higher poloidal and toroidal components of B_{int}.

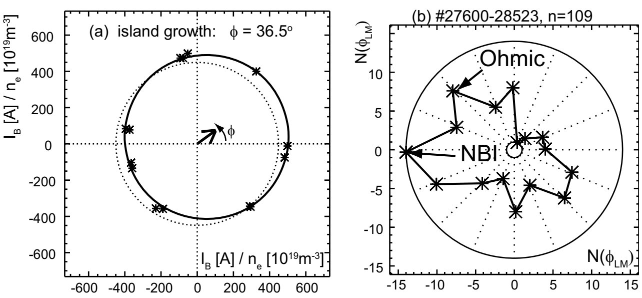

Figure 6: (a) Toroidal distribution for field penetration ($\sim I_{MP}/n_e$) and island formation revealing the orientation of the intrinsic error field B_{int}. The shift of the circle points in the opposite direction as B_{int}. (b) Polar histogram of the mode locking position over a large set of discharges.

In H-mode plasmas, J×B interaction with core modes, such as the (1,1) sawtooth precursor mode (see section 7) and pre-existing neoclassical tearing modes (see section 6.1), is observed only when the MP is non-resonant or not shielded by strong electron flows. These conditions have been probed by variations of MP configuration and torque input to the plasma. In most H-mode plasmas, however, no torque on core modes can be detected and to date, no disruptions due to magnetic perturbations have occurred in H-mode. There is, however, a noticeable increase in the L→H transition power threshold for densities n_e>45 % n_{GW} and no L→H transition was obtained for n_e>65 % n_{GW} up to twice the non-MP power threshold. At densities in-between, the L→H transition power increases when MP is switched on, however measurements of $\nabla p/n_e$ and E×B flow indicate that the transition occurs at similar radial electrical field profile in the edge barrier region. This result suggests that in the L-mode phase just prior to the transition the MP provokes additional radial transport, while the local edge conditions for the H-mode transition itself have not changed, in line with a picture of flow shear being the critical parameter.

4 Real-time NTM Control via ECCD

When aiming for high performance, a magnetically confined fusion plasma is prone to the occurrence of neoclassical tearing modes (NTM), which form magnetic islands. NTM impact negatively on confinement and thus on the efficiency of fusion energy production in a reactor. Moreover, the risk of complete loss of plasma confinement in a disruption is heightened when islands appear in the plasma. In order to achieve optimal performance and stability, NTM need to be controlled.

At AUG, the method for achieving NTM control in real-time is electron cyclotron current drive (ECCD) near the O-point of the magnetic island. The exact location of where the current drive occurs can be changed by individually tilting mirrors, which vary the initial launching angle of an ECCD beam. The propagation of the wave through the plasma to the absorption layer, where the current is driven, can be accurately described in terms of geometrical optics. The deposition location can thus be calculated by the code TORBEAM, when the magnetic equilibrium, plasma density and plasma temperature along the beam path are known. Real-time measurements of those data and subsequent calculation of the locations with a latency well below 20 ms simultaneously for the four suitable launchers marked a major milestone towards achieving the closed control loop.

Other diagnostics detect the location of the island's O-point. The preferred method uses a time correlation of ECE T_e-data with appropriately constructed Mirnov signals and latencies well below 10 ms. Rational q-surfaces from the magnetic equilibrium are another option, with the advantage that these are available even without an NTM present.

The Discharge Control System (DCS) can use either location as a target to control ECCD deposition, at the discretion of the experiment leader. A feedback controller has been optimised to track changes in the specified target as fast as possible while taking into account the mechanical load on the mirror mechanism and various non-linearities. Settling time for a large sudden change in the target position is <300 ms.

The estimate of the NTM location can be refined by considering its amplitude. In this case the controller moves the ECCD location in a series of steps, searching for a minimum in the amplitude, which indicates that the ECCD is deposited in the optimum location.

In the experiment (figure 7), a (3,2)-NTM is triggered at 2.5 s at a plasma $\beta_N \approx 1.8$. The upper plot shows a time-trace of the mode amplitude as seen by magnetic pick-up coils (red) compared to a threshold (black). The middle plot shows plasma β_N (black) and total ECRH power of the gyrotrons used for stabilisation (blue). The lower plot shows the real-time signal of the NTM location (black squares) and the deposition location of three gyrotrons active during this discharge.

When unpowered, the grey colour indicates just the launcher aim, when red, the deposition is mainly in the core (for impurity control), when blue, the deposition occurs at or near the NTM location.
The NTM feedback controller is started at 2.6 s. The off-axis launcher is brought into position and at t=3.0 s, power is turned on. As seen, a clear reduction in mode amplitude can already be achieved with one beam (≈0.7 MW) of ECCD deposited on the island, but full stabilisation (and notable increase of β_N) is only achieved when the second ECCD beam (≈0.65 MW) is added at the same radial location. This happens at t=4.5 s. Less than 300 ms after switching on the second beam in the correct location, the (3,2) NTM disappears. Plasma performance expressed in β_N intermittently reaches 2.2, an increase by ≈20 %, which is in line with predictions for a (3,2) NTM.

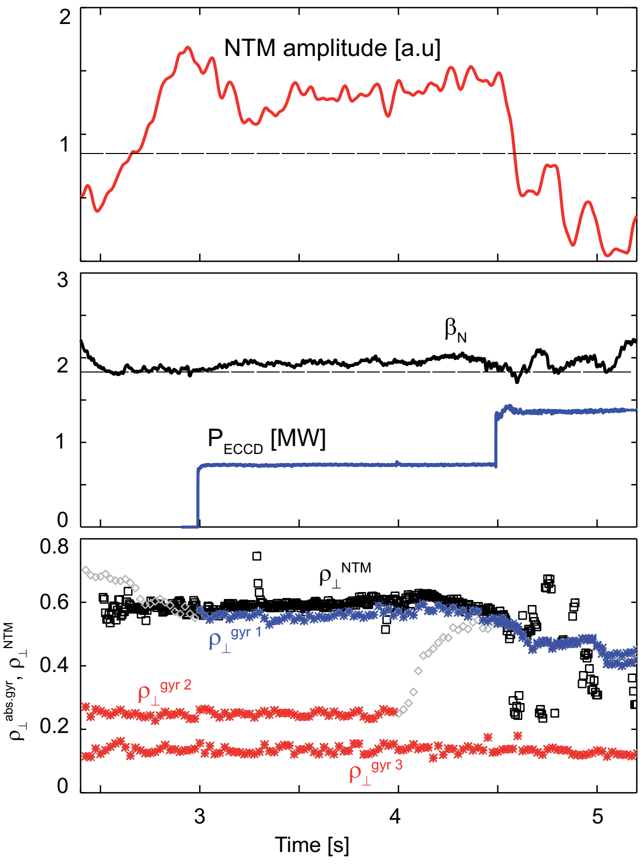

Figure 7: Trace definitions, see text.

With a large number of real-time diagnostics fully operational, the NTM feedback loop is closed and has successfully completed a proof-of-principle experiment for several control modes. Further work will clarify, which combination of controller modes can be a solution for next generation devices such as ITER and DEMO.

5 Technical Systems

The 2012-2013 experimental campaign was comprised of 1740 pulses during 2012 and a further 991 pulses in 2013 for a total of 2731 discharges, 1994 of which were useful for the physics program. 347 discharges were heated with more than 10 MW and 22 of them with more than 17.5 MW. The experimental campaign finished with discharge # 30135 on April 25th 2013. The restart after eight months of AUG modification began in December 2013.

5.1 Machine Core

During the operation in 2013 leakages in the water cooling of the outer divertor occurred starting in sector 15 (# 29287, 22.1.2013) and followed by S5 (# 29695, 8.3.2013), S8 (# 29970, 9.4.2013) and finally S12 (# 30036, 19.4.2013) shortly before the end of operation. As in 2009 and 2011, AUG was operated without water cooling in the sectors suffering from the leakages. This mode of operation requires a moderate adjustment of the experimental programme by combining low power and high power pulses to avoid overheating the divertor structure, T_{max}=150 °C, and the target clamping, T_{max}=550 °C. Investigation of the target cooling plates reveals cracks in the cooling pipes connecting both plates. FEM calculation performed for the Div-III design revealed that the halo-currents flowing to the outer divertor can cause a movement and tilting of the cooling plates. This might in principle cause these cracks. Further investigations to characterize the cracks and the crack mechanism are ongoing. The replacement of all cooling plates was scheduled as part of the Div-II installation for the 2013 opening. The new divertor design has a more flexible connection between the cooling plates.
Vessel inspection after venting reveals AUG to be generally in good condition. In detail, locally molten tungsten coatings were detected. A diagnostic protection cap was broken and ECRH stray radiation has caused damages to isolators and magnetic pick up coils. The affected components were replaced during the opening. Care was taken on the hardening of magnetic pick up coils and inner vessel components, in particular at the high field side in S4-6 and S14, against ECRH stray radiation. The scheduled modifications carried out during the shutdown in 2013 expand the operational range. During the opening the following main projects were realized:
- Installation of a lower outer divertor with solid W-targets.
- Modification the divertor geometry to increase the effective pumping speed below the roof baffle.
- Upgrading the cryo pump to adjust the pumping speed.
- Making a part of the outer divertor replaceable without venting.
- Exchanging two rings of W-coated graphite tiles by Eurofer compatible ferritic steel in preparation of DEMO.
- Upgrading the diagnostic capabilities for divertor, edge and core investigation.

Torus Pumping and Gas Inlet System

The **gas inlet system** was redesigned to minimise mutual interferences with diagnostics and to optimise the experimental options. Now, the mid-plane gas inlet has been relocated to S3 and 4 valves feed the upper divertor region. The vacuum-side of most valves is equipped with tubes to hasten response time. Now all piezo valves are supplied by a gas matrix and can, therefore, be fed independently with different gas species. To enhance the signal quality dedicated cables between valves and their associated controllers were designed and installed. The system is comprised of a high voltage supply for operating the piezo crystal as well as the cabling of the pressure sensor for flow control. For the operation of shutoff and vacuum valves in the torus hall, Siemens Profibus distributed peripherals were installed and now replace ageing central control components. After calibration of the valves the new system is planned to be completely operable in early summer 2014.

Cryo pump partitioning: The toroidal cryo pump (CP) ring consists of seven different modules connected in series. Saturated He keeps the CP He-panel at a constant temperature of 4.5 K. All modules have a combined pumping speed (PS) in deuterium of PS=140 m^3/s at a vessel pressure of 10^{-3} mbar. To enable a variation of PS from 100 % to 30 % a cryo-valve-block (CVB) between module 2 and 3 has been installed. In the case of 30 % operation the CVB deactivates the He-panels of modules 3-7. The CVB contains three valves connected with bellows to actuate the valves with 4 bar He gas. For monitoring the temperature on the connecting pipes to the CVB specially made sensor heads with carbon-ceramic sensors are installed.

Wall conditioning by means of glow discharge cleaning (GDC) is still mandatory after cryo pump regeneration or impurity events, even after transition from C to W first wall. However, its necessity during normal plasma operation is clearly weaker. For homogeneity of GDC several anodes had to be installed close to the midplane, where they hamper the installation of diagnostics. Therefore, an improved, smaller anode based on a W7-X design was developed and installed. For reliable GD break-down the existing starter device was redesigned and fed via an additional power supply. Extensive laboratory tests have been performed to optimise GD and ensure safe operation. To reduce the implantation of He into the W surfaces during GDC, the steady-state GD were replaced by pulsed ones: 10 s of GDC followed by a 50 s pure pumping phase. It could be demonstrated that the wall cleaning efficiency of this pulsed scheme is even higher than continuous GDC.

5.2 Experimental Power Supply

The operating period (January to April 2013) did not reveal any major problems with our power supply systems. To keep the electricity supply of the institute going, one of the two 50 year old IPP 110 kV feeding transformers has been replaced by E.on. A new current measuring device for the 60 kA TF power supply was also tested. The system, on loan from TEXTOR in Jülich, is based on polarized light.

Due to excessive vibrations of generator EZ2, the maximum speed of the generator had to be reduced. In line with the maintenance of EZ3, the problems could be solved and full energy will be available for the next campaign. Control of EZ2 has been improved to allow for more accurate current control and for extended pulses (60 s) at reduced field (1 T). The maintenance of generator EZ3, including the complete dismantling, inspection, cleaning, electrical and ultrasonic testing and re-assembling revealed broken spacers between the rotor poles of the motor drive. Repair work required an asbestos abatement of the rotor. In parallel to the maintenance work, IPP staff dismantled the 35 years old, fault-prone direct converter of EZ3. The new drive converter, commercially used in wind turbines, has been delivered, installed, commissioned and tested by company Siemens. In order to prepare the reconstruction of the drive converter, detailed calculations and simulations of the control system have been performed. The commissioning results show good agreement with the calculated design values. To improve the reliability of the generators excessive torque protection system, first tests of a new, sophisticated measuring system were successfully performed on generator EZ4.

For the new MP-coil power supplies, several interface cards have been designed and manufactured and the drivers for IGBT and system control have been programmed. The Semikube power modules and the cubicle layout have been adapted and gradually improved according to the specific AUG requirements. To make use of thyristor converter group 0 for the direct current link supply, extensive investigations and tests of the voltage control loop were necessary. Further on, the L5E test facility had to be connected to the converter via a crossbar distributor. While testing and programming of the first demo installation went on at the lab, a new platform and the first switching cabinets were mounted at the northern wall of the torus hall. First experimental results with the new system are expected during the 2014 campaign.

The transformers and rectifier of the first 7 MW HV power supply system for the supply of ECRH3 have been reconditioned. The associated converter unit has been dismantled and the re-construction with respect to the pulsed operation was begun. Both systems will successively be maintained and commissioned by 2016.

5.3 Neutral Beam Heating

NBI was available until the end of the 2012/13 experimental campaign in late April. A leak on the large torus gate valve occurred in December 2012, but did not hamper further NBI operation. During the maintenance break that lasted from May to the end of the year it was found that the leak was due to melting of a portion of the gate valve body around the seal seat.

It is believed that re-ionized and magnetically deflected beam particles caused the melting as a result of beam blocking inside the NBI box, although the exact cause for the beam blocking remains unclear. Among the several repair options considered, in situ deposition welding, although highly demanding, was identified as the least time-consuming method. The repair was very successful.

The maintenance break was also used for a variety of other activities. Three long-term stored NBI sources were conditioned for use on W7-X and as spares for AUG. The calorimeter of injector 1 was thoroughly overhauled and many of its worn target plates were replaced pre-emptively to avoid future water leaks. Likewise, liners in the bending magnet that are struck by the few negative ions produced in the neutralizer were approaching the end of their fatigue-life and were replaced on both injectors. Another major effort was the replacement of the outdated SIMATIC S5 control on injector 2 by a new S7 system. Furthermore, preparations have begun for remote pneumatic switching of the deceleration grid bias resistors of all eight NBI sources. So far the switching, necessary whenever the acceleration voltage is changed from above to below a certain threshold and vice versa, required access to the torus hall and a complete shutdown of the injector. The time-saving remote switching will be available early in the 2014 campaign.

5.4 Ion Cyclotron Resonance Heating

The production of new three strap antennas, optimised to reduce impurity production and being built via an international collaboration between ASIPP Hefei, China and ENEA, Frascati, Italy, is progressing well. Following acceptance tests in Hefei, the first ASIPP built antenna (the stainless steel components) reached IPP in July and was successfully tested for high RF voltage handling capability in vacuum (figure 8). The components of the antenna, which are made of special materials, are the responsibility of ENEA. The cooling frame made out of CuCrZr, the Faraday screen made from TZM, and the CuBe springs have passed most material and manufacturing process qualifications and will become available in the near future. The additional limiters (made of C) are already machined and are undergoing a final W coating process. Most of waveguides for the reflectometer system, which is part of the ENEA package and comprises ten microwave antenna pairs, have been installed in the antenna and are in the process of being tested. A special automated U-band test set was designed and built for this purpose at IPP. After a trial installation of a complete antenna in a full scale AUG octant, both antennas will be installed during the 2014 opening.

During the 2013 opening, additional transmission lines leading to two of the four antenna systems and corresponding tuning systems have been installed. These modifications allow the amplitude and phase of the two antennas to be varied independently at their feeding points. This is essential for the new antennas, as the optimisation with respect to reduced electric fields requires specific values of amplitude and phase of the current in the central conductor with respect to the two outer ones (which are connected in parallel). This additional flexibility can already be used for the present antennas and will allow the investigation of the variation of those parameters on heating efficiency, coupling and the impurity production.

Figure 8: The stainless steel components of the ICRF 3-strap antenna, as installed in ICARoS for tests.

5.5 Electron Cyclotron Resonance Heating

In 2013, plasma operation used the 4 old (ECRH1) units and three out of four ECRH2 units, since one new gyrotron was still undergoing a warranty repair. The problem of breakdowns through the body insulators in ECRH2 has been solved by switching to POM-C material, now also used by GYCOM for its ITER-gyrotrons. ECRH was used in the majority of the discharges. Operation at high power was still occasionally hampered by arcing in the waveguide and the mirror box on the torus-side. Towards the end of the 2013 campaign forced flows of dried air through two of the 70 m long ECRH2 waveguides were implemented in order to prevent arcing after several long high power pulses due to ionization of the air in the wave guide. First results are promising, but statistical analysis will only be possible after a long campaign.

The thermo-couples in the O2-reflectors were refurbished during the 2013 opening, after several cables were destroyed during a false-polarisation pulse in 2012. Tests in a specially prepared Mitre-bend indicated that these thermo-couples are directly heated by the beam, i.e. for fastest response they should not be covered by graphite. Protection can be achieved by retracting them a few 100 μm into the bore-hole they are mounted in, although this reduces the signal amplitude (bore-hole diameter below cut-off).
First high-power tests of the ring-resonator based multi-frequency window for the last gyrotron of ECRH2 were carried out at IPP near the end of 2013. Gyrotron oscillation at an intermediate frequency of 127 GHz could be reproducibly excited even for high window reflection (detuned resonator). Unfortunately the tuning of the resonator turned out to be unexpectedly difficult and the resonator will be sent back to GYCOM for optimization. Further tests at IPP are planned after the coming campaign.
Construction of ECRH3 as a replacement of the old ECRH1 system continued in 2013. The largest orders placed in 2013 were semiconductor based body modulators (FuG, Rosenheim), and approx 400 m of waveguide (Mühleisen, Gerlingen). The construction focused on the 400 V systems, cooling systems, HV-room infrastructure, MOU-frames and gyrotron sockets as well as the support structure for the waveguides including independent consoles and bridges for mounting and adjustment. Detailed design activities in 2014 relate to the upgrade of the launcher steering mechanism. The actual ECRH1 system tends to get stuck occasionally. An improved construction will have to be tested in a separate bakeable vacuum chamber, which is still available from ECRH2 launcher-tests. On the electronic side, a DC cathode heater operating at the cathode potential of 45 kV will be developed in order to prevent oscillatory j×B forces on the heating-filament.

5.6 CODAC

A Virtual Desktop Infrastructure (VDI) project has been launched to provide virtual machine remote desktops instead of simple remote desktops on shared server platforms. VirtualBox on Solaris X86 has been chosen as the virtualization host. Supported guest systems are Windows, Linux, and Solaris in various flavours. The whole VDI environment runs on top of the existing SunRay server and thin client hardware layer, which has existed at AUG for 12 years, but has recently been refurbished by new 24" flat screens and modern SunRay boxes.
To manage the challenges of an ever increasing amount of stored data for the experiment a 250 TiB Oracle StorageTek system together with an Oracle SPARC T4-1 file server has been commissioned. As the trend shown in figure 9 is half logarithmic it is foreseeable that the new storage will be sufficient to host data from the last 20 years, but will be exhausted within the next two years by upcoming plasma pulses.

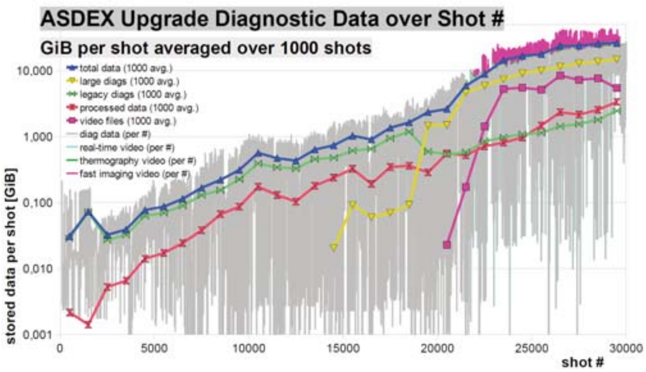

Figure 9: Evolution of AUG pulse data volume.

The AUG Discharge Control System DCS has prepared for ambitious plasma control and monitoring functions. The migration process from the VxWorks operation system to a pure real-time Linux setup has been completed. A new, flexible gas valve mapping system allows the assignment of gas valves to control channels from within the discharge program to be defined. Tilt forces on TF coils are calculated and supervised in real-time extending the operational space for experiments. With the current profile estimator RAPTOR developed by Federico Felici (FOM) a new generation of plasma reconstruction codes built on the observer model was introduced. These observers combine measurement data with model-based prediction in real-time for reconstruction of plasma quantities, which would otherwise only be determined inaccurately or with great difficulty.
This extension does not only offer great potential for future novel plasma control methods. It also opens the path for the introduction of modern control algorithm development methods. Instead of manual re-coding, the real-time algorithm code is automatically generated from the original MATLAB/Simulink model, wrapped in a generic interface module and plugged into the DCS framework. In addition, DCS has been extended with an adaptor to a MARTe real-time executor. MARTe is a real-time control system framework, widespread in the European fusion community. The coupling allows control algorithms, developed at other fusion labs with MARTe, to be executed in AUG experiments and thus will facilitate mutual exchange and test of control strategies.
The benefits of DCS have attracted lots of attention in the fusion community. DCS is considered one of the main models for the future ITER plasma control system. Finally, the French Tore Supra successor project WEST has decided to adopt DCS as the core component of its new control system and a collaboration project between IPP and WEST has been launched.

6 Plasma Core Physics

6.1 Interaction of NTM with MP

External magnetic perturbation (MP) fields can also interact with pre-existing rotating NTMs. The resonant components of the MP-field exert local (j×B)-torques and alter the NTM stability. The non resonant components do not influence NTMs directly but slow down the plasma rotation globally due to a neoclassical toroidal viscous torque (NTV). In experiments, the slowing down of pre-existing NTMs is observed in two discharges (figure 10). Both modes spin up as soon as the MP-field is switched off. It is observed that the mode slows down and additionally that the plasma rotation decreases globally. In contrast, the mode amplitudes are only slightly affected.

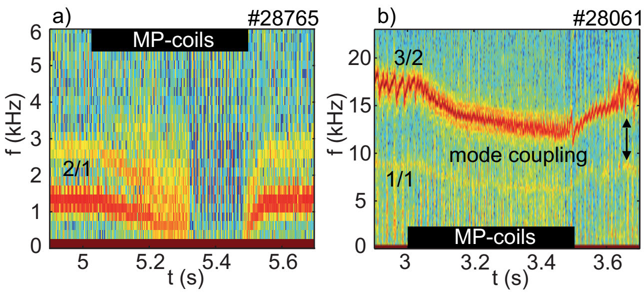

Figure 10: Spectrogram of mode locking a) and braking b) due to MP-fields.

The resonant field components, produce oscillations of the island width and a harmonic mode rotation (figure 11), and hence the higher harmonics are enhanced (figure 10a). To model the interaction, a coupled equation for the mode amplitude and phase is solved, taking into account the resonant effects at the NTM location. It was shown that the NTV torque can be neglected for the investigated discharges. The modeling suggests that in the experiment resonant torques are also acting at surfaces without modes andslow down the plasma rotation. This requires a smaller effect at the NTM surface in order to match the NTM frequency evolution and at the same time explains the small influence on the island stability.

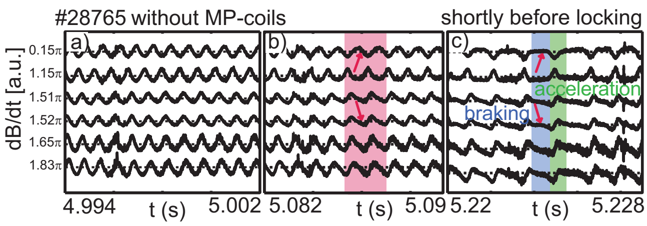

Figure 11: Rotation of NTM with MP-field off a) and on b) and c) shortly before mode locking.

6.2 Real-time Magnetic Equilibria for Pre-emptive NTM Stabilisation

Real-time magnetic equilibria for NTM stabilisation experiments are calculated by a Grad-Shafranov solver constrained to fit 40 magnetic probes and 18 flux loop differences. Without internal constraints for the magnetic equilibrium reconstruction from the Motional Stark Effect (MSE) or polarimeter it is advantageous to introduce a q(0)~1 constraint to provide the best possible estimate of the on-axis current density. In addition, the number of current basis functions has been extended to 12 splines. Despite the increase in the number of current basis functions, a cycle time of 1.5 ms could be maintained for parallel real-time magnetic equilibria using either magnetic probe measurements only or magnetic probe and MSE measurements. The additional constraints on the current basis function coefficients are provided by first order regularisation. Internal constraints for magnetic equilibrium reconstruction from either MSE or polarimetry, which are essential for accurate safety factor profile determination and robust pre-emptive NTM stabilisation, should be available in the next campaign.

The recently installed ferromagnetic tiles generate a perturbation of probe measurements and flux surfaces in the vicinity of the tiles. This perturbation is calculated in real-time to properly account for their effect on the magnetic equilibrium reconstruction for pre-emptive NTM stabilisation experiments. A reduced power requirement for pre-emptive NTM stabilisation in comparison to stabilisation of an existing NTM was documented. In an 1 MA discharge with 10 MW NBI heating only 0.5 MW of electron cyclotron current drive (ECCD) was required to achieve full stabilisation while even 1 MW of ECCD only partially stabilised an established NTM.

6.3 Magnetic Equilibrium Reconstruction with T_e Iso-flux Constraints

Tokamak magnetic equilibria are routinely calculated by a Grad-Shafranov solver using external constraints from magnetic measurements and, if available, internal constraints from MSE measurements. The reconstruction of the magnetic equilibrium poses an ill-conditioned inversion problem using magnetic data only and the internal MSE measurements are not routinely available. Therefore, additional inner constraints using, e.g., temperature and pressure measurements are valuable to provide complementary and redundant information to restrict and validate the ill-posed inversion problem. Pressure constraints allow, e.g., to reconstruct the edge current distribution for plasma stability studies. Alternatively, the current distribution and, hence, the magnetic equilibrium can, in principle, be determined completely from pure geometric information about the shape of the magnetic surfaces. As the temperature is considered to be constant on closed flux surfaces, redundant T_e measurements on the same flux surface can provide sufficient information to determine the position and shape of these surfaces and, hence, the current distribution provided that T_e gradients allow the labelling of flux surfaces with temperature values. Multiple T_e measurements on the same flux surface are provided by ECE measurements in the core plasma allowing geometric iso-flux constraints consisting of multiple points on the contour of a flux surface to be applied. An improved radial position of the magnetic axis could be achieved.

6.4 H-mode Density Limit

Future fusion reactors will most likely be operated in the H-mode. It is desired to operate these devices at plasma density as high as possible in order to increase the produced fusion power. However, this is limited by the H-mode density limit (HDL). Four phases are identified on the approach towards the HDL, which affect the plasma energy and n_e differently. These phases are a stable H-mode (see figure 12, green) followed by a degrading H-mode (yellow). The phase of the breakdown of the H-mode (red) finally leads to the L-mode (blue). With this classification, a new way to explain the HDL was found. This new description involves the coupling of two effects, an increased heat transport at the plasma edge and the ionisation of the neutral gas outside of the confined plasma.

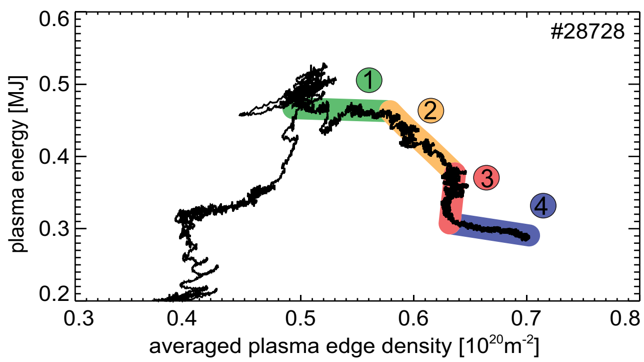

Figure 12: Evolution of plasma energy vs. edge n_e of an HDL discharge.

6.5 Identification of the β-limit

Tokamak plasmas are subject to various resistive and ideal MHD instabilities, which restrict the operation space of the device. For optimal fusion performance, it is preferable to operate the tokamak close to the stability limit with maximal possible pressure characterized by the value of normalised β_N, and thus maximal fusion power $P \sim \beta_N^2$. In AUG, the limit for maximal achievable β_N is typically set by the resistive instabilities (tearing modes). If these instabilities are overcome or prevented, for example by pre-emptive ECCD, higher values of β_N can be potentially reached. These values are limited by the onset of the ideal kink instability, which is an ultimate limit for plasma stability. The actual limit depends on several factors, including the stabilizing influence of the conducting components facing the plasma surface and safety factor profile. It was shown both, experimentally and numerically, that AUG operations at high β_N is around so-called 'no wall' limit (no stabilising wall effect). Resonant field amplification measurements and observed unstable global ideal kink mode demonstrate crossing of the maximal β_N-limit around 'no-wall'. These results suggest that further flattening of the q-factor profile and/or additional conducting structures would extend the operation region to higher β_N.

6.6 ITER Baseline Scenario

In ITER, H-mode operation at 15 MA and q_{95}=3 is planned to achieve 500 MW fusion power at Q=10. This so-called ITER baseline (BL) scenario is characterized by normalised parameters for density $f_{GW}=n/n_{GW}=0.85$, energy confinement $H_{98y2}\sim1$ and $\beta_N\sim1.8$. A high triangularity shape ($\delta_{average}\sim0.4$) has been identified to be best suited to combine high density operation with good H-mode confinement. This ITER reference scenario has been demonstrated on AUG with its full W-wall (AUG-W) in discharges at I_p=1.1 and 1.2 MA with central ECRH and ICRH, respectively. Such discharges showed stable behaviour for many confinement times. Values for density and energy confinement came simultaneously close to the requirements of the ITER BL scenario (figure 13) as long as β_N stayed above 2 (typically $2.0<\beta_N<2.2$). Compared with results with a C-dominated wall (AUG-C) the operation in AUG-W is restricted to higher densities $f_{GW}>0.75$ and confinement is on average reduced by 5-10 %. The very large ELMs that are present, appear difficult to mitigate. The solution of this problem remains the biggest challenge for optimising such plasmas in the coming campaigns.

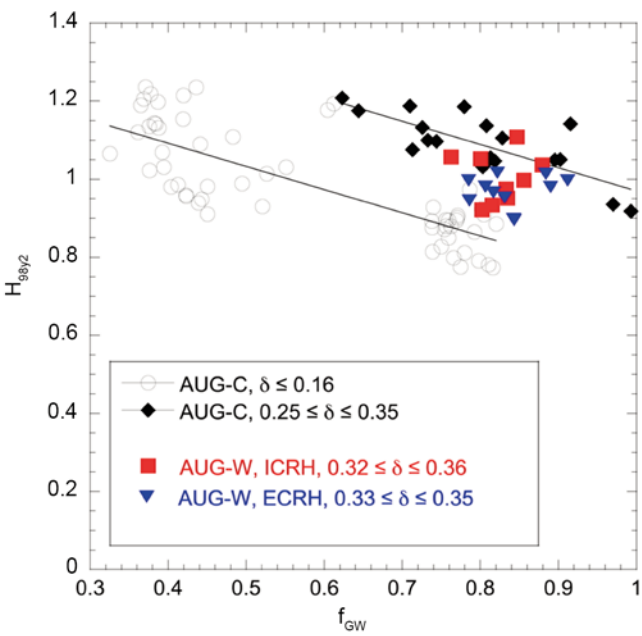

Figure 13: H_{98y2} vs. f_{GW} at q_{95}=3 in AUG-C (black symbols) and AUG-W (blue & red).

6.7 A Novel Free-boundary Transport Solver for I_p-ramps

The coupling of in-house transport solver ASTRA with dynamical free-boundary equilbrium code SPIDER has reached the stage where application to an existing experiment and for predictive purposes are possible.

A dedicated numerical scheme has been devised, which robustly couples the transport equations, in particular for the poloidal magnetic flux, to the free-boundary part, which solves the Grad-Shafranov equation plus circuit equations for the external coils. The first comprehensive simulations, which also include a quasi-linear turbulence transport model TGLF, have been carried out on I_p ramp-up and ramp-down scenarios.

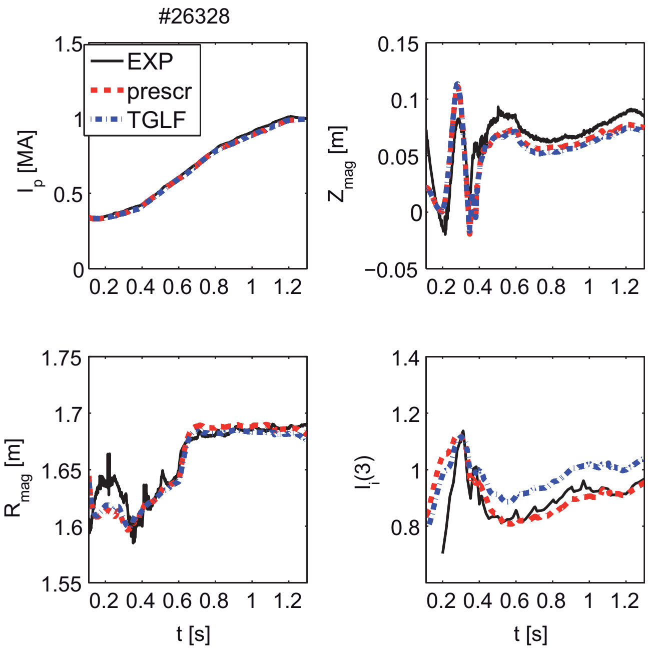

Figure 14: I_p-ramp-up comparison from experiment (EXP), simulation with prescribed profiles (prescr) and TGLF simulation.

An example is given in figure 14, where time traces of some global plasma parameters, i.e. I_p, magnetic axis vertical and radial positions Z_{mag} /R_{mag}, plasma internal inductance l_i. It can be seen that good agreement is obtained in all time traces between experimentally-based equilibrium reconstruction with CLISTE ('EXP'), simulation with experimentally prescribed kinetic profiles ('prescr') and theory-based modeling of electron and ion temperatures ('TGLF'). The ongoing effort in importing more and more physics into this package has already allowed to include a code for impurity transport (STRAHL), and for heating/current drive sources. Development in the near future is focused on extending predictive capabilities of the turbulence transport model as close as possible to the separatrix, which is crucial for correctly predicting internal inductance and flux consumption.

6.8 Pellets for ELM Triggering and High n_e-operation

ELM triggering and pacing in an all-metal wall environment shows significant differences to a first wall configuration containing C. Experiments performed in 2013, with all plasma facing surfaces now fully replaced by W, has added further details. This investigation was motivated by experimental findings indicating ELM triggering becoming more difficult when replacing C by a metal wall. ELM pacing could no longer be achieved by magnetic triggering under conditions that previously showed a positive response. Also, recent investigations from JET indicate that a lag time occurs in pellet ELM triggering when operating with the new ITER like wall. The AUG centrifuge based launching system has been revitalized and upgraded for this study. It now allows for a detailed analysis of the ELM trigger response. The appearance of a lag time for pellet ELM triggering in an all-metal wall environment was confirmed. While different lag time durations were found for several type-I ELMy H-mode scenarios, the magnitude of the pellet perturbation was found to cause no difference. Reducing the auxiliary heating power for ELM triggering obviously makes the pellet tool less efficient for ELM control purposes. However, this results in a major benefit when applying it for fuelling. As shown in figure 15, plasma operation with benign ELM behaviour at core n_e far beyond the Greenwald limit n_{GW} has been demonstrated, fully reversible and without affecting the energy confinement, there is no indication for a τ_E-increase as predicted by the H_{98}-scaling. Obviously, this scaling becomes inappropriate for evaluating the plasma performance once n_e beyond ≈0.85 n_{GW} are achieved.

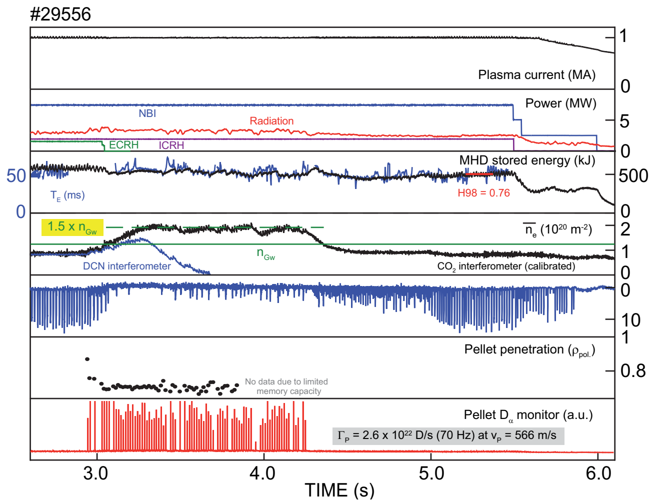

Figure 15: High n_e without τ_E-degradation achieved by pellets. n_e far beyond n_{GW} was achieved with benign ELM behaviour.

6.9 MGI in Locked Modes

Typically, massive gas injection (MGI) has been carried out by injecting impurity gas in H-modes, in order to test the capability of the contaminated plasma in radiating a large amount of thermal energy and to have a target plasma with predefined parameters. Nevertheless MGI will be used in ITER in discharges with a high probability of disrupting and therefore likely with large non-rotating modes. A series of plasmas with locked modes were terminated by MGI in order to study the influence of these modes on the fuelling efficiency and the radiation asymmetry. Mostly Ohmic plasmas were driven to the density limit by means of strong feed-forward gas puffing;

the tearing modes, which develop before disruption, were artificially slowed down and locked by applying an n=1 radial magnetic field with the MP coils switched on well before mode development. Neon quantities per plasma volume comparable to the one foresee for the ITER DMS were injected. A reduction of the pre-TQ phase is observed when large rotating or locked modes are present. These effects decrease the amount of gas assimilated by the plasma up to the TQ (up to a factor of 2) and up to the middle of the CQ and should be taken into account when dimensioning the ITER DMS. Large radiation asymmetries are observed during the pre-TQ phase when the plasma is locked. Nevertheless, in these cases the plasma thermal energy is small (order of 10 % of the maximum thermal energy) and would not cause the melting of the ITER wall. The radiation asymmetry during the TQ is smaller.

6.10 Detection of MHD via sub-mm DCN Interferometry

In the presence of MHD activity in the plasma, the probing beams of the DCN interferometer λ_{DCN}= 0.195 mm often suffer from refraction, which modulates the beam intensity arriving at the detector with the MHD frequency f_{MHD}. In January 2012, a digitizer with 1 MHz sampling frequency was installed to record the detector raw signals. In their frequency spectrum, MHD activity appears at f_0+f_{MHD} and $|f_0-f_{MHD}|$, with f_0=10 kHz being the beat frequency of the heterodyne interferometer. Accordingly, the DCN interferometer can now be used for MHD detection, with a spatial resolution given by its five different lines of sight.

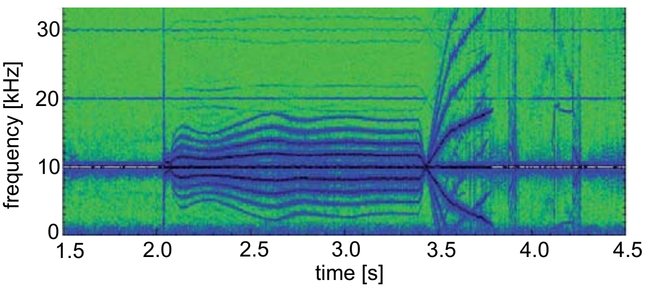

Figure 16: Spectrogram of the detector raw signal for the innermost interferometer channel of # 29307. Several harmonics of MHD modes starting at t=2.1 s are clearly visible.

7 Edge and Divertor Physics

7.1 Rotation and n_e-asymmetries during Large Poloidal Impurity Flows in the Edge Pedestal

The new edge CXRS diagnostic suite available allows for CX measurements at two poloidal locations to be obtained and thus, to study asymmetries on a flux surface. The new measurements revealed that in the ETB the flow structure is asymmetric on a flux surface. The asymmetry in the flow pattern can be explained by an excess of impurity density at the HFS following the condition of divergence-free flows. The impurity densities on the LFS and HFS were investigated and the measured HFS impurity density was found to be up to a factor of three higher than at the LFS, demonstrating that in the edge pedestal the impurity density is asymmetric on a flux surface. Accounting for the measured poloidal asymmetry in the impurity density, the HFS and LFS measurements are consistent with the condition of divergence-free flows. Comparison of the measured data to theoretical predictions based on the parallel momentum balance reveals the nature of the parallel impurity dynamics. The key features of the experimental data including the shape of the rotation profiles and the poloidal impurity density asymmetry were reproduced quantitatively for the first time.

7.2 Inter-ELM Pedestal Physics

The evolution of the edge pedestal between two ELMs can be characterized by consecutive phases, in which n_e and T_e show different recovery rates. Also the edge current density can now be determined for the full ELM cycle using magnetic measurements and pressure profile constraints as shown in figure 17.

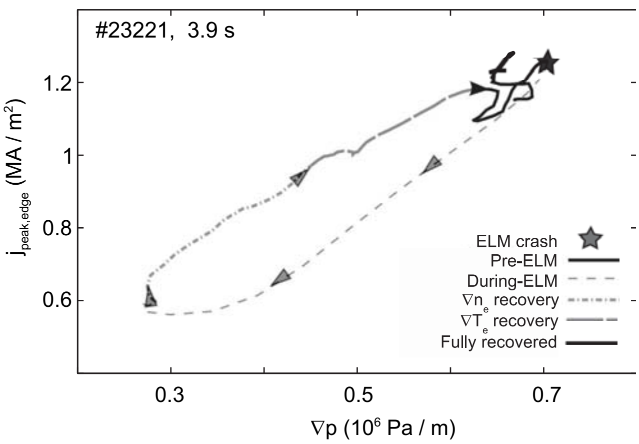

Figure 17: Edge current density during full ELM cycle.

The measured edge current density agrees well with neoclassical theory. Using this data as input, the ideal linear peeling ballooning code suite ILSA/MISHKA was used to determine the stability limit in the different phases in the ELM cycle. As expected, the operational point is far away from the stability limit in the early phases after the ELM crash. Later the operational point stays constant, i.e. the current density and the pressure gradient do not change anymore, while the stability limit moves closer until the ELM crash occurs. Due to the increasing width of the edge transport barrier region, more poloidal harmonics become unstable leading to the reduced j-∇p values of the stability boundary. The final ELM trigger condition cannot be explained by this analysis, since for several analysed cases the operational point does not always meet the calculated stability boundary, but can lie either in the stable region or in the unstable region.

The same data have also been used as input for GENE runs in order to determine the dominant microturbulence. In the phase just before the ELM crash, analysis of the gyrokinetic runs shows robustly unstable micro-tearing modes (MTM) at the top of the pedestal as well as unstable kinetic ballooning modes in the whole pedestal region. This is consistent with the results of velocimetry of ECEI data, which demonstrate the existence of MTMs at the pedestal top. Additionally, there is evidence that the MTMs could couple to low n ballooning modes leading to the ELM crash.

7.3 Phases during an ELM Crash with N_2-seeding

A new method was applied to indirectly obtain information about the features of the crash of the H-mode edge transport barrier in consequence of an ELM. The method is based on a combination of fast measurements, without spatial resolution, and relatively slow measurements, with high spatial resolution. The comparison of 2 different ELM – a standard scenario and one with additional N_2-seeding – revealed a 2-fold nature of the ELM crash. In the case with additional N_2 only a part of the standard crash is observed. This suggests the standard ELM crash consists of two or more consecutive events instead of a single distinct one. Some of these events are observed to be suppressed with changes in plasma parameters. The radial extent of the phases observed during the ELM crash differs in the kinetic profiles, with one instability extending inside of the pedestal top and the other being confined to the pedestal region as shown in figure 18.

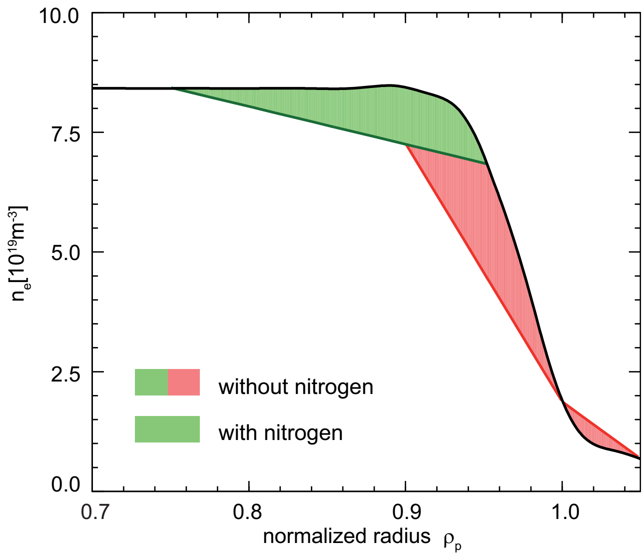

Figure 18: Sketch of ELM affected area with and without N_2-seeding.

This picture can explain the differences in loss of stored energy and the change in ELM frequency, which are observed for the analysed pair of discharges. It also suggests that the ELM crash starts at the pedestal top and only then affects the steep gradient region.

7.4 Impact of MP on the Edge E_r

The basic understanding of the MP field penetration and its dependence on the tokamak edge parameters remain outstanding issues. Doppler reflectometry shows the radial electric field E_r and density turbulence δn to be particularly sensitive indicators of the MP impact. In L-mode, clear n_e dependent MP field penetration thresholds are observed, resulting in E_r and density flattening in the near SOL and a reversal of the edge negative E_r well, consistent with field-line ergodisation. The radial structure of the edge E_r and δn are sensitive to the degree of MP resonance with the edge rational field-lines (e.g. q-profile & MP poloidal spectrum). Specifically, short-wavelength δn is enhanced where the MP is resonant and reduced when non-resonant. The MP toroidal structure has also been mapped for various n=1, 2 & 4 MP configurations by rotating the MP coil phases – and is found to be different for the edge and near SOL regions. Initial matching simulations (field-line tracing and EMC3-Eirene) are promising, aiding a consistent interpretation of the MP impact at low plasma collisionality. The search for full ELM suppression with magnetic perturbations at low pedestal collisionality ν_{ped}* (as observed at DIII-D) has continued. A hypothesis put forward by the DIII-D team involves the existence of a rational surface with sufficiently strong resonant MP, i.e. a magnetic island, at the pedestal top, which is thought to stop the H-mode barrier expansion before it drives the plasma unstable and an ELM occurs. The resonant MP strength near the pedestal top depends (a) on the alignment of the field structure with the plasma magnetic background field, and (b) on the strength of shielding currents induced by perpendicular electron flow. Both parameters have been varied experimentally but in neither case, full ELM suppression has been obtained. Surprisingly, the strongest effect on ELMs, reduction of type-I ELM losses by a factor of up to 3 at ν_{ped}*~0.5, along with an increase of ELM frequency, reduction of pedestal density, and braking of the plasma rotation is found only for the special case of non-resonant magnetic perturbation and low or moderate torque input (figure 19).

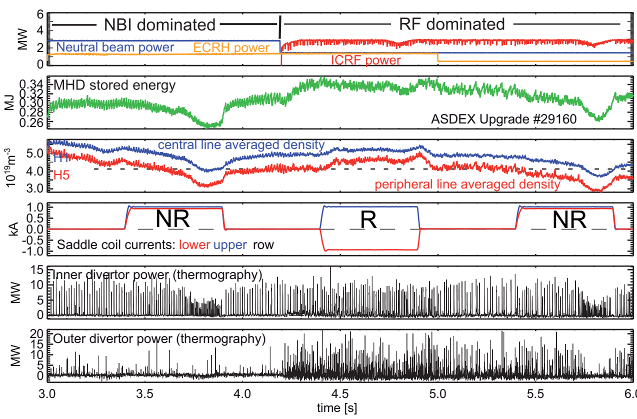

Figure 19: Time traces of # 29160 with resonant and non-resonant MP, and varied heating method (torque input).

Modulation of the non-resonant field amplitude reveals J×B interaction with the (1,1) sawtooth precursor mode, i.e. a core mode, as the source of the torque on the plasma. The absence of interaction with core modes in all other cases demonstrates the relevance of rotational shielding due to strong flows, the usual case in NBI heated H-modes.

7.5 T_e Evolution during Mitigated ELMs

This contribution is related to the electron temperature dynamics in the pedestal region during mitigated ELM regimes with MP. The analysis of several discharges with different heating methods supports previous experiments. The T_e drop – in the pedestal top – associated to large type-I ELMs is typically ΔT_e>100 eV, while for mitigated ELMs the temperature crash is faster (~100 µs) and smaller ΔT_e<20-50 eV. The drop of the pedestal temperature ΔT_e, and the relative drop $\Delta T_e/T_e$ depends on density and temperature, diminishing the drop for higher density or lower temperature. For the cases with lower temperatures and MP, the mitigated ELMs become smaller (ΔT_e<20 eV) and a second transition from mitigated ELMs to grassy ELMs occurs. The recovery time of the T_e profile for mitigated ELMs varies from 0.5 to 2 ms, depending on how big ΔT_e is. The duration of the divertor ELM power pulse for mitigated ELMs is ~200-600 µs, which is correlated with the typical time of the ion parallel transport from the pedestal to the divertor target $\tau=2\pi$ R q_{95}/cs,i similar to results observed for typical type-I ELMs.

7.6 EMC3-Eirene Simulations of the Impact of MP on Recycling

MP is applied at AUG and many other divertor Tokamaks in the world to mitigate ELMs. The non-axisymmetric MP fields strongly modify the magnetic structure of the plasma edge and lead to the formation of so-called lobes. While we reported recently on simulations with the Edge Monte Carlo 3D-Eirene code package focusing on the plasma transport and the power deposition pattern at the target observed as a splitting of the strike line, we now studied the impact of the MP fields on the neutral particle recycling. The MP fields effectively increase the radial transport of particles and heat to the outer regions of the plasma where n_e and T_e increase. As a consequence the mean free path of the neutrals decreases and their recycling flux increases. Similarities to the mitigation of type-I ELMs due to a transition to a regime of smaller type-III ELMs observed at high gas puff rates are presently discussed.

7.7 Fluctuating Detachment State

The influence of the heating power and the connection length, L_c, on the onset of the fluctuating detachment state, FDS, has been investigated. In order to trigger the detachment process, the divertor temperature is the critical parameter as it has to be reduced below ≈5 eV to make volumetric processes become important. Assuming a constant T_{div} at the FDS onset, the line integrated plasma edge density scales as $n_{e,FDS}$~$P^{5/7}L_c^{-2/7}$, according to the simple 2-Point-Model. This scaling fits very well to the measured data (figure 20a), verifying a constant critical T_{div} at the FDS onset.

The influence of the X-point position was also investigated. Moving the X-point further away from the inner target or further down increases $n_{e,FDS}$ (figure 20b, c). This shows that the change of the 2-D recycling and ionisation distribution in the divertor, due to the X-point scan, has an important influence on the detachment process. Moreover, in a freshly boronised machine with less impurity content, a similar $n_{e,FDS}$ but a 30 % higher gas fuelling is needed.

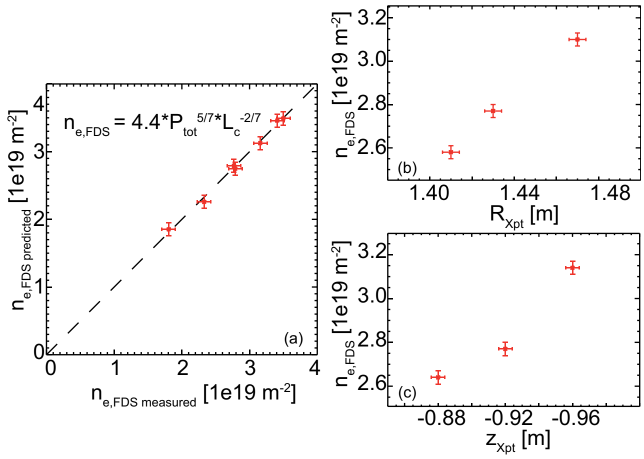

Figure 20: (a) Measured versus predicted edge n_e at the FDS onset at fixed X-point position and edge n_e at the FDS onset versus (b) horizontal and (c) vertical X-point position.

7.8 Impurity Seeding for Power Exhaust

High power seeding experiments were continued in 2013, with particular emphasis on core radiative cooling. For this purpose, Kr was added into the portfolio of seeding gases. Kr is a sole core radiator, with negligible divertor radiation and smaller Z_{eff} increase in comparison to Ar for a comparable radiation level. Thus, Kr has been used in combination with nitrogen in double feedback mode for divertor cooling and protection. Even with the pronounced core radiator Kr an improvement of the H-factor at high heating power levels up to H_{98}=1.1 has been observed. Since dilution effects can be excluded for Kr, the improvement of H_{98} is preliminarily attributed to the general effect of rising H_{98} at high β-values. Under the present experimental conditions, high β can only be achieved with radiative cooling, since the divertor protection system does not allow rising of the heating power to 20 MW without radiative cooling. Despite its relatively high Z, no particular disposition of Kr seeded discharges for impurity accumulation and central radiation peaking was observed, making Kr a candidate seed species for DEMO.

7.9 N-induced, Complete H-mode Divertor Detachment

Future fusion devices like ITER and DEMO will have to be operated with a detached divertor to meet material limits –

complete detachment defined as detachment over several power fall-off length, λ_q, is likely required for DEMO. For the first time stable H-mode operation with both targets completely detached has been demonstrated in the all-W AUG. Strong N_2 and D_2 puffing into the private-flux region is required. Target temperatures are well below 5 eV across most of the targets, the target peak heat flux is below 1 MW/m^2 and the peak ion saturation current is reduced by one order of magnitude to below $5 \cdot 10^{22}$ e$^-$/m^{2}s. Fuelling of the plasma seems to change due to detachment as the pedestal top n_e increases abruptly by about 15 %. Complete detachment of the outer target is correlated with a stable state of intense radiation around the X-point, that induces localized cooling of the confined plasma above the X-point. Simultaneously, a loss of 30 % in both n_e and $T_{e,i}$ at the pedestal top is observed while the profile changes only less than 10 % inside $\rho_{pol} < 0.8$. Core plasma performance ($H_{98} \sim 0.9$) is unchanged despite the reduced pedestal pressure and mitigated ELMs in this phase. The latter two relax divertor requirements additionally and could be a very desirable property of this regime for future fusion reactors.

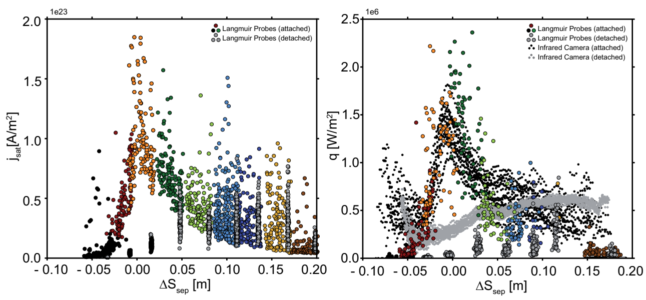

Figure 21: Divertor target profiles

7.10 N-balance and Ammonia Formation during N_2-seeding

Nitrogen, a candidate for radiation cooling of the SOL, produces ammonia in the presence of hydrogen plasmas. These chemical active species influence the recycling and storage of nitrogen at the PFCs and, at ITER, will affect the tritium gas plant. Quadruple gas analysers were used to determine the amount of ammonia in the pumped gas. For deuterated species the spectra of ammonia, water and methane overlap. Therefore careful determination of the cracking patterns is needed to disentangle these species, especially when the molecules feature different H/D ratios. Special gas mixtures and capacitive gauges are used for absolute calibrations. In the first of a series of identical discharges 30 % of the seeded N_2 is stored in the vessel. This fraction decreases for subsequent discharges, building up an inventory, which is released as ammonia mainly in between plasma discharges. This inventory may explain the contamination of subsequent non-N_2-seeded discharges. Typically 8 % of the injected N_2 is converted into ammonia. The importance of surface activated processes is shown by injecting of non-deuterated ammonia into a device with deuterium saturated surfaces, which leads to the production of deuterated ammonia.

8 Stuttgart

8.1 Blob Detection by Gas Puff Imaging

Turbulent pressure fluctuations in the scrape-off layer of fusion plasmas can be visualized by increasing the local neutral background pressure using typically deuterium or helium puffs (gas-puff imaging, GPI). With GPI the structure and dynamics of these turbulent fluctuations – so-called blobs – can be studied in a cross section perpendicular to the magnetic field. Using a fast camera, GPI was employed to study the blob detection rate, cross-field size and velocity in L-mode and inter-ELM H-mode plasmas.

It was found that the blob properties do not differ strongly in the two confinement regimes. In both regimes, the detection rate is of the order of a few kHz, which is comparable to the typical time scales of edge turbulence. The blob size increases in H-mode, while the radial velocity decreases slightly. The blob size agrees with predictions from a novel model, which incorporates finite ion temperature. While all these properties change only moderately, the poloidal velocity, in contrast, changes drastically during the L→H transition. Even a reversal of the poloidal propagation is observed. This could reflect a change in the radial electrical field. Furthermore, it is observed that the radial propagation of the blobs decelerates, while they move radially outwards, which is probably due to a parallel pressure loss.

8.2 High-Power Diplexer Studies

After successful technical tests of the Mk II diplexer in the ECRH system, the device was used for stabilisation of NTM. Mk II is a narrow-band quasi-optical diplexer, which – owing to the steep slopes in the resonant characteristics for the two transmission channels – allows electronically controlled, non-mechanical switching between the two outputs by frequency-shift keying of the gyrotron. In the experiments, the diplexer was connected to two launchers (L1 and L3), which were scanning around the expected location of the (3,2) NTM (q=1.5). In two discharges, the toggling of the power was such that ECCD was driven in the O-point of the rotating islands (typ. 20 kHz), whereas for another discharge, the phase was inverted to drive ECCD in the X-point to destabilise the mode. For ECCD in the O-point (# 29570/29575), a reduction of the mode amplitude is seen where the power deposition coincides with q=1.5; for # 29576 with inversed phasing, an increase of the amplitude is observed. A complete stabilisation of the NTM could not be reached due to lack of power and imperfect resonator control. In conjunction with a radiometer system operated by colleagues from DIFFER, ECE could be measured via the same line of sight simultaneous with the stabilisation experiments, and the modulation of the ECE signal due to NTM could be detected.

9 European Co-operations

In 2013 AUG operation lasted until the end of April and has to be considered from the programmatic point of view as an extension of the 2012 programme. For this 4-month period of operation no individual call had been launched. As in previous years, many EURATOM Associates continued to be involved in the AUG Programme. A few reports on physics results as well as on diagnostic improvements conducted during the shutdown in the second half of 2013 are given in the following. In 2013 also the preparation of the 2014 MST1 AUG campaign under the new EUROFUSION Consortium was started involving intensive cooperative activities among all EU research units.

CCFE

The avoidance of large ELMs is an important issue for future devices such as ITER due to the potential for damage to the divertor structure. Thereby a key requirement is to understand the factors that affect the ELM mitigation and suppression techniques currently being developed. CCFE staff participated in AUG experiments to investigate the influence of plasma shape on the suppression of type-I ELMs when magnetic perturbations are applied to the plasma at high density. The experiments suggest that it is easier to suppress ELMs when the plasma is nearer to a double-null magnetic configuration.
A key issue for ICRF plasma heating, which is envisaged for ITER, is the optimisation of power transmission at the plasma edge where the RF wave is evanescent. CCFE staff participated in AUG experiments to investigate the effect of local gas puffing on ICRF coupling. Coupling improvement was also found in H-mode conditions, but differences compared with L-mode experiments could be due to changes in the SOL parameters when the edge transport barrier is present. The coupling improvement with local gas puffing was found to be sensitive to the level of coupled power, highlighting the competing effects from the RF power that influence the plasma density in front of the antenna. In some cases with intense gas puffing at the ICRF antenna high voltage arcing was observed, suggesting that an optimisation in terms of gas source location and gas injection rate is required to obtain both good coupling and reliable operation.
Improved H-mode scenarios are currently being developed on several tokamaks with the aim to either improve the potential fusion performance of ITER or allow operation with high fusion yield at lower plasma current and longer pulse duration. Unlike the baseline ELMy H-modes envisaged for ITER, however, there are as yet no well-established confinement scalings for these improved scenarios. CCFE staff participated in joint experiments proposed by the ITPA-IOS group to investigate the confinement scaling of improved H-modes including data from AUG. Experiments were performed on AUG to make an identity match with previously obtained JET plasmas, which requires profiles of the key dimensionless parameters (β, ρ^*, ν^*, etc.) to be as similar as possible. This is a necessary prerequisite for confinement studies that combine data from the two devices. Despite the fact that the JET data were taken with the previous carbon wall and the AUG comparison was made with the W-wall (albeit with a recent boronisation) a good match was achieved. This indicates that joint analysis of AUG and JET experiments may provide useful information for the extrapolation of these plasma scenarios to ITER.

DCU – University College Cork

The principal enhancements to the CLISTE equilibrium reconstruction code during 2013 were: (i) $E=v\times B$ Lorentz field data from spectral MSE was added as an additional equilibrium constraint. (ii) To generate snowflake-like equilibrium configurations in the presence of finite current density at the X-point, specification of two adjacent X-points as a substitute for the ideal snowflake condition was added to the predictive kernel of CLISTE. (iii) Work is in progress to extend CLISTE to incorporate the influence of axisymmetric ferrite tiles on the equilibrium calculations.
Over the past few years, much has been achieved in determining the ELM-resolved edge current density with CLISTE. While the analysis of complete ELM cycles is one important facet of this work, understanding ELM mitigation regimes is also of critical importance. To this end, several ELM mitigation scenarios were considered. First, a comparison between type-I reference and type-II ELMs was conducted. This analysis showed that the increased density in this plasma scenario decreased the edge current density, causing the plasma to become more unstable to ideal ballooning modes. The same analysis was also applied to discharges featuring external magnetic perturbations and corresponding reference cases without perturbations. All discharges considered featured type-I ELM suppression, the principal difference being the time point in the discharge, at which suppression was achieved. A phenomenology similar to the type-II case was observed here, with the edge current density decreasing in time as the density increased.

DIFFER

One of the lines of research in the FOM Institute DIFFER (Dutch Institute for Fundamental Energy Research) is focussed on advanced control of MHD modes in burning plasmas. This programme is largely executed at AUG. An important aspect is how fast particles, that will be present in copious amounts in burning plasmas, interact with the various MHD modes. The research programme of the FOM-DIFFER team at AUG is largely concentrated on a number of diagnostics. In 2013 the following activities were employed:
A novel spectrometer with high-optical throughput has been installed for charge exchange recombination spectroscopy measurements. The spectrometer, that has been developed by ITER-NL, can measure simultaneously C, He and D-lines and has been specifically used to study the fast ion population;

in particular the slowing down of beam-injected He ions and the effect that fast He ions have on the stabilization and/or suppression of MHD modes.

The ECE imaging system that has been jointly developed with UC Davis, features 128 channels (16 vertically by 8 radially) to measure the 2D T_e with high spatial and temporal resolution. In 2013 the system was not operated due to malfunctioning of the Backward Wave Oscillator. Therefore, the focus was largely on the detailed analysis of measurements of ELMs taken at earlier date. The system is being upgraded with a second view at a slightly different toroidal location to investigate the 3D nature of MHD modes.

The tunable mm-wave cavity FADIS has been used to enable ECE measurements along the same line as one of the AUG ECCD microwave beams. This allows a direct observation of the response of MHD modes to ECCD, without the need of using any magnetic equilibrium calculations. A direct digitizing radiometer observes back-scattered waves, while a 6-channel radiometer is installed to determine the radial location and phase of tearing modes for control. In 2013 measurements were successfully done with an improved low-power double-notch mm-wave filter. This work is a joint collaboration of IPF Stuttgart, IPP, FOM-DIFFER and TNO.

A multi-pass Thomson scattering system is presently in the implementation phase. The system will be used to monitor a vertical plasma chord that is just inside the edge pedestal. Thanks to the very high effective laser power that is achieved in a multi-pass cavity, the system is suited to measure the local edge current density, additional to the more standard T_e and n_e measurements. The edge current density is deduced from measuring the small Doppler wavelength shift (a few nm) of the scattering distribution, which is much wider (~100 nm). The multi-pass cavity features in-vessel mirrors and piezo-driven shutters, and much attention is devoted to assess their critical design issues.

DTU

Collective Thomson scattering (CTS) diagnostics seek to infer localized information about confined ion populations from measurements of the spectral properties of electromagnetic radiation scattered off microscopic collective fluctuation in the plasma. In previous years we reported that the CTS spectra measured on AUG include spurious signals, which do not originate from the scattering volume. By operating the two CTS receivers at simultaneously, the spurious signal has successfully been isolated from the CTS signal. Using this technique, the measured spectra are found to be in agreement with theoretical predictions. To verify the quality of the CTS spectra, the bulk T_i and drift velocity measurements from CTS were compared with CXRS measurements and very good agreement has been found.

The 1D fast-ion distribution from the CTS spectra has been extracted for plasmas with different heating schemes. In figure 22 the measured 1D fast-ion distribution function is shown for plasmas heated with one and two NBI sources. The distribution function calculated by TRANSP is overlaid and good agreement between measurements and simulation has been found.

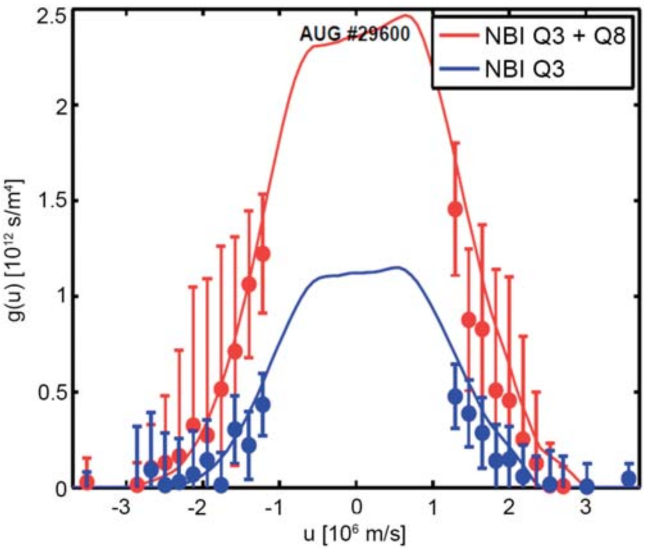

Figure 22: Measured (dots) and simulated (lines) 1D fast-ion distribution function with one (blue) and two (red) NBI sources respectively.

Also the sensitivity of the CTS spectrum to the D and H-concentration in the plasma centre was demonstrated experimentally in 2013. This result is a large step towards detection of the ion composition and especially the fuel ion ratio in devices like ITER and DEMO.

In addition to our CTS activities we have performed the first-ever measurement of a local fast-ion 2D velocity distribution function $f(v_\parallel, v_\perp)$ based on the fast-ion D_α (FIDA) spectra with three different views. The 2D velocity distribution function $f(v_\parallel, v_\perp)$ is deduced from the FIDA data by tomographic inversion. Salient features of our measurement of $f(v_\parallel, v_\perp)$ agree reasonably well with a TRANSP simulation. The measured as well as the simulated $f(v_\parallel, v_\perp)$ are lopsided towards negative velocities parallel to the magnetic field.

Probe measurements of the turbulent plasma evolution in the SOL have been performed in close collaboration with ÖAW/University of Innsbruck and ENEA-RFX/Padova, by employing the so-called Innsbruck-Padova probe head mounted on the mid-plane manipulator. The results comprise turbulent transport characterization and investigations of the poloidal flow profile in the neighbourhood of the last closed flux surface. The results are supported by numerical simulations applying the ESEL-code.

IST – Centro de Fusão Nuclear

Physics studies: (i) First measurements of the poloidal rotation of edge Quasi-Coherent (QC) modes were performed using dual-channel poloidal correlation reflectometry. In steady-state conditions the QC poloidal velocity from reflectometry is in agreement with the E×B velocity obtained by Charge Exchange Spectroscopy and Doppler reflectometry measurements. Generally, a decrease in velocity associated with fast events, such as ELMs, is observed; (ii) Plasma filament studies with frequency hopping reflectometers have focused on the filamentary activity close to the separatrix during the type-I ELM cycle. An intense filamentary activity is detected at the ELM onset associated with the n_e profile collapse. A conditional average technique was able to extract the coherent fraction of the reflectometry signals relative to the filament signatures. Typical features are jumps in the phase signal (i.e. radial displacement) and dips in the amplitude signal (fluctuation scattering). A 2D full-wave code was used to emulate the reflectometer filament measurements confirming the experimental findings; (iii) The FM-CW reflectometry system, which can provide HFS and LFS n_e profiles with a temporal resolution down to 35 µs, was used to investigate the edge density evolution during the L→H transition, as well as the impact of the MP coils, revealing distinct profile evolutions at the LFS and HFS; (iv) Radial profiles of the n_e fluctuation level for L-mode and Ohmic conditions were measured at the LFS using the frequency hopping system, showing an increase towards the edge plasma. The 1D Fannack model was used to interpret plasma response.

Diagnostic developments: The scientific exploitation of the IST reflectometer systems was hampered in 2013 due to the unavailability of the V and W channels, restricting the highest n_e available to the upper limit of the Q-band (3×10^{19} m^{-3}). After the 2013 campaigns all the in-vessel HFS & LFS wave-guides were installed and tested. New µ-wave calibrations were obtained and included in the data evaluation software. The µ-wave electronics and control system for all profile channel reflectometer electronics was revised. New mixers were installed on V band HFS and LFS channels. Tests with a metallic mirror show a significant improvement of the S/N ratio. A more modern and powerful data acquisition and processing system was installed to allow the acquisition of all bands for both real-time and standard post-shot analysis. The n_e-profile evaluation codes (interactive, level-1 and level-2) have been completely overhauled to develop a single code compatible with the different acquisition systems. The upgrades are expected to bring the different reflectometry systems back to full operation, ready for the intense scientific exploitation anticipated for 2014.

TEKES

TEKES has continued contributing to AUG relevant research on three frontiers: transport, fast ion physics and PWI. The latter work consisted of (1) global modelling of the 2011 $^{13}C/^{15}N$ tracer-injection experiment, (2) experimental study of mid-plane erosion, and (3) validation of plasma models in the divertor region.

The tracer experiment was modelled using SOLPS to give the plasma background, ERO for the dissociation of puffed $^{13}CH_4$ and $^{15}N_2$, and ASCOT to follow the resulting tracer ions. Migration of the tracers was found to be largely governed by strong SOL flows. Unfortunately, SOLPS could not reproduce the experimentally observed high flow velocities and therefore had to be imposed in ERO and ASCOT. The magnetic configuration and local plasma conditions also affected the deposition patterns, and thus the process required 3D treatment. The results and the related code development have so far resulted in three publications and a plenary talk in the 40th EPS conference.

Erosion at the outer mid-plane was investigated by exposing a marker probe to low-power H-modes (# 29187-29190). The probe was equipped with W, Ni, Al, and C marker stripes, and its tip was moved 20 mm outside the limiter shadow. The net erosion of the different markers peaked close to the tip, being ~1 nm for W and 10-20 nm for the other elements. The outer mid-plane is thus a heavy erosion zone, even for W.

A set of L-mode discharges was used to validate SOLPS5.0 simulations. The main discrepancies with experimental probe data were observed at the inner divertor. However, at low detachment levels n_e showed a good agreement with measurements, which helps identifying the location of the discrepancies. Activation of drift terms increased asymmetry in the divertor temperature distribution, explaining the radiation distributions observed in N-seeded discharges.

Work on fast ions consisted of (1) ASCOT modelling of experiments with fast ion diagnostics, and (2) benchmarking between ASCOT and HAGIS. Experimental data of the activation probe was compared to the calculated flux of D-D fusion products (# 29226) received by the probe. Its orientation was found suboptimal, with flux largely filtered by the graphite cap.

Simulations of the FILD data were continued within ITPA-EP. The ASCOT-HAGIS benchmarking was performed for NBI-generated fast ions using three different scenarios: (i) MHD quiescent plasma, (ii) plasma with a (3,2) NTM island, and (iii) plasma with a TAE mode. In all cases, the single particle orbits were found to be practically identical.

Also NBI modulation experiments to study intrinsic torque were performed. A 4-point q-scan, representing also a pedestal strength scan with q_{95} ranging from 4 up to 11, revealed that the intrinsic torque increases with decreasing q_{95} from 1.5 to 4 Nm. When scanning the ECRH power, the result was not as straightforward: with high NBI powers ECRH seems to create a negative core intrinsic torque source while with low NBI power ECRH rather changes momentum transport.

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JET Cooperation

Head: Dr. Josef Schweinzer

The ITER-like wall exploitation in JET continued for a few months in 2013. IPP's participation remained on the high level of previous years. Successful JET operation with the ITER-like wall and the long-term success of ASDEX Upgrade with its tungsten wall have paved the way towards positive recommendation of the ITER STAC for starting with a full tungsten divertor in ITER. This decision was approved by the ITER Council at the end of November 2013.

Introduction

A total of 23 IPP scientists were seconded to JET in 2013, leading to a total of ~9 ppy of on-site support for the operation of JET. Two IPP scientists were almost permanently on site, being involved in the management of the JET Task Forces E1 & E2. Eight long-term secondments of IPP staff to the Close Support Unit (2) and to the JET Operator (6) were active in 2013. The majority of the 23 IPP scientists participated in the campaigns C31 – C32 from July to October 2013. Unfortunately, the 2013 campaigns – originally planned up to the end of 2013 – had to be stopped owing to technical problems with the neutral beam heating system and with the reciprocating probe at the beginning of October.
The following summarises selected results obtained with significant IPP involvement during the 2013 JET campaigns, in the field of modelling and as contributions to the Fusion Technology Task Force.

ELM Studies

The short, burst-like heat loads due to ELMs were intensively investigated in JET during the past few years, with the objective to scale such ELM-induced heat loads to ITER and DEMO by combining data from JET with AUG or DIII-D. The ITER-like wall (ILW) in JET offered the possibility of extending the database for such scalings to full-metal machines. As a first intermediate result it was shown that in JET-ILW the pedestal conditions for identical machine parameters such as plasma current, toroidal field, magnetic shaping and heating power were similar for pedestal pressure but with reduced temperature and increased density.
The well-established idea that mitigation of ELMs could be achieved by increasing the ELM frequency on the assumption that many small ELMs, each releasing a small amount of energy, are more benign than a few ELMs releasing larger amounts of energy per individual event has been critically examined in IR thermography studies. It turned out that for the thermal load onto the divertor target the loss in plasma-stored-energy per individual ELM is not the decisive quantity, since neither the area, on which the energy is deposited nor the actual deposition time is taken into account.
The way to describe ELM heat loads in tokamaks has therefore been revolutionized by introducing the local heat impact factor. The latter is less than linearly dependent on the duration of the energy deposition and increases linearly with the energy fluency (unit: J/m^2) of the ELM.
For JET it has been observed that the average ELM duration in the ILW era is longer than the duration observed with carbon plasma-facing components (JET-C). However, the ELM duration depends on the condition of the plasma at the pedestal and is not intrinsically linked to the wall material or the resulting impurity composition. The ELM duration is increased with pedestal density and decreased with the pedestal temperature. The different observed ELM durations in JET-ILW (typically higher density than in JET-C) and in JET-C are therefore a result of different pedestal conditions. Furthermore it was shown, that for the same pedestal condition, a similar ELM duration is found with both wall materials.

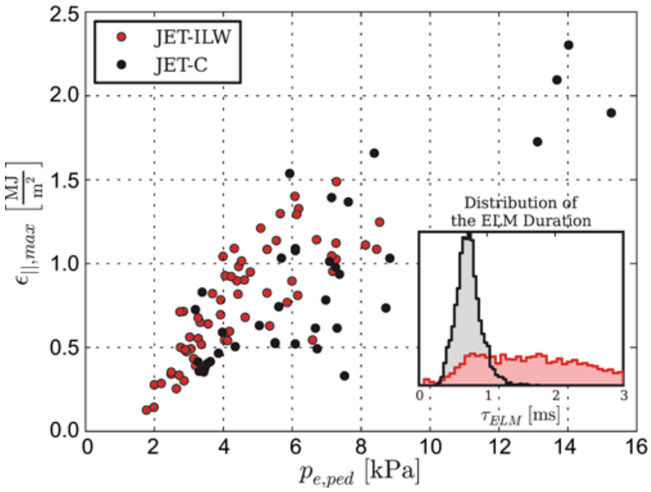

Figure 1: Energy fluency of ELMs vs. pedestal pressure and the distribution of the ELM duration in JET-C and JET-ILW.

The energy fluency depends almost linearly on the pedestal plasma pressure and has only a weak dependence on the relative loss of stored energy. This was observed at higher plasma currents, which allow a higher pedestal pressure inducing a higher energy density on the target. The weak dependence of the energy fluency on the relative loss in stored energy is explained by an increase of the area, on which the ELM deposits its energy. The larger the ELM is in terms of loss energy the larger is the ELM-affected area for a given pedestal pressure. The observation that the energy fluency is the same for JET-ILW and JET-C is noteworthy since the ELM duration is observed to be different.

Power Exhaust Studies

For future device such as ITER and DEMO high radiative power fractions, f_{rad} will be required for limiting the power load to values below the tolerable boundaries set by the plasma-facing components. It is estimated that the value of f_{rad} required for a fusion reactor will be beyond 90 %. At JET the aim was therefore to demonstrate whether it is possible to achieve stable discharges with values of $f_{rad} \geq 90$ % independently of the confinement mode while simultaneously limiting the core radiation and dilution to a minimum. The maximum heating power available in these experiments was limited to ~18 MW. Impurity seeding was done with N, Ar and Ne. Mixing of these seed impurities has not yet been attempted and is envisaged for the future. For Ar and Ne the maximum f_{rad} achieved is 40 % in H-mode and 60 % in L-mode, with unstable transients of 90 % when using Ne. Neither Ar nor Ne resulted in stable highly radiating discharges and consistently led to disruptions. The maximum radiative power fraction was achieved with N in a stable discharge with mitigated ELMs and connected to a strong X-point radiation. A f_{rad} level of ~75 % was reached. In this strongly radiative regime a drop of the pedestal density was observed, with the T_e and n_e profiles recovering inside $\rho<0.8$ and with no degradation of the overall confinement level. These observations are very similar to those reported for AUG.

A further similarity to AUG results was found when applying the spectroscopic Stark broadening method to the inner divertor. In the above-mentioned H-mode discharges a region of high n_e is observed in the far Scrape Off Layer, SOL, at the lowest N-seeding levels. With increasing N seeding this region of high n_e in the far SOL disappears and only a region of high n_e close to the X-point remains, as was also seen in AUG. Furthermore, in L-mode density ramp discharges the appearance of the far-SOL high n_e is seen as the vertical inner target detaches and the outer target transits into the high-recycling regime, similarly to previous findings in AUG. These latter observations demonstrate that the phenomenon first reported for AUG was not a unique peculiarity, but could be an important ingredient in understanding divertor detachment in metal devices and its asymmetries in general.

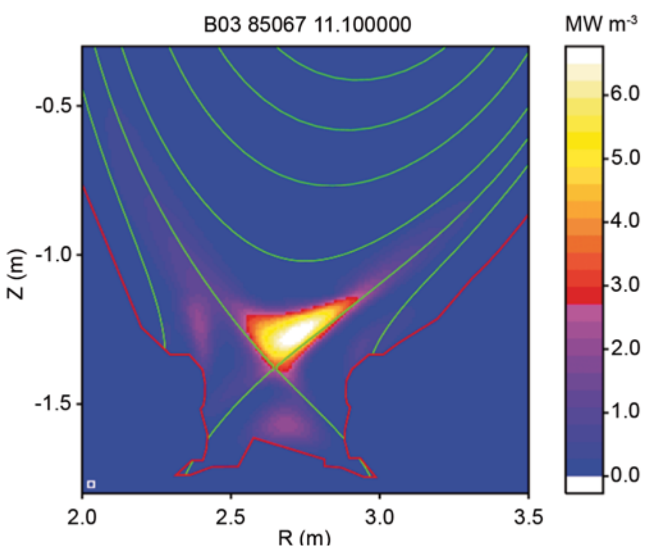

Figure 2: Stable X-point radiation in a nitrogen-seeded discharge.

Controlled H-mode Initiation with Pellets

ITER maintains interest in demonstration of ELM control under conditions mimicking operation of the non-nuclear phase (H and He plasmas) having the L- to H-mode transition already during the current (I_p) ramp-up. ELM pacing already starting with the first ELM is expected to prevent early impurity (most likely W) accumulation and a too strong plasma energy increase during a probably ELM-free H-mode phase. Corresponding experiments employing pellet injection for ELM triggering have been conducted at AUG and JET.

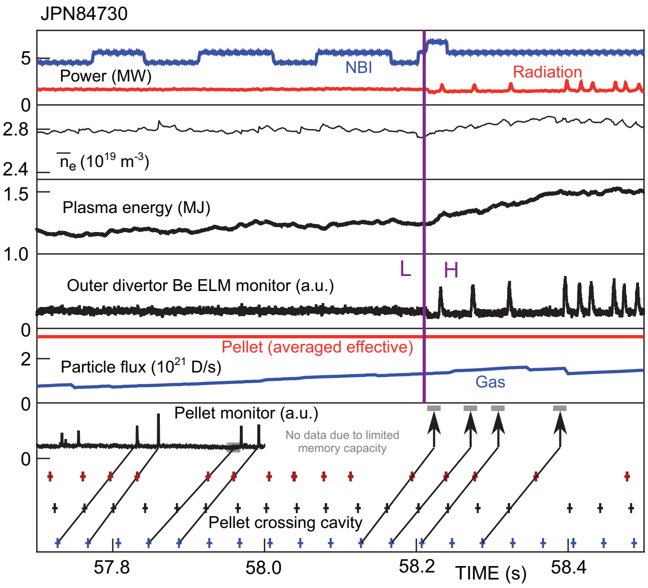

Figure 3: Time traces of a L-to-H transition with pellet injection to avoid an ELM-free phase.

A first full demonstration of such a scenario, using D pellets in a D plasma, was achieved at AUG. These experiments are hampered by the unfavourable ratio of pellet to plasma particle content, because it is technically almost impossible to produce and launch sub-mm-size pellets. Additional fuelling is therefore unavoidable and has a significant impact on plasma density. This situation can definitely be improved at JET when pellets of about the same size are injected into plasmas with much larger volume, preventing objectionable density build-up. Here, experiments were embedded in studies of the L-H transition investigating the power threshold. These investigations assess the impact of the fuelling method and location on the power threshold value. Replacement of the gas puff partially by pellets (again D pellets in D plasmas) showed that pellets do have higher fuelling efficiency, but do not alter the transition parameters with respect to density and heating power. Substituting gas by pellet fuelling showed the desired additional benefit of achieving instant ELM control. Due to the moderate rise of density per pellet even the density evolution could be matched to a purely gas-fuelled reference discharge.

In figure 3 the evolution of the pellet-controlled discharge in the vicinity of the L-H transition is shown. Obviously, every pellet arriving after the transition enforces an ELM, hence avoiding an ELM-free phase typical of the reference case. Notably, the density evolution is essentially influenced by the confinement rather than the pellets. Once the H-mode is invoked, reduced edge transport causes a gradual rise of density and stored energy.

Experimental Characterisation and Modelling of W Transport

A comprehensive study dedicated to experimental characterisation of the tungsten (W) behaviour in JET hybrid scenarios and modelling with a combination of turbulent and neoclassical transport codes was made in order to identify the main causes of W accumulation in this scenario. The GKW gyrokinetic code and the NEO drift-kinetic code were utilised since they allow consistent treatment of centrifugal effects in turbulent and neoclassical transport, respectively. These effects are significant in these plasmas, where the W central thermal Mach number can approach 4. This study has thus produced the first comparison between the theoretical predictions of the 2D W density distribution on the poloidal cross-section and the experimental results of an interpretive SXR W density diagnostic. The theoretical modelling has revealed the dominant role of neoclassical transport, which is largely enhanced by the poloidal asymmetry of the W density induced by centrifugal effects. (Additional details of this work can be found in the 'Plasma Theory' section.) Quantitative agreement is found between the results of the modelling and the observations of a representative discharge, both during the phase prior to the accumulation, featuring a low-field-side, bean-shaped W density localization, and during the phase, in which central accumulation develops. The modelling results show that the dominant transport mechanism governing the W accumulation is the neoclassical convection in the central region of the plasma ($r/a<0.3$), driven by the peaking of the main ion plasma density. The plasma density exhibits a transient behaviour in the early times of the high-power phase of the discharge. After the L-to-H transition, the build-up of the pedestal density is not followed by a corresponding increase of the central density, leading to development of transiently hollow plasma density profiles, which, by neoclassical convection in combination with the centrifugal effect, produce extremely hollow LFS W density profiles. Later in the high-power phase of the discharge, the plasma density acquires a stationary profile shape, with central peaking also very close to the magnetic axis. This is probably produced by the combination of central neutral-beam fuelling and low particle diffusion. This central density peaking drives the neoclassical pinch and is the main cause of the observed accumulation. The described behaviour of W is generic in this scenario, as demonstrated in figure 4.
Here a proxy of the W density peaking, provided by the ratio of the signal of a central line of sight to that of a peripheral line of sight of the vertical SXR camera, appropriately normalized by the length of the chords and electron densities, is plotted as a function of a simplified analytical expression, which is proportional to the neoclassical convection-to-diffusion ratio in the central region of the plasma ($r/a=0.15$). We observe that all of the discharges of this extended database approximately follow the same curve when plotted in terms of these parameters, which demonstrates the generality of the results obtained with the theory-based modelling of specific time slices of a representative discharge. This strongly supports the conclusion that neoclassical convection close to the magnetic axis is the main drive of accumulation in this scenario.

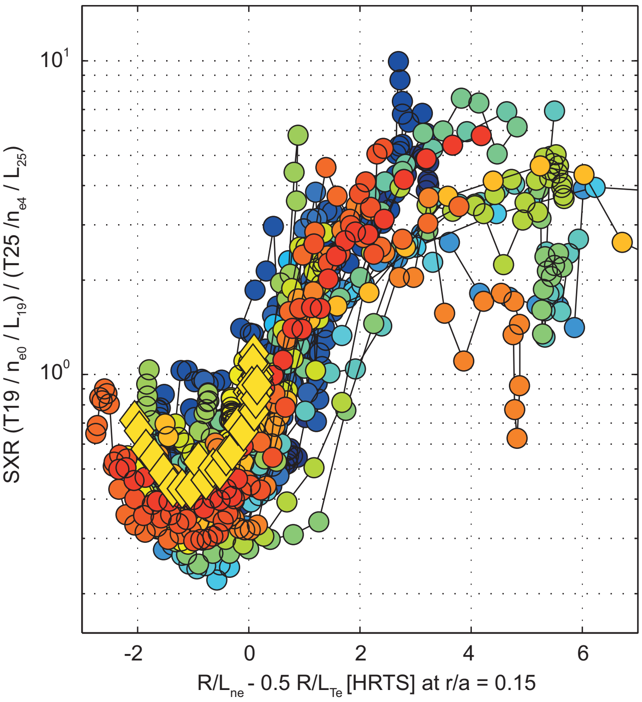

Figure 4: W density peaking vs. an analytical expression proportional to the neoclassical convection-to-diffusion ratio at $r/a=0.15$.

Residual Gas Analysis in JET-ILW

The JET-ILW provides a unique test bed to study plasma operation with the ITER material mix. W sputtering – which determines the lifetime of the divertor components – is induced by intrinsic impurities such as Be, O, C and extrinsic impurities such as N_2 and Ar, which are used for radiation cooling to mitigate heat loads at the W target plates. A complex set of impurities can therefore interact with the first wall and has an impact on plasma operation.
To study the impact of volatile impurities on plasma and wall conditions, the residual gas was analysed with a Hiden Analytical HAL 201 RC mass spectrometer (MS) located in the sub-divertor region of JET. This analytical system was fully integrated into the general data acquisition system at JET: In close collaboration with the CODAS group on site the MS

acquisition software was further developed and thoroughly tested. It is now routinely used to record pulse-related data and to switch spectrometer parameters even during a pulse. The latter feature is essential to fulfil different requirements on sensitivity and time resolution. Furthermore, automatic post-processing of the recorded signals was developed to make the time traces from this diagnostic available to the general user via the common software tools (e.g. JETDSP).

The MS system was used to measure the intensities at around 20 discrete mass-to-charge ratios during discharges (i.e. 20 amu/e for Ne^{+}, 28 amu/e for N^{2+}, 40 amu/e for Ar^{+}) with a typical sampling time of 1.5 s , which provides several measurement cycles (mass scans) in the discharge flat-top phase. In-between discharges full spectra were continuously acquired in the range of 1-45 amu/e with a sampling rate of 23 s.

The signal intensities observed in the range between 14 to 20 amu/e are not straightforward to interpret because of the possible contributions from various species (water, methane, ammonia) at various degrees of deuteration. A code was developed to decompose the mass spectra in this range into the underlying molecular species, with the known cracking patterns being taken into account. As an example, this code was applied to a spectrum recorded during regeneration to room temperature of the liquid nitrogen cryo panel of the JET pumped divertor, see figure 5. Only water and ammonia were taken into account for this decomposition. Their hydrogen-to-deuterium ratio was varied in the fitting routine to account for the possibility of isotopic exchange. This method will be further developed to quantify the amount of ammonia produced in N_2-seeded discharges in JET.

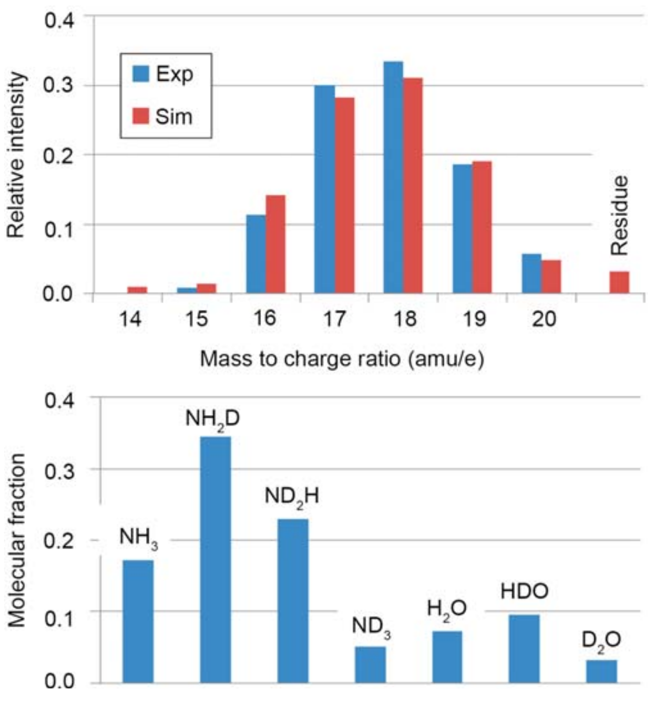

Figure 5: Relative signal intensities in the range 14-20 amu/e from a mass spectrum recorded during regeneration of the liquid nitrogen cryo panel to room temperature (blue) and simulated intensities resulting from decomposition of the mass spectrum (red). Bottom: Relative abundances of water and ammonia species resulting from decomposition.

Fusion Technology Tasks

A new, beryllium-compatible analysis chamber for the analysis of samples from JET was commissioned at the tandem accelerator of the E2M division. The analysis chamber consists of an under-pressurised glove-box, which allows safe handling of the noxious material, beryllium, and an attached ion-beam analysis chamber, which offers possibilities of ion beam analysis methods, such as Rutherford backscattering (RBS) and nuclear reaction analysis (NRA).

The erosion of Be and W marker layers in JET was investigated using long-term samples during the first ITER-like wall discharge campaign 2011-2012. The markers were mounted at the inner wall in Be-coated Inconel tiles between the inner wall guard limiters. They were analysed using RBS before and after exposure. All samples showed strong erosion. The results were compared with the data for Be and W erosion rates for the 2005-2009 and 2001-2004 campaigns, respectively. The mean erosion rates and the toroidal and poloidal distributions of the W mean erosion were the same for the 2001-2004 and the 2011-2012 campaigns. The mean erosion rate of Be during the 2011-2012 campaign was a factor of about two smaller than in the 2005-2009 campaign and showed a different poloidal distribution. The net erosion rate of Be during the 2011-2012 campaign was a factor of about 5 smaller than the erosion rate of carbon during the previous carbon-dominated campaigns.

The 2013 JET shutdown was also used for installation (April 2013) of AUG-type dust collectors manufactured by IPP. These collectors will be exposed to the JET plasma until the next shutdown in 2014 and promise highly ITER-relevant information of dust production in a machine with exactly the ITER material mix.

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Stellarator Research

Wendelstein 7-X

Head: Prof. Thomas Klinger

In 2013 considerable progress was achieved in the construction of Wendelstein 7-X. By the end of 2013 all five magnet modules have been connected (mechanically, electrically and hydraulically) and the current leads are being assembled in different stages. Assembly of the in-vessel components and diagnostic in the plasma vessel as well as assembly of the periphery systems in the torus hall are in full swing.

1 Introduction

In 2013 the organisation of the project Wendelstein 7-X (see figure 1) underwent a few changes. In January 2013 the sub-division head "Engineering" also took over the department diagnostics engineering within the sub-division "Diagnostics". In October a new sub-division "Wendelstein 7-X Operations" was set-up to prepare the commissioning of the device. The CoDaC department was transferred into this new sub-division and a new department "Device Operations" was established, which includes the device safety group. In the "Magnets and Cryostat" sub-division a new department "Electrical Cabinets" concentrates all the resources for development and manufacturing of the electrical cabinets in the project.

Design and manufacturing of the different components of the basic device have significantly progressed, as described in chapters 2 to 4. Assembly of the stellarator device and development of the related technologies have made great progress, as described in chapter 5. The accompanying efforts of the engineering subdivision (chapter 6) and the design and configuration control (chapter 7) are still indispensable. Heating systems (chapter 8) and diagnostics developments (chapter 9) have continued. The development of control systems and the preparation of commissioning are performed in the new sub-division "Wendelstein 7-X Operations" (chapter 10).

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.

1.1 Quality Management

The Quality Management (QM) department reports directly to the project director via the associate director coordination. The department organizes the QM system within the project Wendelstein 7-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 November 2013 the QM system of Wendelstein 7-X has been recertified by the TÜV NORD CERT in a regular annual check.

1.2 Project Coordination

This sub-division 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;

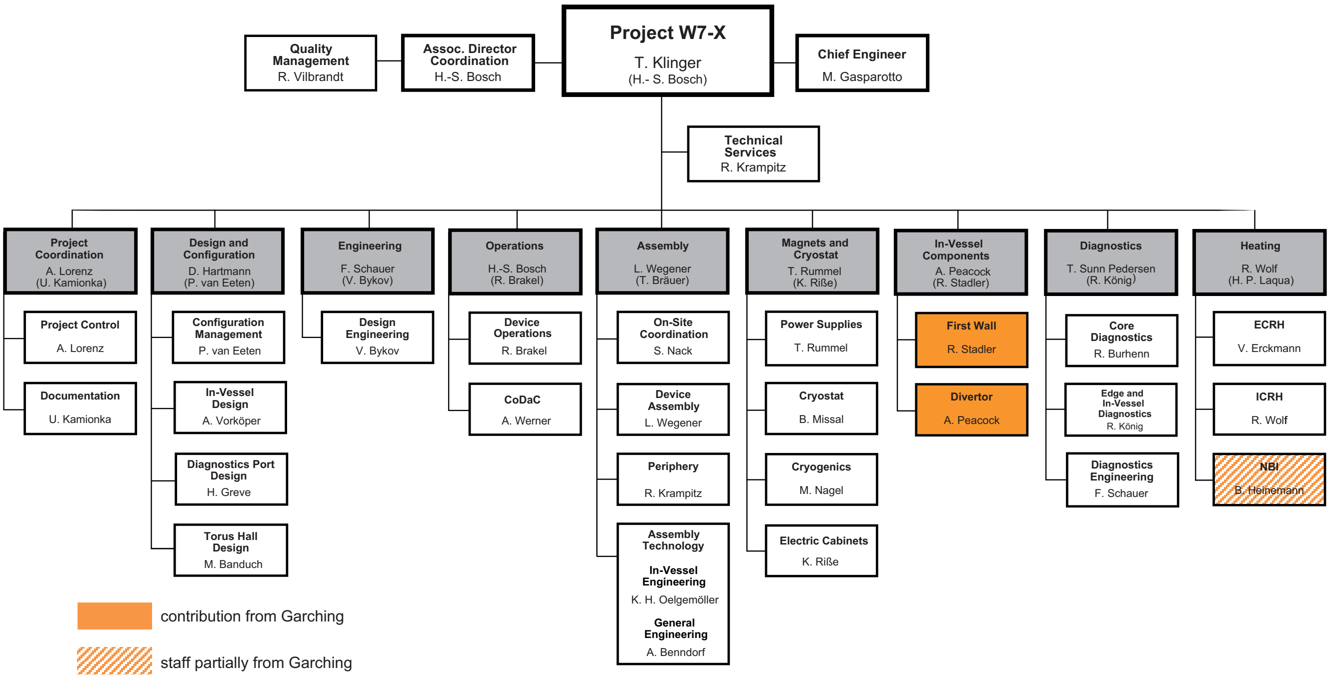

Figure 1: Organigramme of Wendelstein 7-X project as of 31.12.2013.

it deals with organizational aspects of the project and is responsible for the reporting to all external supervising bodies, especially the supervising body of the financing institutions (project council). The department is using a variety of planning and controlling tools to co-ordinate and to control the Wendelstein 7-X project progress. By now, the Integrated Planning Tool (IPT), developed up to the end of 2009, 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 AGILE-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 Wendelstein 7-X models, the so-called "Wendelstein 7-X Assembly".

1.3 Schedule

The time schedule of the so-called "scenario 3" (developed in fall of 2007) was followed in 2012 as the years before. All milestones scheduled in 2013 have been achieved, the milestone "all modules connected" even two weeks earlier than planned. The assembly of the in-vessel components and the diagnostics inside the plasma vessel, which started in 2012, turned out to require much more time for preparation and the assembly steps. Without appropriate counter measures, increased assembly times for in-vessel components and -diagnostics would have caused significant delays in the project schedule. Therefore, it was decided to shift the assembly of the test divertor unit to separate assembly phase, which is scheduled to follow a three-month phase of operating a first commissioning plasma (OP 1.1), starting in April 2015. In April 2013, the Wendelstein 7-X project council has approved the revised schedule for assembly and commissioning of the Stellarator Wendelstein 7-X. The restructuring of the first operation phase in two separate phases OP 1.1 and OP 1.2 and the revised plan of the in-vessel components assembly in three installations phases are now the working basis for the project schedule. Milestone 27 "Completion of Cryostat", which marks the start of commissioning, is now the top priority of the project.

2 Magnets and Cryostat

2.1 Magnet System

2.1.1 Coils

Wendelstein 7-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 have been placed in their final position in the machine. In addition to the superconducting coils, normal conducting coils were developed to fine tune the magnetic field and to increase the flexibility of the magnetic field configuration. The so-called trim coils will be mounted on the outer cryostat wall, one coil per each of the five Wendelstein 7-X modules. Due to construction space restrictions, two different coil types were developed: four type A coils and one coil of type B. The type A coil has a nearly rectangular shape with dimensions of 3.5 m × 3.3 m and 48 turns in 8 pancakes. The 110×151 mm² coil cross section is comparably compact. The type B coil with outer dimensions of 2.2 m × 2.8 m is smaller than the type A coil. To compensate the smaller size, the B coil has more turns (72 turns) and a higher operational current. In the frame of an international cooperation program of the US Department of Energy (DOE), the US laboratories Princeton Plasma Physics Laboratory (PPPL), Oak Ridge Laboratories (ORNL) and Los Alamos National Laboratories (LANL) received a 3 year grant to participate in the stellarator research at IPP. PPPL contributes in-kind the five trim coils with their power supplies. The coil delivery was completed with the arrival of the type B coil in April 2013. Three of the Type A coils and the Type B coil were already assembled at the outer cryostat wall. The last coil assembly is planned for January 2014. PPPL has designed and manufactured an Input/Output electronic enclosure (I/O box), which collects and pre-processes the coil sensor data. Ten temperature sensors, eight voltage signals and one flow monitor will be connected to each I/O box. IPP has received the five I/O boxes in April 2013, the assembly into the torus hall is intended in 2014. The five power supplies are also part of the US in-kind contribution to Wendelstein 7-X, whereas the control system, the cooling water units and the grid transformer are part of the IPP. The power supplies are state of the art four quadrant converters with nominal ratings of 2200 Amps and 230 Volts. In 2013 all power supplies were fabricated and tested by Applied Power Systems, from Hicksville, N.Y., USA. After the delivery in October 2013, the assembly preparation is running. It is foreseen to commission the power supplies together with the US colleagues. In order to allow tests at full current, a dummy load is under preparation at IPP. The design work of the control system was finished in 2013, too. It allows for the operation of the trim coil power supplies either from the main Wendelstein 7-X control room or from the local power supply control room.

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 vessel and the outer vessel. Together with the ports, the two vessels create a cryostat keeping the magnet system at cryogenic temperature and constitute the boundary between the Wendelstein 7-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, was 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. The manufacturing of all ten half-modules was completed in 2005; the installation of the superconducting coils and the thermal insulation has been completed as well. All 15 vertical supports of the plasma vessel have been assembled successfully in 2011. In 2013 the last of five module connection was welded. The installation of the last horizontal support (centring system) was also finished in 2013. The contract with MAN-DT was successfully completed in December 2013.

2.2.2 Outer Vessel

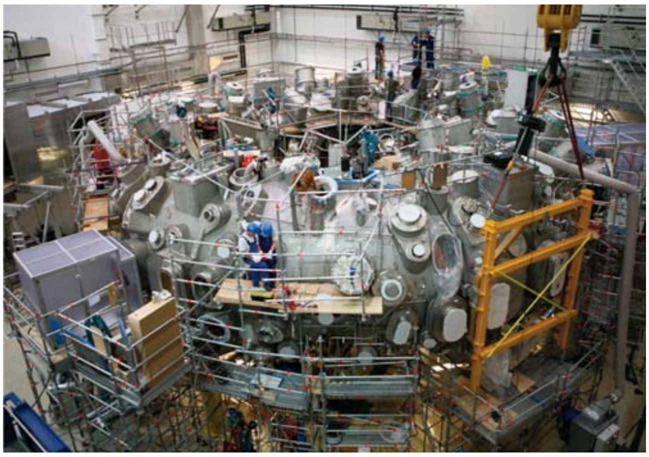

Figure 2: General view Wendelstein 7-X Torus complete 22.05.2013.

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. The outer vessel consist of five modules; as well, each module 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 have been delivered to IPP and upper and lower shells have been welded. In 2013 the last (of five) module connections was welded. The contract with MAN-DT was successfully completed in December 2013. The closing of all openings of the outer vessel and the installation of the current leads will continue up to end of March 2014.

2.2.3 Ports

A total of 254 ports will be used to evacuate the plasma vessel, for plasma diagnostics and heating, and for supply lines and sensor cables. The cross sections of the ports range between 100 mm circular up to 400×1000 mm² 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 had already been delivered until 2007. Because of growing vacuum requirements new feedthroughs for measurement lines had to be provided. This task was fulfilled and the assembly was completed in 2013. To generate ultra high vacuum conditions in the plasma vessel the ports must be thermally insulated and heated during the baking phase of the plasma vessel. In addition to the heating by hot water, about 140 ports have to be heated additionally by electrical heaters. The heating mats, the thermal insulation and the cables for the electrical connections were designed and procured in 2013. The assembly of the components on the ports is running. A concept for the control systems has been developed. The heating mats are equipped with temperature sensors and bimetallic switches. The temperature sensor signal will be used to control the temperature during warm-up, flat top and cool down; the bimetallic switches serve as protection against overheating in case of failures.

2.2.4 Exhaust Gas System

To avoid overpressure in the plasma vessel, safety valves with rupture discs and a piping system to bring the gas outside the torus hall were designed. In 2013 the type of safety valves was selected and the valves were ordered. The concept design of the piping system had to be changed because of collisions with other components in the torus hall. The work at a new design is running with high priority.
The outer vessel is equipped with pressure caps to avoid overpressure. To avoid human hazard by the gas, exhaust

gas chimneys were designed and a technical specifications for the procurement was created. The parts were delivered end of 2013. The assembly preparation is running.

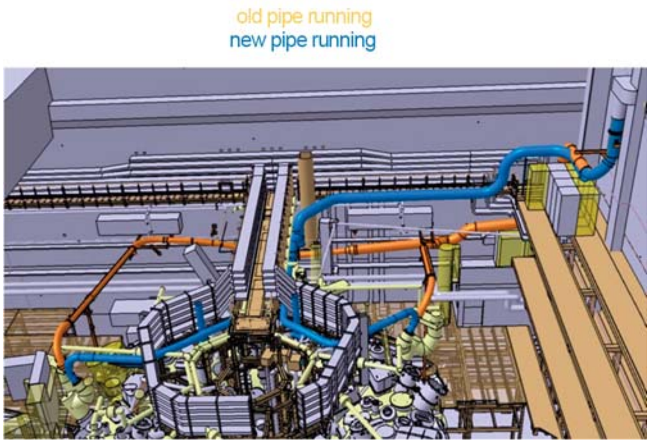

Figure 3: Routing design of exhaust gas system for the PV.

2.2.5 Quench Gas Exhaust System

Helium gas is released by the cryo pipes in case of a malfunction. It is guided outside the cryostat via quench pipes or special safety lines. In case of a quench of the superconducting magnet system, helium gas is collected in a ring manifold outside the cryostat and then transported to the gas storage tanks. In the very unlikely event of a very huge mass flow rate, the helium gas cannot be transported to the gas storage tanks any more. In such a case the expulsed helium will be directly released into the torus hall and guided to the ceiling via chimneys. The quench gas exhaust system is divided in two parts. Part I consists of the piping directly related to a quench, e.g. the valve groups, the ring manifold and connecting piping to the cryo plant exhaust piping. Part II includes the remaining helium safety lines and the chimneys. In 2013, the manufacturing drawings for piping and the support structure of part I were made by KrioSystem (Wrocław, Poland). The pipe segments were welded together to pipe groups and geometrically checked. Welding seams were visually inspected and partially X ray tested. Pressure and helium leak tests carried out. Also the required support structures were manufactured. Piping and supports were delivered. The manufacturing drawings for part II were done by IPP. The contract for manufacturing and testing was given to KrioSystem. According to the planning the part II components will be manufactured at the end of March 2014.

2.2.6 Thermal Insulation

The thermal insulation of the Wendelstein 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. In 2013, the thermal insulation was closed at the module separation area M3/4 for the plasma vessel and outer vessel. The final ten ports were insulated close to module separation areas M2/3 and M3/4 were installed inside the cryostat. 13 domes on the outer vessel were insulated and about 30 assembly openings and manholes were covered with insulation. Additionally, the insulation of the current lead domes was started. The very tight space inside and around the domes required a sophisticated insulation procedure that is tightly connected with the dome assembly. Successful tests at two mock-ups were performed in 2012 to qualify the insulation and assembly concept. Therefore, in 2013, the current lead domes could be successfully insulated in M5, M1 and M4. The remaining four domes in M2 and M3 will be insulated in 2014.

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 Wendelstein 7-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 the bottom. In total, 14 current leads are needed. The production and the tests were performed by the Karlsruhe Institute of Technology (KIT). In each test campaign, two current leads were connected to form an electrical circuit. After a thorough check under room temperature, the whole test arrangement is cooled down to cryogenic temperature with a rate of 10 Kelvin per hour. After the hydraulic and thermal stabilization, the CLs are loaded several times up to the maximum current of 18.2 kA. The test of a loss-of-Helium-flow accident has demonstrated the ability to de-energize the Wendelstein 7-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 all requirements. The necessary helium mass flow rates to operate the current leads meet the expectations. After the test under cryogenic conditions, a high voltage test under different environmental pressures is performed. By the end of 2012, 12 current leads had been finally tested under cryogenic conditions. In 2013 the remaining four current leads were successfully tested and all current leads were delivered to the IPP. The assembly at IPP has made significant progress. By the end of 2013 all current leads were placed at their final position in the Wendelstein 7-X cryostat. At ten current leads, the assembly work was completed by installing the last bellows. The completion of the installation work for the four remaining current leads is planned for spring 2014.

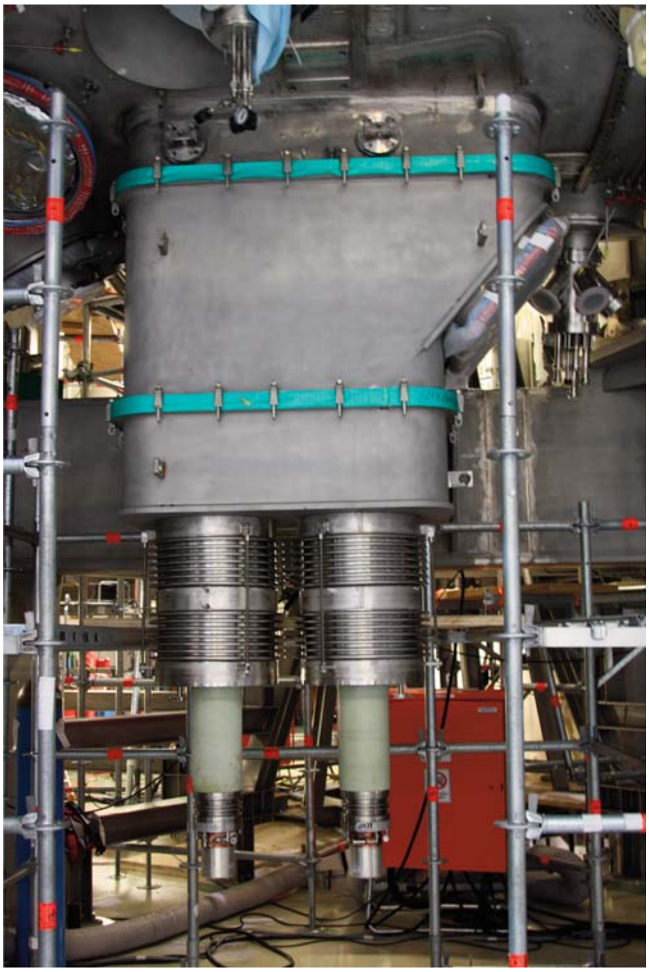

Figure 4: Current lead by the end of installation with dom.

3 Supply Systems

3.1 Helium Refrigerator

The helium refrigerator produces and distributes the cold helium required to cool the cold components of Wendelstein 7-X. The cryo plant was installed and commissioned. Most of the acceptance tests were carried out in 2012. In 2013, the cool-down of the refrigerator was done with an additional heat load simulating the warm mass of Wendelstein 7-X. The guarantee cooling power of 20 kW was demonstrated down to a return temperature of 50 K. The overall cool-down to 10 K took one week. The requirements for the maximum allowed temperature difference of 40 K were achieved between feed and return flow. During cool-down, the temperature of the thermal shield followed the temperature of the conductor cooling as specified. The mode "cleaning of Wendelstein 7-X" was demonstrated with He-gas at ambient temperature. The internal cold adsorbers inside the cold box of the cryo plant were used. The He-gas was cooled down to 80 K, than cleaned inside the adsorber and finally warmed up to ambient temperature. IPP personnel was trained by LKT in a one week session. Safety issues and the process topics were discussed. Information was given on "how to run the plant". After finalizing the acceptance test and the documentation the contract was completed.

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 coils of one type 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 already in 2005. In order to prepare the system for the operation phase of Wendelstein 7-X, several test campaigns were carried out in 2013 as well. Finally, the system was operated at nominal current over a period of 100 hours, which corresponds to the planned maximum operating time during the experimental campaigns of Wendelstein 7-X. After evaluation of the results, only few improvements were necessary for auxiliary systems. The energizing and de-energizing process of the Wendelstein 7-X super conducting magnet system could stress the electrical insulation of the coils, and in the far future lead to cracks in the insulation. This can result in a fault to ground. In case of a fast discharge, both events together would lead to a doubled voltage between coil and ground which should be avoided. In order to prevent such undesirable occasions, the insulation of the superconducting magnet system will be monitored by regular high voltage tests with very low energy. The check should also be performed after substantial changes of the current, which consequently means that the high voltage test must also be performed when the magnets are energized. The main idea of such an "In-Service-Test" is to induce a high voltage directly into the grounding point of the system and measure the leak current. The measured leak current can then be used to determine any changes in the quality of the insulation. In 2013 the development of the system was finished, small scale test have been performed and all five units of the In-Service-Test system have been manufactured, tested and installed in the power supply system of the superconducting magnet system. The control system, which integrates the system into the overall control system of the magnets, has been designed and is in production.

3.3 Quench Detection System

The quench detection system of Wendelstein 7-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. It must operate also at high voltages during a rapid shutdown of the magnets. In total, 560 quench detection units are necessary. The quench detection units will be put into ten 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 which secures 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 for a full remote control. The fabrication of all subsystems has been finished, and in a steady state test over several months, the faultless operation has been demonstrated. The signals of the subsystems will be transferred to the magnet protection systems via so-called interface racks. These interfaces combine the signals from the quench detection units and the signals from the monitoring system, which checks permanently the proper data transmission and the function of all components. The quench detection system will be controlled by a central control station that allows fully automatic as well as manual operation. The human machine interface will be realized via WinCC. The design of the central control system has been completed; a first prototype has been built and successfully tested, followed by the production of the final control racks. The programming of the human machine interface has been started.

4 In-vessel Components

In 2013 the finalisation of the design, manufacture and testing of all of the in-vessel components (KiPs) necessary for operational phase OP 1.1 took place. This included adaptations of the components and in particular their holders to take into account the real plasma vessel geometry, unforeseen collisions with diagnostic components, and adaptions found necessary during the installation process. In parallel, the design, manufacture, and testing of the remaining KiPs necessary for the full water cooled phase continued. The KiPs consist of the divertor components (target, baffles, and toroidal closure plates), plasma vessel protection (panels and heat shields), control coils, cryo-pumps, port protections, and special port liners for the different heating systems, together with the complex system of cooling water supply lines. The high heat flux (HHF) divertor, port protection liners, and the cryo-pumps are the main components that still need to be completed. The detailed design of the modules of the high iota tail of the divertor was completed in 2012 with a successful design review, and the manufacture of the components has begun. In 2013 the detailed design of the vertical target modules was also brought to a status where a successful design review could be held, and the design of the main horizontal target modules, the only remaining target modules, for which the design is to be finalised, was begun.

4.1 Target Elements

The main building blocks of the HHF divertor are the 890 target elements being manufactured by Plansee SE. These HHF divertor elements consist of 8 mm thick carbon fibre reinforced composite (CFC) tiles joined to a water-cooled CuCrZr heat sink and are designed to withstand power fluxes up to 10 MW/m^2 in steady-state and should operate with 12 MW/m^2 for a reduced number of cycles. At the end of 2013, more than half of the elements had been delivered. All the incoming tests on the newly delivered components showed that they were within the specification. This includes the testing in the Gladis HHF facility. Production of the remaining elements continues at Plansee with the final deliveries expected by the middle of 2014.

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. The divertor consists of three main HHF target areas. The high iota tail target area has three modules TMh7, TMh8 and TMh9, which are in manufacture. The vertical target area, also with three modules, TMv1, TMv2 and TMv3, was designed in 2013. The remaining target area, the horizontal target with four modules, TMh1 to TMh4 began its design at the end of 2013. The manufacturing of the modules TMh7, TMh8 and TM9h is mainly performed in the IPP workshop in Garching, ITZ. Two components are manufactured externally: the water manifolds at Dockweiler and the 3D machined target elements at GEWO. Figure 5 shows one of the water manifold for the TM9h, and figure 6 shows the assembled 3D machined target elements on TM9h.

Figure 5: Water manifold of the TM9h.

The design of the TMv1-TMv3 modules proved more complex than was originally foreseen. The small space envelope available for the components meant that it was difficult to implement existing technologies for the manufacture of the target module cooling circuits. A number of iterations were necessary before a solution could be found without significantly affecting the other KiPs. The manufacture of these modules will be initiated in 2014. With the design of the TMv1-TMv3 completed, the start of the design of the target modules TMh1-TMh4 was initiated.

Figure 6: The plasma facing surface of the 3D machined elements mounted onto their frames.

4.3 Test Divertor Unit (TDU)

The interim solution for the Divertor to be used during OP 1.2 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. The TDU is already in HGW, and parts of it will be installed into the machine in 2014. The TDU has been built in co-operation with Garching, Greifswald and by external companies.

4.4 Baffle Modules

The manufacture of the final baffle modules continued in 2013. The last vertical baffle modules are geometrically more complex than the earlier modules, and the experience built up over the years has been necessary to complete these modules in the IPP workshop in Garching.

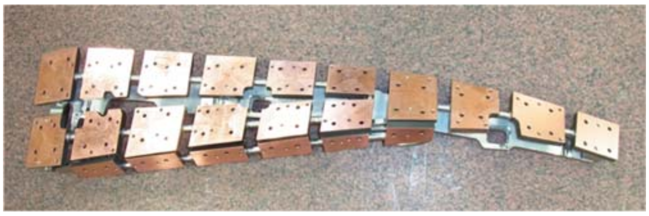

Figure 7: Baffle module Type 8v without graphite tiles showing complex 3-D form.

Figure 7 shows a baffle module of type 8v with its complex geometrical form. At the end of 2013, all of the baffle modules had been manufactured and only the final testing was outstanding, delayed as a result of the need to support the assembly process in HGW.

4.5 Wall Protection

Apart from the divertor components, the KiPs consist of double walled stainless steel panels (covering approx 70 m² of the inside of the plasma vessel) and heat shields (covering approx 50 m²) consisting of water cooled copper plates coated with graphite tiles (similar to the baffles). 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. Particularly sensitive are the welds between the plasma vessel and the ports. Hence, it is necessary to minimise the gaps between the port protection liners and the wall panels. In 2013 conceptual work began in detail to define the exact requirements of these components, to clarify the interfaces with the diagnostic systems (the main users of the ports), and to identify, which technologies needed to be further developed.

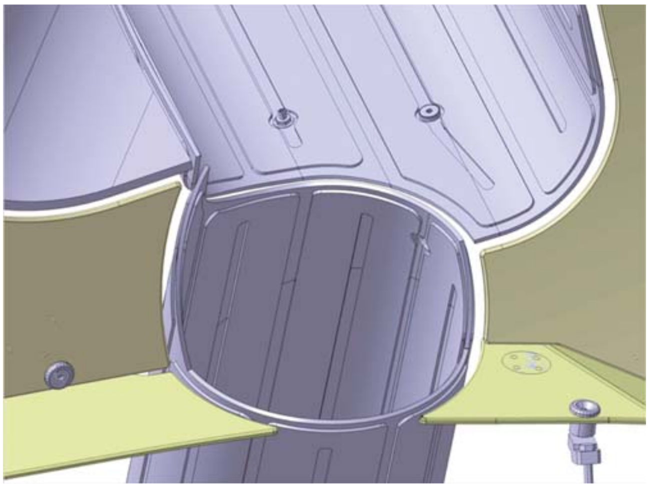

Figure 8: Intersection of the port liner AEE41 with the existing panels.

Figure 8 schematically shows the intersection of a typical port protection liner with the existing panels used to protect to plasma vessel.

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 workshop 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 coating is to reduce the ECRH stray radiation in the vicinity of the cold areas of the cryo-pump in order to stop them becoming warm. 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 cryo-pump against ECRH stray radiation. The remaining water baffles (19) will be coated during 2014. Resources should also be available to re-start the manufacture of the cryo-pumps during 2014.

4.7 Control Coils

The control coils are equipped with 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 2013 the test operation of ten power supplies was 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 and adjusted. The control coils are planned to be installed during 2014.

4.8 Plug-ins

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 supply ports. These plug-ins consist of a flange, through which welded tubes are mounted to allow water to be fed to and removed from the KiPs. There are eight different types of plug-ins depending on the port they are going through and the components they are supplying. All 80 plug-ins have been completed and delivered to Greifswald. Dependent on whether or not water will flow through the plug-ins during OP 1.1 or OP 1.2 adaptations of the plug-ins have been performed to ensure that the vacuum integrity of the plasma vessel is maintained.

4.9 Water Supply Lines inside the Plasma Vessel

The cooling water supply lines of the in-vessel components run from the plug-ins, via a complicated system of manifolds and pipes, to the various components via flanges. In total, 308 cooling circuits are foreseen. In OP 1.2 26 cooling circuits will be completed and filled with water. The panels and the heat shields will have their pipework completely welded in OP 1.1 and OP 1.2, but will not be filled with water, as this is not necessary during these phases. However, the panel circuits will be filled with inert gas, providing some thermal conduction inside the panels to avoid hot spots. The IVCs are cooled partly in parallel and partly in series. Adequate water flow has to be guaranteed to all of the components; for this purpose software from Flowmaster has been used, which makes it possible to calculate the flow in the different cooling circuits based on the measured pressure drop in the individual components and associated pipe work. These calculations were also necessary because of the large number of different variations, which occur as a consequence of the many diagnostics and heating systems. Through the use of this and other calculation methods, it was found necessary to build restrictions into the cooling system at a number of locations to balance the water flow. These restrictions were tested in Garching and delivered separately to Greifswald to be introduced into the cooling circuits on installation. The manifolds of the HHF divertor have been calculated and manufactured based on the experience gained from the manufacture of the water circuits. The port liners will also rely on this type of calculations to ensure sufficient cooling in all of the water circuits.

5 Assembly

In 2013 the qualification and procurement of assembly equipment mainly for the installation of in-vessel components have been continued. At the basic machine of Wendelstein 7-X, i.e. the cryostat and the magnet system, completion works were carried out. This included the fixation at the machine-foundation, the installation of alignment bearings, the closure of cryostat-domes and the assembly of feed-throughs for sensors, water pipes, and QD-wires. During the works at QD-wires, electrical insulation failures were observed, which were mainly caused the extremely poor accessibility. However, the failures could be detected and repaired, despite the fact that all wires are connected to one magnet system in the interior of the closed cryostat. The last dome-openings of the cryostat's outer vessel (OV) will be closed by mid of February 2014. Latest surveys showed unexpected deformations at the OV. These were accumulated through weld-shrinkages caused by the successive connection of the vessel modules. However, after a first check, these deviations appear to be admissible. In the beginning of 2013, the design of the connection between the cold-end of the current lead and the superconducting busbar system has been thoroughly checked in collaboration with the KIT in Karlsruhe, the CRPP in Switzerland and the Efremov-Institute in St. Petersburg. Reasons were ambiguous results of tests by the involved parties. However, insufficiencies in the design could not be proved. All seven pairs of current leads were installed; three of them are already complemented with domes and pivot-bearings at the bottom side (figure 9). The last CL-dome will be completed by mid of April 2014. This terminates the work at the Wendelstein 7-X cryostat-vessel. The assembly and welding of aluminium bus-bars connecting the power supplies with the CL has begun. All five normal-conductive trim coils were successfully mounted at the outer vessel. The assembly of in-vessel components (KiP) and the associated magnetic disagnostics (e.g. Mirnov and Rogowski coils; diamagnetic loops) was continued in all five modules in parallel. The progress here is still smaller than expected. Too many first of its-kind installations, too many deviations and changes at components and processes prevent a sufficient increase of the efficiency. In addition these works need an unexpectedly large assistance from both the assembly technology and the work-preparation groups. This requires the constant allocation of at least nine engineers. The scope of the KiP assembly was reduced in 2013 in conjunction with the decision not to install the test divertor unit in the first construction phase.

(This has been shifted to a second phase in 2016). Other works had to be extended in conjunction with the ongoing design of in-vessel diagnostics. The assembly plan was updated accordingly and now shows the completion of the KiP assembly in November 2014. Support was provided for the assembly of both the first diagnostics at the machine and the heating systems ECRH and NBI. A major task in 2014 was the significant enlargement of the assembly capacity for peripheral systems (systems for cooling water, vacuum and gas-supply; cablings and auxiliary structures). Though not technologically challenging, these systems require large efforts for planning and preparation, due to the large number of parts and the very limited space. The assembly processes, responsibilities, and staffing were reorganised according to the changing focus of works from the basic machine towards the work at both the in-vessel components and the periphery. Meanwhile about 150 employees are working again in the assembly division; most of them are coming from external partners.

Figure 9: One CL-pair, protruding out of the CL-dome with bellows and pivot-bearings; below: aluminium bus-bars during the installation.

5.1 Basic Machine

Though almost all works are done, there are still some important tasks remaining. The last five massive auxiliary supports underneath the machine foundation must be removed, and the setting-behaviour of the machine must be monitored. A uniform setting of few millimetres is predicted from FE-analyses. The plasma vessel still rests onto its 15 temporary assembly supports. These supports have to be adapted to pendulum supports, which enable movements like thermal expansion during operation. At the same time the associated five horizontal adjustment-supports must be put into operation. These activities might deform the plasma vessel by a few millimetres. This adaptation is made as late as possible in order to minimise the influence on the ongoing assembly work in the plasma-vessel.

5.2 In-vessel Components

In the beginning of 2013, the number of staff was massively increased after a basic efficiency in the work flow was achieved. That allowed simultaneous work in all five modules (figure 10). A second positioning manipulator was procured for the positioning of several thousand bolts and brackets. The main challenge in this context was the definition of target-coordinates for these bolts. The coordinates depend on the as-built geometries of both the in-vessel components and the plasma-vessel. In addition, an individual collision study for every position is needed to identify the bolt-type that ensures sufficient access for the assembly. A complex preparation process was established under close involvement of the responsible officer, the back-office, metrology, and the assembly technology. Only with this massive resource allotment and after more than six months of improvements and adaptations, this process became stable. Despite pre-positioned bolts, in-vessel components need to be additionally aligned to achieve a spatial accuracy of about 1 mm. Every component becomes marked either during the manufacturing or immediately before the component is being installed (laser scanning, best-fit positioning to CAD).

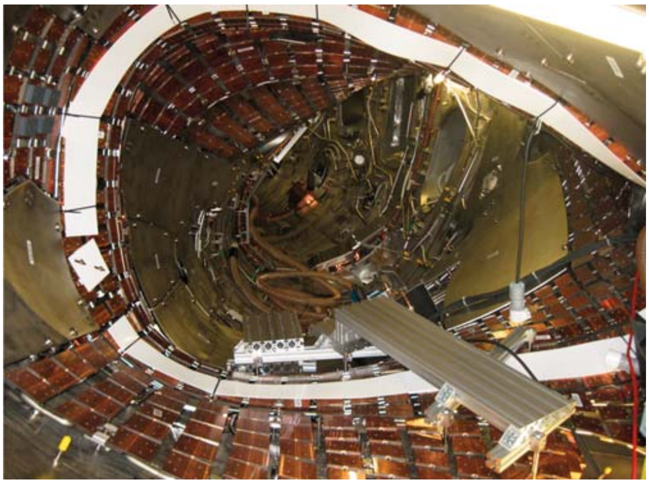

Figure 10: KiP assembly: Heat shields and cooling panels cover the PV wall; the white cover temporarily protects the diamagnetic loop underneath; front: aluminium structure as temporary carrier for measuring arms; background: a few cooling circuits.

Measurement arms, which are referenced in the Wendelstein 7-X coordinate system, are used to take the actual coordinates of the marks and to accordingly correct the components position online. A report is automatically created and attached to the assembly documentation. Measurement arms are operated by every worker of the KiP-assembly team. Typical process interruptions happen if components are not designed to as-built geometries, or if components are not installable as planned (mostly because of the extreme space-limitations). Nearly all first time assemblies suffered from that.

In the middle of 2013, the brand of measuring arms was switched and the number of arms was doubled to four. This provided the needed robustness and reliability for the shift work on-site. The installation of cooling circuits in the plasma-vessel is still problematic. An unexpectedly high number of complex fitting pieces must be customised on-site according to the narrow as-built conditions. In addition, the tight tolerances for the orbital welding must be considered. That leads to an intensive use of computer-aided bending machines and milling machines, together with a comprehensive technological preparation. Accuracies of 1/10 of a millimetre must be achieved. The customisation leads to numerous process-interruptions, and it prevents the planned standardised assembly of the pipe-system. More than a year is needed to implement functioning technical procedures for these customisations at least routinely.

5.3 Periphery

About 70 T man hours are needed to assemble all pipes, manifolds, valves, and sensors – only at the outside of the cryostat – together with the cable-trays and cables needed for the instrumentation of the basic machine (figure 11).

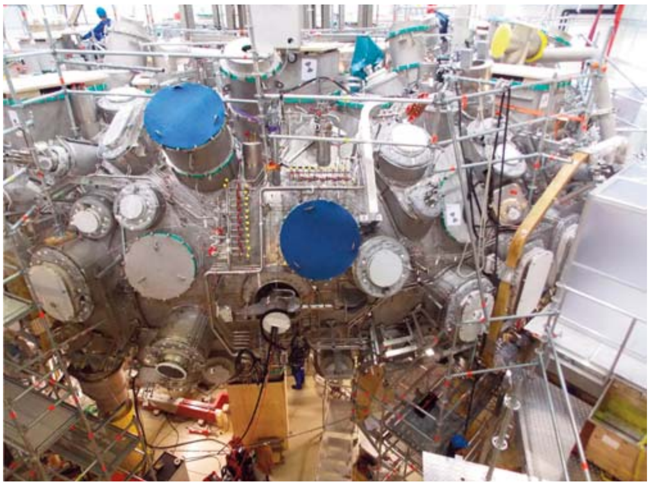

Figure 11: Cable trays and piping at the outer vessel.

This area is very crowded and there is the permanent danger to damage already installed components. Huge efforts are needed to warrant sufficient work-safety. The installation of the main cooling systems (in-vessel components, cryostat, cold-water, filling and draining) in the torus hall progresses as planned. This work is performed by external companies. The installation of the helium quench-gas system and the cryostat overpressure protection system is planned in detail. These works will start end of January 2014 and will last about six months. Massive supports structures e.g. for cables, pipes and diagnostics (HDS, TSS, MUS) were procured and assembled in the centre of the machine (figure 12).

Figure 12: Wendelstein 7-X with periphery and first diagnostics (auxiliary structures, cable trays, pipe-systems).

The last parts will be assembled until January 2014. The central platform is nearly complete. It provides access to the machine in the middle plane. The platform also serves as carrier and distribution for cables and pipes between the machine and walls, cubicles etc. The installation of thousands of cables and their connections with cubicles and components will start in February 2014. The periphery works are carried out in a two-shift system.

5.4 Vacuum Technology

Leak-tests and Paschen-tests accompanying the ongoing assembly were carried out as in the years before. However, the scope of works has significantly grown. In addition, the test conditions worsen rapidly with the increasing connection of all component groups among each other. Spatially narrow test-conditions caused test-failures and even severe damages at components. Necessary repairs and re-works influenced the work-progress noticeably. All procurements for the three vacuum systems are nearly complete. The assembly of the systems for the inter-vacuum and the cryostat-vacuum progresses as planned. A prototype was set up for the local control system of the vacuum systems. It is planned to start the commissioning of the interspace vacuum system in April 2014 in parallel to the ongoing assembly works. Special safety and precaution measures were considered in the associated commissioning planning, which was completed at the end of 2013. Altogether, in 2013 assembly has progressed as planned in 2013. However, the KiP assembly might be subject to future schedule risks. Peripheral works at pipes, cables and structures were massively extended. The co-operation with external partners who provide skilled and well-trained technicians and engineers for the realisation of the assembly work on Wendelstein 7-X proved to be flexible, stabile and smoothly.

6 Engineering

The sub-division "Engineering" (EN) provides engineering support to the Wendelstein 7-X project. EN was subdivided in the departments "Design Engineering" (EN-DE) and "Instrumentation" (EN-IN). EN-IN was transferred in the middle of October to the sub-division "Magnets and Cryostat" (MC) in the course of a project re-organization.

6.1 Design Engineering

Focus of the EN-DE department's work has been further shifted from the basic machine design towards fast analyses of non-conformity consequences, determination of deformations as input for collision checks, additional support of assembly with respect to new or changed procedures, and towards analyses of in-vessel components, diagnostics and periphery. Considerable work activity was devoted to preparation for commissioning, exploration of operational limits of the as-built machine, determination of expected signals from the mechanical instrumentation, and clarification of interfaces with CoDaC. The stellarator reactor study contributions had to be reduced during the reporting period due to lack of resources. Main results of the department's activities were successfully presented during international conferences and published in scientific journals.

6.1.1 Superconducting Magnet System

6.1.1.1 Mechanical Analysis

The magnet system comprising 70 superconducting coils and their support structure is being analysed using finite element (FE) model trees created with ANSYS and ABAQUS codes. The FE global models (GMs) of a complete module including the cryo-legs have been further improved for more reliable extraction of critical results as well as stress and strain values in the sensor locations. Intensive benchmarking between independent FE models maintained in two different codes remains the main EN-DE approach to avoid mistakes and inaccuracies in these complex and highly non-linear analyses. Elaboration of full 360-degree FE models was required for the following tasks: – The ABAQUS FE model including the machine fundament was used to estimate coil asymmetries caused by torus assembly and removal of temporary supports. Disassembly of the latter was supervised and accompanied with detailed force and displacement measurements whose results have been used for model validation. – The ANSYS FE model was used for the definition of asymmetries caused by the observed unintended 1 mm lifting of a cryoleg during assembly. Local models using both finite element and boundary element methods were used for further analyses of cracks (in collaboration with Prof. Citarella, Italy) in the welded lateral support elements between the non-planar coils. Based on these results, allowed load cycle combinations from 0 to 2.5 T, from 2.5 T to 3 T, and from switching from one electromagnetic configuration to another were defined. It was demonstrated that the specified number of load cycles is not jeopardised by such cracks. Moreover, a method how to count contributions from commissioning cycles, quenches, and any other non-standard cycles in terms of the allowed cycle budget has been developed.

6.1.1.2 Electromagnetic Analyses

Analyses were continued to assess the impact of slightly non-symmetric coil deformations originating from the final torus assembly as predicted by the ABAQUS 360° FE model. Consequences of non-symmetric deformations during operation, originating from magnet system parameter uncertainties, on the magnetic field error and corresponding requirements for the trim coils were investigated. It was concluded that the trim coil capacities are sufficient to compensate for the expected asymmetries. Transient events like fast coil discharges, plasma current decay, and assumed plasma disruptions cause eddy currents within the plasma vessel (PV) wall, diagnostics, and in-vessel components. The development of an electromagnetic global 360° FE PV model to assess the effect of openings and ports on the induced current and force distributions has been started in the code MAXWELL 3D in collaboration with LTC comp., Italy.

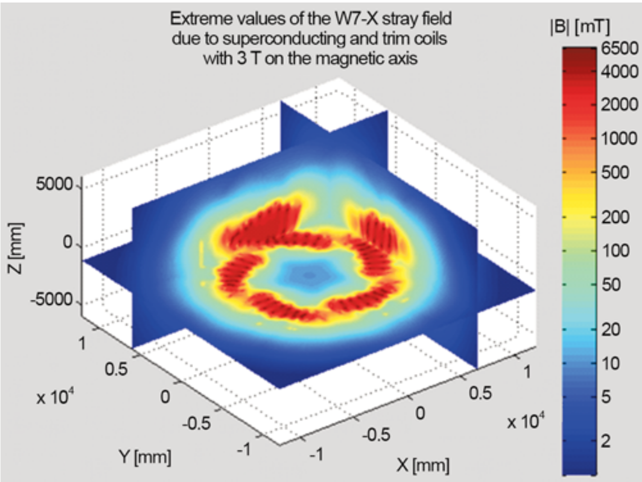

Figure 13: Visualization of the magnetic field of coil and plasma currents, shown in the planes X = 6500 mm, Y = 6000 mm, and Z = -1200 mm.

First results show that the field configurations (figure 13) due to the coil and plasma currents, together with the specific PV geometry, lead to a complex pattern of induced PV wall currents. However, for rough and quick estimations of eddy currents and corresponding forces on reduced in-vessel component and diagnostic geometries, available simple models and approaches are still employed. For some complex geometries MAXWELL 3D was also used to calculate field disturbances due to permeable materials.

However, this approach requires great effort to achieve the necessary accuracy. In order to obtain fast results – as needed by the tight W7-X assembly schedule – a new MATLAB code was successfully developed and is now in use. It includes field calculations for all defined magnetic configurations and provides a graphic user interface (GUI). In some cases, detailed information on the magnetic stray fields within the machine or the torus hall is required. Corresponding calculations were performed for all defined magnetic configurations, and an easy-to-use GUI was provided with a 3D navigation tool through the stray field with indication of local extremes. Fast current change in planar coils is being considered to provide corresponding field ramps for proper plasma shaping, as an alternative to scraper elements, to protect the divertor edges from overheating. Corresponding field and force calculations were performed and it was concluded that neither structural problems nor inacceptable ac-losses are expected in any of the superconducting Wendelstein 7-X coils.

6.1.2 Trim Coils

EN-DE defined assembly fixtures, supports and attachments, which were implemented during the successful installation of all trim coils of both types. In addition, the positioning of one coil out of tolerance was assessed, and a correction scheme was provided to the assembly team. A test program was carried out in collaboration with FH Stralsund to quantify the cyclic and temperature influences on the pre-stress of the synthetical coil support pads.

6.1.3 Cryostat

Main application of the ANSYS global model of the cryostat system (GMCS, figure 14) is to provide input for collision checks, for local analyses of port welds, PV and outer vessel (OV) supports, local OV deformations under trim coil and port loads, port movements, PV deformations in regions of in-vessel component attachments, etc. A new version of the GMCS with updated geometry, created in 2012, was introduced in the analysis activities to define port displacements as well as stress and strain values at sensor locations more accurately. For this purpose, the loads on ports and domes were updated to account for the up-to-date design and construction of the diagnostics. In addition, assembly steps including removal of temporary supports underneath the machine base were analysed, as well as the expected PV behaviour during OV evacuation with on-going in-vessel assembly activities. The GMCS results are widely used by designers of diagnostics, NBI, ICRH, and by the AS sub-division.

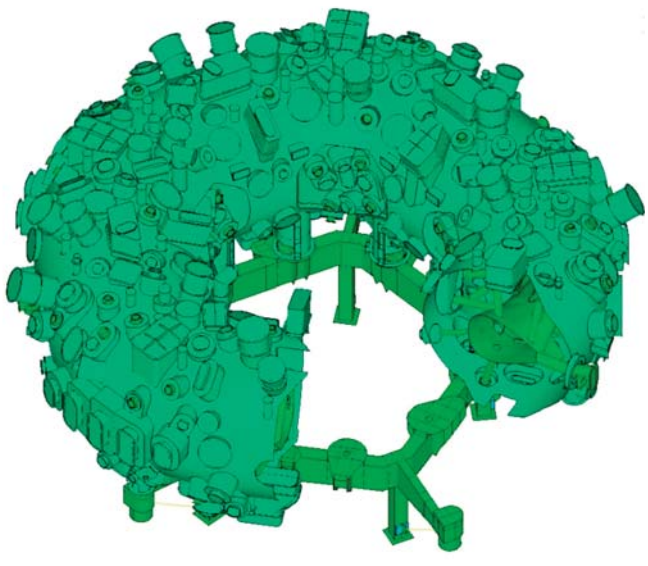

Figure 14: Updated global model of the cryostat system in ANSYS. Bellows are represented by shell, beam and contact elements, as well as by superelements.

6.1.4 In-vessel Components (KiPs)

Several options of limiters for the operation phase OP 1.1, without TDU, were checked, and one version has finally been chosen. Based on thermal analyses a recommendation for temperature measurements was given. Further activities supporting the design and assembly of KiP components for the operation phases OP 1 and OP 2 are listed in the following: (1) Determination of heat loads on KiPs as well as on the PV and port walls due to ECRH stray radiation, to heat radiation from the first wall backside, and plasma radiation through the first wall gaps. (2) Evaluation of temperatures, thermal stresses, and deformations of the high heat flux (HHF) divertor module # 2. (3) Assessment of tolerances of gaps and steps between wall panels, based on the thermo-mechanical behavior of these components under internal pressure, baking and plasma operation. (4) Start of a collaboration with LTC comp., Italy, to prepare a set of FE-models for predicting heat shield gaps and steps under internal pressure, baking and operation, and to identify regions to be equipped with additional backside protection.

6.1.5 Diagnostics

The following main tasks were executed: (1) Updated acceptable loads on diagnostic port flanges were tabulated. (2) Thermal-mechanical simulations of retro-reflectors were completed. Aim was to ensure parallelism of the incoming and outgoing laser beams under reflector deformation. (3) Analyses were performed and design support was provided for the Thomson radiation diagnostics, flux surface measurement equipment, and multi-purpose diagnostic manipulator. (4) The diamagnetic loops were mechanically analysed and their production and installation supervised. (5) Immersion tubes, port flanges, and front plates including shutters (figure 15) for various diagnostics, as well as the neutron counter calibration vehicle rails were analysed and corresponding design support was provided. (6) Thermal analysis has been performed of the port parts protruding from the OV as well as of the attached diagnostics in order to specify the necessary heating and thermal insulation during PV and port baking. (7) Diagnostics, which are exposed during operation to heat loads from the back side of the first wall and from ECRH stray radiation were analysed with regard to overheating and/or critical thermal stresses. In addition, several approaches to calculate the ECRH stray radiation distribution for complex 3D geometries have been considered. The originally favoured ANSYS radiosity method, which is limited to grey and diffuse radiation was dropped after it was proven that these conditions do not reflect the behaviour of the ECRH stray radiation in Wendelstein 7-X. Preference is now given to the ray trace method developed by EN-DE, which is under benchmarking with available measurement results.

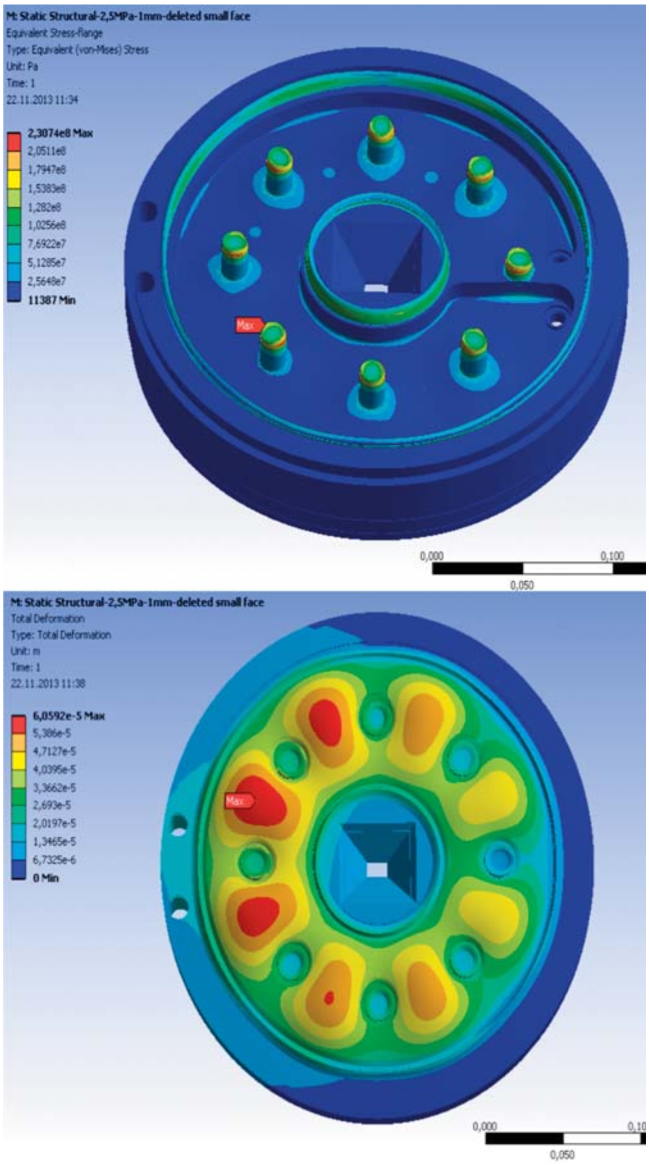

Figure 15: Mechanical analysis of the water cooled front plate of the AEU30 bolometer under pressure test conditions.

6.1.6 Periphery

Various components in the centre and direct vicinity of the torus, like current lead return lines, quench exhaust gas system etc., have been investigated concerning structural integrity and deformations. Particularly, the structural behaviour of the heavy duty structure was re-analyzed because of the introduction of the multi-user support structure as well as changes of the load distribution, attachment and anchoring schemes. The results were implemented in the designs. The stellarator field disturbances caused by increased steel permeabilities of periphery structures, valves, motors, pumps, etc. were assessed and found to be acceptable.

6.1.7 Preparation for Wendelstein 7-X Operation

A traffic light system for criticality identification was proposed to be used for the mechanical instrumentation signal monitoring during commissioning and operation. Yellow and red lights indicate warnings and stop signals, respectively, due to discrepancies between predicted and measured conditions of the magnet system structure. Several activities have been started to create and implement this system, with priorities laid on the sensors, which are relevant for the first commissioning step. A list of all sensors to be monitored has been set up with a collection of relevant information like type, coordinates, etc. The last entries of the list will be the expected signal levels of each sensor corresponding to the yellow and red lights. The structural analyses to derive these signals are under way. During commissioning, the superconducting coils will partly be operated outside the specified field configurations, which were the base for the magnet system design. A method was developed to quickly compare the forces, moments and displacements of all structural elements for the new load cases with the previously defined design values, which were checked in detail and confirmed to be safe. In addition, considerable efforts were allocated to develop easy-to-use post-processing tools in MATLAB for the main global models of the cryostat and magnet system, resp. These tools allow fast monitoring of all critical results, to compare them with each other, and with the defined design values. In order to assess the electromagnetic fields and forces for any new coil current distribution, a linear vector superposition procedure has been developed and implemented. The procedure allows for any field point to calculate quickly the individual field contribution coming from each coil group.

6.2 Instrumentation

The department Instrumentation (EN-IN) was part of the Engineering subdivision until mid of October 2013 and then transferred to the Magnets and Cryostat (MC) subdivision in the course of a re-organization of the project Wendelstein 7-X. Up to then – and also within MC until the end of the year – EN-IN was responsible for the (1) mechanical instrumentation of the magnet system (2) data collection for TDU and NBI beam dump thermocouples, plasma vessel (PV) temperature and strain sensors, and for part of the cryo-shield temperature sensors (3) PV and cryoleg position monitoring system (4) temperature monitoring of the AE- and AF-ports (5) design and construction of the cubicles for the above instrumentation ("machine instrumentation cubicles") (6) cabling between the feed throughs on Wendelstein 7-X and the cubicles under consideration of appropriate shielding. In the following, some of the main tasks are described in more detail.

6.2.1 Monitoring System for Toroidal Loads on the Cryolegs

A system to monitor toroidal loads on the cyolegs was developed, built, calibrated, and applied. It consists of three strain gauge (SG) rosettes placed on every tie-rod. The latter restrict toroidal and allow radial cryoleg movements towards the torus centre. The three rosettes are arranged circumferentially at 120° around the tie-rods and allow discrimination between bending moments and tension stresses.

6.2.2 Plasma Vessel and Cryoleg Position Monitoring System

Plasma vessel movements and deformations during evacuation and operation can be measured at the supply port ends sticking out of the outer vessel. The supply ports are firmly fixed to the PV, such that its movements and deformations are translated to corre-sponding shifts of port ends. A system was developed to continuously measure such 3D movements with regard to the OV. Several options were investigated; the chosen measurement principle was to use three string potentiometers fixed on the OV (P1-P3 in figure 16) with the ends of their strings attached to a point (Q in figure 16), which is firmly connected to and moves with the port.

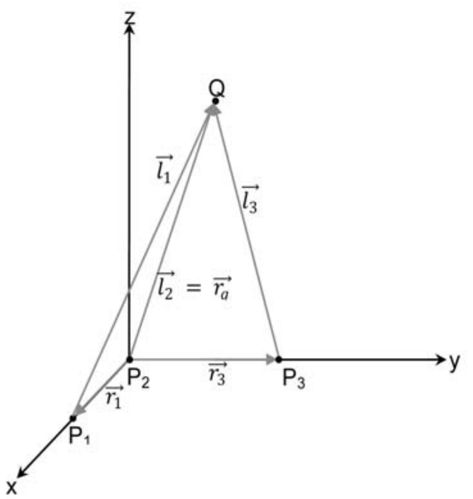

Figure 16: Principle of PV and cryoleg position monitoring system. P1, P2, P3 – string potentiometers on OV; Q – moving point connected with the port or cryoleg, resp.

The changes of the string lengths (l1, l2, l3) are translated to electrical signals, from which the displacement vector of Q can be derived. The same string potentiometer arrangement is also used to measure movements of the bottom parts of the cryolegs, i.e. displacements in radial direction (w.r.t. torus centre), and also possible lifting as well as tilting. Such movements are expected during cool-down and excitation of the magnet system. A prototype of this measurement system was built, and the positions of the potentiometers as well as the measurement point Q in the Wendelstein 7-X coordinate system were determined. Procurement of components for 25 such measurement units, as well as the conceptual design of the supports on the OV and of the fixation arm for point Q on the corresponding ports has been started.

6.2.3 TDU Thermocouples (TC)

One task of EN-IN is to complete the TDU as well as NBI beam dump and duct TC measurement chains from the port feedthroughs up to the machine instrumentation cubicles. Short thermo wires transfer the signals from the feedthroughs to nearby junction boxes, which in turn are connected with the distant (»100 m) cubicles via cheap copper wires. Electronics were developed to measure the temperatures of the connection boxes in order to correct the TC measurement signals correspondingly. It was experimentally confirmed that the influences of the connection box housing, torus hall cable, and vacuum feed through temperatures are kept within acceptable levels.

6.2.4 Machine Instrumentation Cubicles

The five machine instrumentation cubicles contain the data acquisition systems for the mechanical instrumentation of the magnet system (SGs, displacement and contact sensors), the PV deformation and displacement monitoring system, the cryoleg toroidal load and displacement monitoring systems, the PV temperature sensors and SGs, the port temperature sensors, the TDU and NBI beam dump thermocouples, and finally part of the temperature sensors on the cryoshield. Some final design changes prior to the start of the cubicle series production were performed. In particular, an improved, i.e. significantly simplified, design was created for the EMI electronics shielding cages inside the cubicles, which are needed to reduce electromagnetic disturbances to acceptable levels. The series production of the cubicles has been started. All five of them are already mechanically assembled, and the wiring is under way. Figure 17 gives an impression of the effective use of space inside a cubicle, which allows processing of ≈ 480 sensor signals. The electronics are arranged in four planes (two in the middle of the cubicle, one at the front and back door each; one side wall is removed for better clarity); in the figure, only the EMI cages covering the electronics can be seen. Each cubicle has its own filter unit, power supply, Ethernet switch, and fire extinguisher.

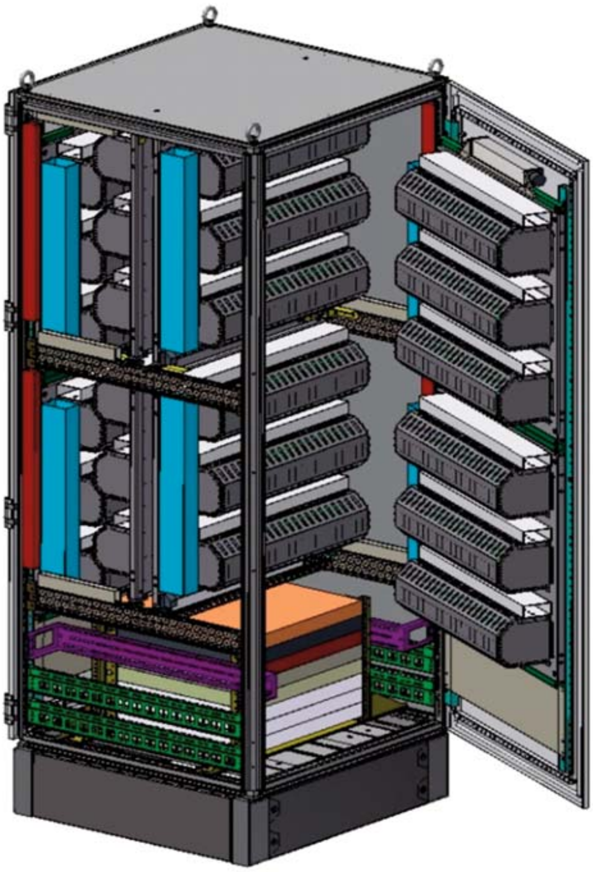

Figure 17: Effective use of space inside a machine instrumentation cubicle.

Several grounding options are foreseen in order to comply with any Wendelstein 7-X grounding concept in question. No active external cooling is neccessary, the 500 Watts dissipated per cubicle are transferred to the torus hall air via heat exchange through the doors.

7 Design & Configuration

The subdivision "Design & Configuration" provides for Wendelstein 7-X the configuration management of its components, design solutions, fabrications drawings and the integration of all components in the torus hall and adjacent areas. About 60 different projects in the torus hall require integration and design activities of various extent for the first operational phase. The deliverables range from integration and conceptual design all the way to the generation of fabrication drawings and assembly documents. In order to ensure that the design activities meet all functional aspects of these projects and are conform to the boundary conditions, a step-wise 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 updated 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 preliminary 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 integration in the torus hall. This integration encompasses the actual design space including tolerance areas and additional space needed for minor and major maintenance. The detail design activities are finally concluded with the generation of all neccessary fabrication documents, if required.

7.1 Configuration Management

In 2013 the configuration management DC-CM continued the coordination of the system identification, change and deviation management and interface documentation. Currently, 1176 change requests (CR) are registered in the DC-CM database. 87 % of the CR have been accepted, 2 % are in the decision process and 12 % have either been rejected, withdrawn or became obsolete due to a revision. 78 % of the accepted CRs have been closed, i.e. full confirmation of the implementation of the change was given and documented in the CRs. The typical topics for CRs changed over time with the current assembly activities from the basic machine and KiP components to the peripheral systems (media supply systems, peripheral support systems etc.). Similar holds for the interface description (ID). The interface control is now predominantly dealing with interfaces between the basic machine and the port users (diagnostics, supply systems, heating systems) and peripheral interfaces. The identification of the interfaces between the about 60 projects that are relevant for the first operational phases OP 1.1 and OP 1.2 has been finalized. Only for a small number of new OP 1.2 diagnostics the identification is still ongoing. For each of the Wendelstein 7-X projects an interface scheme has been created to provide an overview of its interface description with the rest of Wendelstein 7-X. In figure 18 a typical example of such a scheme is shown.

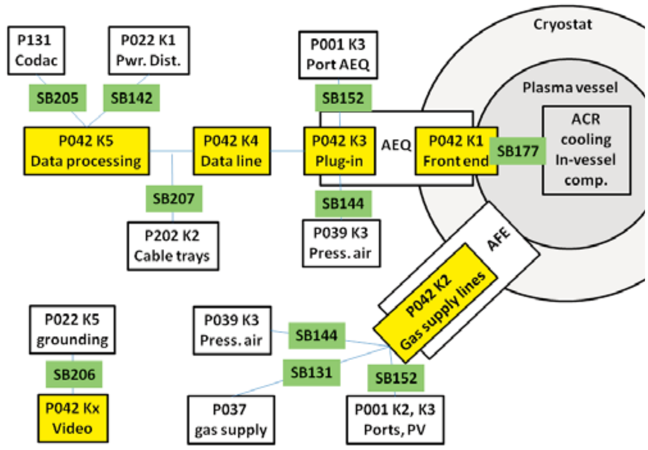

Figure 18: Example of a schematic identification of interface descriptions between projects that are required for configuration management.

The numbers "SB xyz" refer to the running number of the interface description. A total of 270 IDs are currently documented. 13 % of the IDs are comprehensive and completed, 50 % are comprehensive but not yet completed, i.e. some issues still require quantification, and 35 % of the IDs are still in the draft phase and are not yet comprehensive. As a general starting point to find information on any system of Wendelstein 7-X or of general device related topics an electronic "loose leaf binder" is being created. By now 152 individual topics have been identified. For 63 % of these topics a well developed entry in the "loose leaf binder" is available. For 37 % of the topics, work is still ongoing to establish a first version.

7.2 Integration and 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. In 2013, the established tools have been updated according to changing needs and continue to work properly to efficiently and effectively manage and advance the design activities in the torus hall. These tools include daily CAD data base updates, collision report tools, delivery tools, and various exports for communication inside and outside the department. To cope with the fact that the aspect of the integration into already existing solutions constitutes the dominant part of the work, it is imperative to clearly identify the functional requirements and boundary conditions that need to be considered in order to develop design solutions that both meet the requirement of the customer but also properly integrate them into the torus hall. To that purpose the department has trained "mechanical design integration project leaders" which are supported by a pool of designers. These project leaders clarify the needs together with the customer in order be able to search for optimal design solutions. The conceptual design that is being developed meets the main elements of the specifications, is proven integrable in the torus hall, and takes into account further design aspects like manufacturing and maintainability. After each design step a formal configuration control test is performed on the basis of the agreed upon fabrication and assembly tolerances and documented in order to be able to release a proposed design and define a place holder or a space reservation, and in order to keep track of interfaces that still require further detailing since the neighboring components are not sufficiently far advanced. In case of conflicts the department organizes and performs mitigation measures. For supply networks, e.g. cable trays, gas lines, vacuum lines, cooling lines, and general support structures the design principles have been defined, approved by the Chief Engineer, and implemented so as to provide overall guidance and ordering.

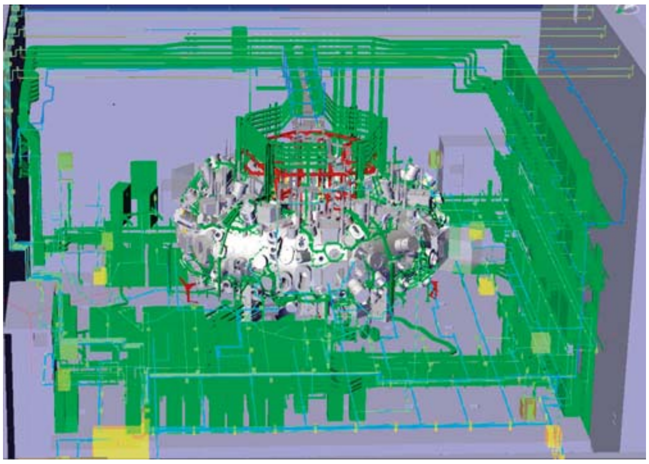

Figure 19: Layout of the electric system including the cubicles (green), the multi usage support structure (red), the fire extinguishing system (blue) in the torus hall. Other peripheral systems are not shown.

During later phases of the evolution of the projects (detail design, fabrication, assembly), the customers are being supported with further configuration checks, e.g. whether the detailed models are still within the agreed upon space reservation or whether deviations are permissible, with assessments of detailed design solutions at the interfaces to other projects. Various back office activities are also being continued. These include the processing of measurement data for design and assessment activities, and the generation of as-built design information for various cryostat and plasma vessel components. Due to an overall tight personnel situation, the department focuses on the conceptual, preliminary design phases and detail design phases in as much as they directly pertain to the integration into the torus hall. As soon as a stable design solution whose interfaces to the other projects are clearly defined and documented has been developed, further detailing is most often done in other departments or directly by an external supplier. In 2013 design work has been done on all projects directly relevant to the first operational phase. In the following, some examples are shown: The heavy duty structure that supports water pipes, quench release pipes and other components in the center of the device that are not sensitive to vibrations has been extended to support also components that are located on the top of the cryostat but that cannot be support on the cryostat itself. Care has been taken to obtain a module symmetric design of the multi-usage support structure (MUS). Figure 19 shows in red the MUS additions to the heavy duty structure. There are several hundred electronic cubicles and electronic boxes used by the peripheral and diagnostic components that have to be integrated into the torus hall and adjacent areas. As a general guide line, cubicles are to be placed outside the torus hall to maintain maximum flexibility for later additional components in the torus hall and to allow trouble shooting without requiring torus hall access and maintenance. Nevertheless some cubicles have to be placed inside the tours hall, e.g. to keep the signal-to-noise ratio of the signal sufficiently small, or to reduce the cabling cost. DC-TH collected all the requirements that were needed for the layout of these cubicles and electronic boxes, and identified possible locations of clusters of cubicles. Based on general assessments on the total cross sections of the required cables the preliminary design of the main cable trays was developed using standardized supports and commercially available parts. On the basis of these cable trays and thus the estimated total cable lengths, all cubicles were allocated to the clusters of cubicles.

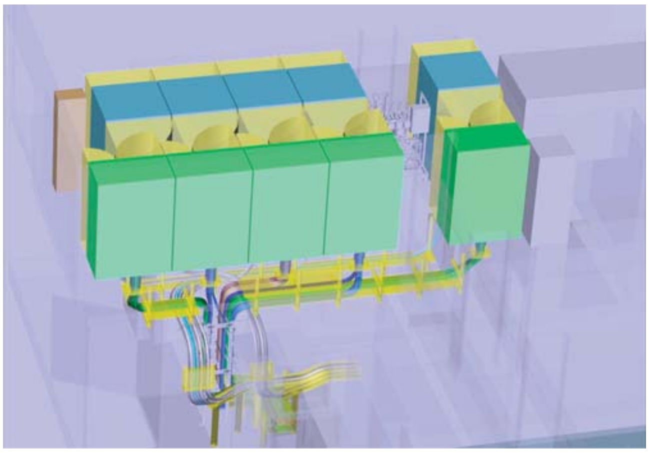

Figure 20: Detail of routing of the supply cables of the power supplies for the trim coils.

Work has started to develop design solutions for the remaining branch cable trays, which provide local routing of any source/sink point to the nearest main cable tray. The present status of the design of the main cable trays and the branch cable trays is shown in green in figure 19. The torus hall is to be equipped with a fire extinguishing system that operates by a local distribution of a fine mist of water. About 30 different regions were identified in the torus hall where this mist of water has to be provided individually. The design of the corresponding routing of the water lines and the supply units are shown in blue in figure 19. Figure 20 shows an example of the rather intricate routing for the cables between the power supplies for the trim coils and the cable duct into the torus hall that was done on the basis of the minimal bending radius etc.

7.3 Design of In-vessel and In-port Diagnostics

In 2013 the remaining design activities of diagnostics integrated in the plasma vessel and in the ports for the first operational phase were completed including the fabrications drawings and the required information for installation. These diagnostics included about 100 Rogowski coil segments, about 130 Mirnov coils, 2 diamagnetic loops, Langmuir probes for the test divertor unit, video diagnostic interfaces to the plasma vessel vacuum, XMCTS diagnostics, and a calibration device, with which the neutron counters signals can be calibrated via a neutron source that is moved to different positions along the later axis of the plasma. Figure 21 shows the rail system in the plasma vessel and the autonomously moving transport unit for the neutron source.

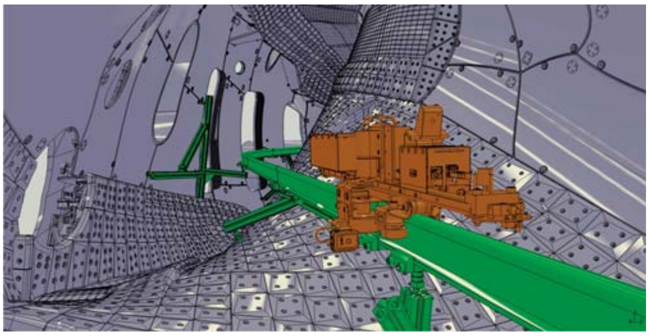

Figure 21: Section of the rail system in the plasma vessel with the probe moving unit.

The supports of the rail system were designed to be compatible with the wall lining elements. Further diagnostics in the ports were the flux surface measurements, the Thomson diagnostics, the electron cyclotron emission antenna.

8 Heating

8.1 Project Microwave Heating for Wendelstein 7-X (PMW)

The ECRH-system is being developed and built by the “Karlsruher Institut für Technologie” (KIT) as a joint project with IPP and IGVP Stuttgart. The “Project Microwave Heating for Wendelstein 7-X” (PMW) coordinates all engineering and scientific ECRH-activities. The 10 MW ECRH-system for Wendelstein 7-X operates in continuous wave

(CW, 30 min) mode at 140 GHz, which is resonant with the Wendelstein 7-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. Standard wave coupling for the initial operation phase is from the low field side via front steering launchers, which provide on-and off-axis heating and current drive. More sophisticated scenarios are being prepared for a later state of operation through remote steering launchers (RSL's) located in separate poloidal planes with almost zero-magnetic field gradient. RSL's are particularly attractive for DEMO application because of their mechanical robustness and high power density. RSL's for Wendelstein 7-X with full cw-capability are being developed and manufactured in the frame of a separate project with special support by the "Bundesministerium für Bildung und Forschung" (BMBF).

8.1.1 The Wendelstein 7-X Gyrotrons (KIT/IPP)

The series production of the gyrotrons at THALES continued and the gyrotron TH1507 SN7 was shipped to KIT in January. Short pulse measurements showed a regular behavior of the tube in terms of output power and efficiency, similar to the previously tested SN6. However, the rf-beam measurements, which were routinely performed in the early phase of short pulse tests, revealed a pronounced sidelobe in the beam pattern. After extension of the pulse length, a strong temperature increase of the gyrotron shaft was measured already at moderate power (700 kW, 4 s) indicating an enhanced internal stray radiation level. The tests were stopped and the gyrotron was shipped back to TED for inspection, which showed that the internal mode converter, which is supplied by a subcontractor of TED, was not correctly manufactured. The tests at KIT continued in May with the gyrotron TH1507-SN5R, which opened a vacuum leak after first heating of the filament. This tube also had to be returned to TED for repair in June. A leaky cooling pipe was replaced, and the repaired gyrotron was shipped again to KIT in late October. The tests developed very promising and 500 kW were achieved for 30 min (limited by the test stand PS). During conditioning with high power at 900 kW and extended pulse length, the window broke and the tests had to be terminated. The gyrotron was returned to TED in late December and SN2i was installed in the KIT test stand. Tests on this tube are scheduled for early January 2014.

8.1.2 Transmission Line and Control System (IGVP/IPP)

Two ECRH towers which house all optical transmission line elements in the main torus hall were preassembled in the ECRH-hall and tested with respect to their functionality. Access to the torus hall was provided in autumn 2013, and both towers were successfully transported in segmented modules from the ECRH-hall to their final location the torus hall. Both towers are in place with the required high positioning accuracy of a few millimetres. The towers are equipped with the control units for remote control of the front steering launchers, the vacuum shutters, arc detectors, and beam monitoring diagnostics, respectively. Data acquisition modules for slow and fast recording of Wendelstein 7-X relevant signals and the ADCs for the ECA- and protective diagnostics are installed. The installation and connection of cooling tubes to supply the mirrors and stray radiation absorbers in the towers is underway. Beside the ECRH-beam transmission towards the launcher, they provide the cooling media for the ECRH components in the experimental hall. The pipe work inside the towers is on going. As the first control units for subcomponents of the ECRH were programmed and put into operation already in 2003 with step-by-step extension and add-ons throughout the following years, the entire control system had to be revised and updated with respect to hardware and software. This turned out to be a major effort, as part of the control system had to be developed in-house at KIT/IPP, because no adequate commercial solutions were available on the market. Other parts are standard industrial components which had to be replaced or upgraded to be compatible with recent standards. Most of the work could be completed and tested; there are, however, challenging issues still to be solved. The integration of the entire ECRH-system into the Wendelstein 7-X control system has commenced. The parallel operation of all gyrotrons and the integration of front-end transmission components in the towers still need to be tested.

8.1.3 The N-port Remote Steering Launcher R&D ('Verbundprojekt')

ECRH and ECCD in a poloidal plane with low or vanishing magnetic field gradient offers the possibility to investigate particular physics issues such as the confinement of trapped and passing particles. Theoretical studies showed that the different behaviour of the two particle species with respect to current drive and confinement can be nicely distinguished by scanning the launch angle of the incident rf-beam. The transmission system was therefore designed to allow switching of two out of total 10 rf-beams towards special launchers at the N-ports, which are located in a poloidal plane with weak magnetic field gradient. Access to the narrow N-ports is only possible with "remote-steering" launchers (RSL). The theoretical investigation of the RSL-concept and high power, cw tests are important also in view of future ECRH-applications in a radioactive environment e.g. in DEMO. The area of the plasma facing RSL front end is small and movable parts and steering mechanisms are avoided inside the vacuum vessel with the hostile environment of a burning plasma. The rf-power density of RSL-arrays is typically 100 MW/m^2 as compared to front steering launchers with about 10-20 MW/m^2. Only small ports are therefore required to supply future fusion devices with the necessary microwave heating power. The remote-steering properties are based on multi-mode interference in a square waveguide leading to imaging effects: For a proper length of the waveguide which matches the Talbot condition, a microwave beam, which is fed at the input of the waveguide with some inclination with respect to the waveguide axis will exit the waveguide under the same, but opposite angle. Making use of these imaging features, the steering mechanism for the microwave beam can be located remotely outside the vacuum vessel. The drawback of the RSL-concept is a reduced steering range as compared to front steering launchers and a somewhat larger beam size.

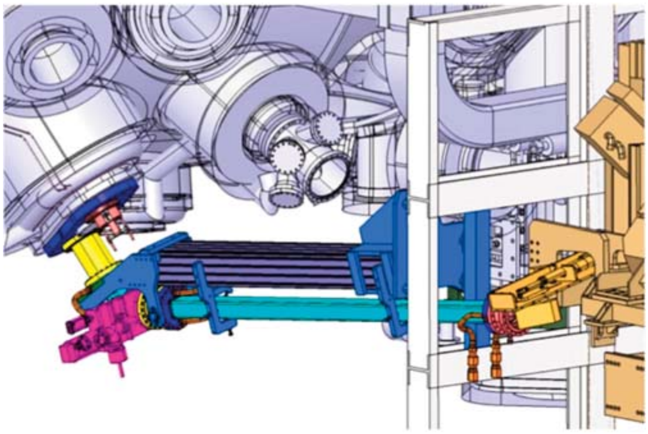

Figure 22: Arrangement of the N-Port Remote Steering Launcher. The RSL is fed from the beam distribution optic in the ECRH tower at module 1, shown on the lower right side.

An R&D project was thus established with preferential support by the BMBF to investigate, develop, manufacture and operate an RSL with 1 MW, cw transmission capability, extended steering range by optimization of the cross section, and low loss by optimization of the waveguide corrugation profile. A CAD-sketch of the RSL-design for Wendelstein 7-X is seen from figure 22. Bends, which are mandatory for dogleg structures embedded in radioactive shields in DEMO-type devices (not required for Wendelstein 7-X), and gaps for integration of fast shutters are part of the design to demonstrate the reactor compatibility; details are seen from figure 23. The project combines the expertise of two research laboratories, IGVP, University of Stuttgart, and IPP, respectively, and two industrial partners, NTG Neue Technologien GmbH und Co. KG and Galvano-T GmbH. Significant progress was made with respect to optimization of the waveguide characteristics and development of innovative manufacturing processes, which are compatible with the demanding accuracy requirements. For further details, see the report of IGVP, University of Stuttgart, this issue.

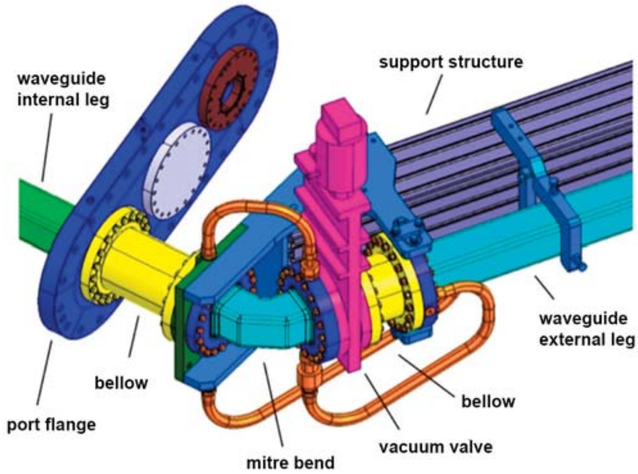

Figure 23: Detail of the RSL. The mitre bend and the vacuum valve are seen, respectively, together with the support structure mounted in the lower part of the N-Port flange. The upper section will house the immersion tube for the IR-camera.

8.1.4 In-vessel Components (IPP/IPF)

The four ECRH-plug-in launchers have been equipped with silicon oil manifolds for the cooling of the diamond disc vacuum barrier windows. Silicon oil cooling is mandatory to prohibit corrosion of the brazing at the diamond metal interface. Each window is equipped with a vacuum shutter for safety reason. The vacuum measurement and pumping valves for each shutter were also installed. The thermal isolation and the electric flange heating for the vacuum bake-out have been defined. Cabling and pressured air connections have been completed. Each launcher will be equipped with a video system for protection, which will observe the microwave exposed heat shield in front of the launcher. The video cameras must be positioned inside compact immersion tubes with their optics in front of the launcher. The design of the immersion tubes has been finished and fabrication has started. It fulfils the requirements of strong microwave environment und high plasma radiation. Even if the most critical component, the sapphire window, breaks, the immersion tube can be closed and externally vacuum pumped. Thus machine operation is still possible. Several compact cameras have been tested in the 3 T magnetic field of a gyrotron magnet. A near infrared video camera was chosen to be installed in the immersion tubes, since it allows temperatures measurement already above 320 °C. The electron cyclotron absorption (ECA) diagnostics (128 waveguides), which measures the transmitted ECRH power, the beam position and polarization, was assembled inside the plasma vessel. Eight compact amplifier boxes with 16 channels each have been manufactured at the IGVP Stuttgart University. These boxes have been mounted on the protection housing of the ECA-diagnostic outside the vacuum vessel.

They guarantee a high signal to noise ratio at the ADCs located in the ECRH-towers. The design of the microwave stray radiation monitors, so called sniffer probes, was finished. The manufacturing drawings are presently being produced. The required wide angle antenna sensitivity could be achieved by inserting a transmitting random phase plate (Schroeder diffusor) into the microwave optic system.

8.1.5 Staff

Staff at IPP (Wendelstein 7-X-HT and ITZ): B. Berndt, H. Braune, V. Erckmann, F. Hollmann, L. Jonitz, H. P. Laqua, G. Michel, F. Noke, M. Preynas, F. Purps, T. Schulz, T. Stange, P. Uhren, M. Weissgerber.
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Staff at IGVP (Stuttgart University): W. Kasparek, C. Lechte, R. Munk, B. Plaum, Z. Popovic, H. Röhlinger, F. Remppel, K.-H. Schlüter, S. Wolf, A. Zeitler.

8.2 ECRH Contributions (IGVP Stuttgart)

8.2.1 Gyrotron Beam Matching and Transmission Diagnostics

Work for beam diagnostics and power measurement of the gyrotron beams continued. Concepts for 2-frequency sensors were followed, and linearization amplifiers for the detectors were built. For the receivers attributed to the directional couplers on the mirrors M14, the conical scan mechanics and electronics for the alignment control were further developed. For gyrotron SN7 and S5R2, which had been delivered to KIT for acceptance tests, beam characterization and phase retrieval was performed. Both gyrotrons finally were not accepted. SN7 had a strongly structured output beam with low Gaussian contents and high stray radiation, which did not allow long pulses. Nevertheless, the time until rejection of the tube was used to upgrade the PROFUSION program package, and to design phase-correcting surfaces for matching mirrors.

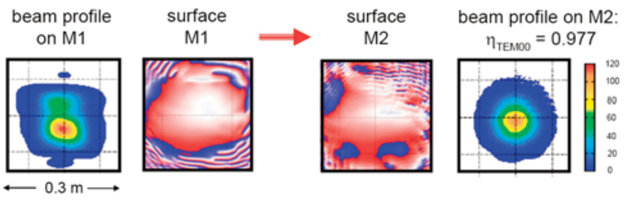

Figure 24: From left to right: Gyrotron SN7 output beam profile at position of mirror M1; Phase profile for surface of M1; Phase profile for surface of M2; Beam profile on M2, with 97.7 % TEM00 contents.

As can be seen from figure 24, surfaces for the matching mirrors could be designed, which in principle – for perfect alignment and without aberration due to curved mirrors – allow a conversion of the gyrotron beam with a TEM00 contents of about 80 % to a good Gaussian beam with a mode purity of 97.7 %.

8.2.2 Remote-steering Launchers for ECRH on Wendelstein 7-X

Development and tests of the remote-steering launchers (RSL), which are being built for ECRH on Wendelstein 7-X (see figure 22 of this report), were pursued further. The RSLs will be fed from the main transmission via one (RSL1) or two reflectors (RSL5), respectively. The design of the reflectors was performed, and fabrication is under way. A cooling technique as used for the Wendelstein 7-X transmission will be used, i.e., stainless steel mirrors with cooling channels milled into the basic surface, subsequent copper coating and final machining of the surface. The RSL1 in Port AEN10 will consist of two straight corrugated square waveguides (total length 4.6 m) which will be connected via mitre bends to fit the antenna into the available space at Wendelstein 7-X. The beam steering at the entrance of the square waveguide was optimized, as for a standard feed beam pivoting around the centre of the input aperture, the imaging characteristics of square waveguides diminish at angles $|\varphi|>12°$. The optimized beam steering at the waveguide entrance aims at a symmetric field distribution in the waveguide. This leads to a steering range of $|\varphi|\leq 14.5°$; simultaneously the transmission loss at the gap in the vacuum valve is minimized. The structure of the grooves in the mitre bend walls was optimized for minimum mode conversion and cross-polarisation. For RSL5, further optimization is underway. The imaging characteristics of the RSL waveguides depend on the dispersion of the waveguide modes, which are excited by the input beam. For square waveguide, the phase slippage of the modes increases strongly for $|\varphi|>12°$; therefore a numerical optimisation project using the IPF-FD3D and the PROFUSION code was started. The goal is a waveguide cross-section, which exhibits a mode dispersion guaranteeing a large steering range.

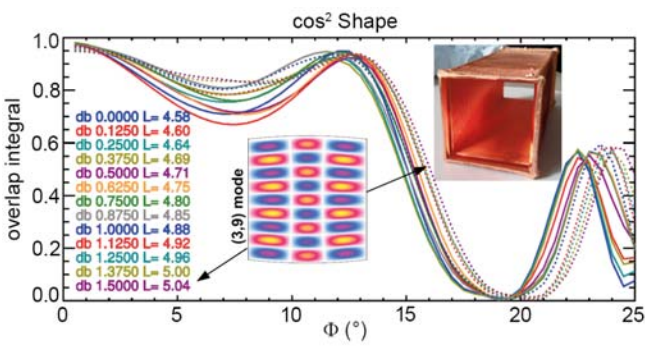

Figure 25: Moderate improvement of steering range as a function of deformation amplitude db. The overlap integral is a direct measure of the output beam quality. Also shown is the eigenfunction for a (3,9) mode at db = 1.5 mm, and a picture of a waveguide test piece.

Figure 25 shows the effect of increasing amplitude of a cos2-deformation on the quality of the output beam. A moderate increase of the steering range of 1.5 degrees compared to standard square guide is obtained; at present, other deformation types are investigated.

The waveguide parts will be manufactured from copper by electroforming techniques. This method is well suited for long, vacuum compatible, corrugated waveguides, which need relatively strong water cooling. At the partner companies NTG, Gelnhausen, and GT, Windeck, a mock-up of a 2 m waveguide was successfully produced, and several short pieces were manufactured, as a reasonable compromise between robust design and low loss has to be found for the corrugation profile. For this purpose, various corrugation profiles had been optimized, and three of them were chosen for further investigation with respect to easy manufacturing by electroforming, absorption, and phase shift between the polarisation perpendicular (TM) and parallel (TE) with respect to the grooves. Results from resonator measurements for a corrugation profile are shown in figure 26 (left).

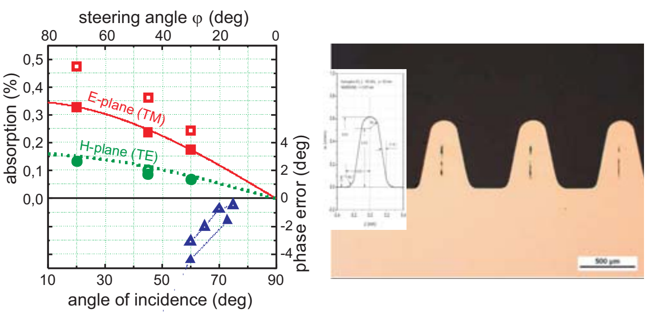

Figure 26: Left: Measured absorption and phase deviation from 180° for waveguide walls with corrugation E4. One can see that strong electro-polished samples (solid squares, circles) have lower absorption compared to slightly polished samples (open symbols), and are close to theory (lines). However, strong polishing leads to a reduction of the groove depth, and thus to higher phase errors (triangles). Right: Cross-section (drawing and polished cut image) of the chosen corrugation profile (E5).

Here, the comparison between two identical samples, but with different electro-polishing clearly shows the influence of the polishing process on surface roughness (thus reduction of absorption) and groove depth (reduction of phase shift). Meanwhile, a corrugation profile has been identified, which has an average absorption for a single reflection at the reference steering angle (φ=12°) of only 0.052 %, and a phase error below 2° within the complete steering range (|φ|<23°). Figure 26, right, shows a cross-section.

8.2.3 Advanced Antennas for Reflectometry

Design work for the quasi-optical antennas for Doppler reflectometry was performed. For a broadband (50-110 GHz) performance of such antennas, feed horns were optimized, which feature frequency-dependent Gaussian beam parameters, but a constant Rayleigh length (see figure 27). By using a Gaussian imaging system with an odd number of focusing mirrors, the inevitable shift of the beam waist of these horns is transferred such that the position of the waist in the plasma follows the probing location, when the frequency of the reflectometry system is varied.

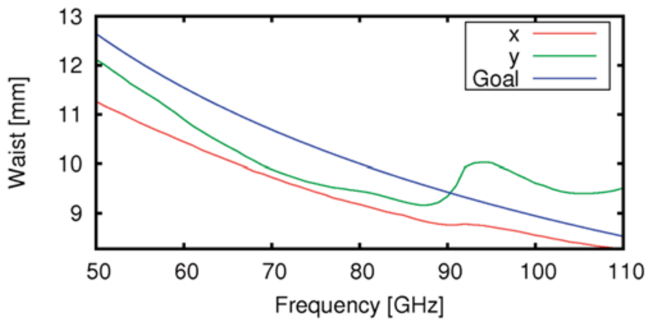

Figure 27: Waist radii of an optimized Gauss horn. The target function for the waist was w_0=10 mm · √(80 GHz/f), which corresponds to a frequency-independent Rayleigh length.

For Doppler reflectometry at various probing angles, the concept for a 32-element phased array antenna has been developed further. This activity is performed within the Virtual HGF Institute "Plasma Dynamical Processes and Turbulence Studies using Advanced Microwave Diagnostics", and aims at fixed antennas with Gaussian beam characteristics and angular steering actuated by small frequency variations. Application at Wendelstein 7-X as well as ASDEX Upgrade is planned. After a successful test of a first prototype, another two helical series feeds have been manufactured to investigate possible approaches for reducing internal reflections. To meet the requirements of a realistic profile measurement, antennas with a higher frequency agility of about 41 °/GHz are in fabrication; a compact design mandatory for installation in the narrow ports is employed, as indicated in figure 28, left.

Figure 28: Left: Revised design of a helical series feed with a larger helix diameter. Right: Stacked copper and aluminium sheets of the 32-element horn array before electro-forming.

Simulations are used to examine the implications of any design changes and possible design improvements. Moreover, a prototype of the 32-element horn array that is to be used with the feed has been designed and is being manufactured.

It is realised by alternatively stacking copper and aluminium sheets (figure 28, right), and connecting the copper sheets by galvanic copper. The structure is then milled into the desired shape and, finally, the aluminium sheets are dissolved, such that 32 H-plane sectoral horns are formed.

8.3 Ion Cyclotron Range of Frequency Heating

An ion cyclotron range of frequency heating system is planned to be available for experiments, with the aim to be ready for use starting from operational phase 1.2. This system is to facilitate fast wave heating with absorption mechanisms that are accessible with a generator frequency of 25 to 38 MHz at magnetic fields on axis of generally 2.5 T, i.e. D(H), H(He3). The complete system is being developed, designed, built, and commissioned within the framework of a collaboration with the Trilateral European Cluster under the leadership of ERM/KMS Brussels. It makes use of one, possibly two RF generators and other surplus equipment of TEXTOR useful for Wendelstein 7-X. The generators will be connected to one double strap antenna in the plasma vessel. The system should be able to operate for pulse lengths of about 10 sec every five minutes at a maximum RF power per generator of 2 MW or longer time at reduced power. In 2013 the conceptual and preliminary design of the antenna was further advanced. The antenna completely fits into one of the largest ports of Wendelstein 7-X that have an inner usable width of about 39.5 cm. Computer codes for wave excitation, coupling, propagation and absorption have confirmed that a double strap antenna of a toroidal width given by the available port size should be able to radiate up to 1 MW of power depending on the plasma density profile in front of the antenna. Only the graphite side limiters have to be installed from inside of the plasma vessel after the antenna has been mounted in the port. The plasma radiation exposed areas of the antenna are actively water cooled to withstand 30 minute long plasma discharges at an average heat load of 100 kW/m^2. The two straps are resonantly connected to variable capacitors to produce a pre-matching close to the antenna in order to lower the voltage standing wave ratio in the transmission lines. The complete antenna can be moved radially for about 30 cm by remote control even in the presence of the magnetic field to facilitate good wave excitation at the plasma edge for all reference magnetic configurations of Wendelstein 7-X. Various electromagnetic calculations and comparisons with measurements on real models in a scale of 1:4 have been done to optimize the geometry of the antenna, the transmissions lines and the capacitors for low voltages over the whole frequency range of operation.

8.4 Neutral Beam Injection

In 2013 a decision by the management board of Wendelstein 7-X split the first operation period of the machine into two phases (operational phases OP 1.1 & OP 1.2). The cooling of the beam duct protection will not be available during OP 1.1; therefore, the start of NBI operation has been shifted to OP 1.2 in the summer of 2016. The NBI group focused in 2013 on the goal of going into operation in OP 1.2 with 1 injector box with 2 ion sources while at the same time having the second injector box as complete as funding allowed. Pre-assembly of the neutral beam injector boxes in the NBI hall is nearing completion with the installation almost complete for all parts that are possible to be installed there. The cabling of the sensors and controls has begun for the boxes and the secondary vacuum system. The magnetic shielding – both interior and exterior – has been completed for both boxes. The assembly work for the NBI inside the torus hall is ongoing. The work on the installation of the cooling water pipes has started. It was planned to install the box support structures in the summer of 2013, but concern over the damage to the concrete reinforcement bars in the torus hall floor during the drilling of the anchor boltholes delayed the drilling process significantly. With the help of an external company, it was possible to map the position of the steel reinforcement bars. The boxes are now expected to be installed in the torus hall in the summer of 2014. The last components necessary for making the connection between the injector box and torus beam duct have been designed and the manufacturing has been put out for tender. The motors for moving the calorimeter up and down have been delivered to Greifswald and are currently being cabled. They will be tested in the early part of 2014. The collaboration with the Polish institute NCBJ Swierk, which was was highly successful, has been completed. The cooling water system, which was designed and manufactured by the Polish company INSS-POL, was installed and successfully commissioned in the NBI hall basement. Final tests of the cooling water system require that the torus hall pipe work is finished. They will occur after the installation of the injector boxes have been in the torus hall. The injector boxes gate-valves (VAT, Switzerland) and heating system (PREVAC, Poland) were delivered and have been installed on the boxes. The two ion reflection magnets (TESLA, Great Britain) were delivered and are in storage. Lastly, the injector box support structures (TEPRO, Poland), together with their hydraulic position adjustment system, have been delivered to Greifswald and are awaiting installation in the torus hall. Work has started on the control system for two sub components: the secondary vacuum system and the gas system. As the principle mechanical systems will be complete in 2014, the focus of the group will shift to the control system and data acquisition. A test facility for the AC driven Ti sublimation pumps has been completed in Garching, and test results show that it is possible to operate the pumps even in the presence of the Wendelstein 7-X magnetic field. Procurement of the necessary AC power supplies has begun. The HST and thermocouples in the beam dump and duct project progressed well over 2013. The thermocouples for the beam dump and duct have been handed over to Assembly for installation in Wendelstein 7-X. The immersion tube, fibre optical cables, and pyrometers for the HST have been purchased and have been delivered to HGW. Progress has been slower on the HST due to the shifting priority in the project in terms of getting designer time, but ongoing good support from the diagnostic engineering departmentshould enable the project to be completed in time for beam commissioning on Wendelstein 7-X. A master's student, Ms. D. Gradic (Greifswald University), worked with the NBI group to determine if it would be possible to use the Wendelstein 7-X neutral beam system to ignite a plasma without ICRH or ECRH pre-heating. Her thesis work was completed this year, with the conclusion that the time required to ignite a plasma in Wendelstein 7-X greatly exceeded the time allowable by the beam dump. The time restriction exists due to the high thermal power loading of the beam dump when no plasma exists to absorb the neutral beam energy.

9 Diagnostics

The work focused strongly on the in-vessel diagnostics and the diagnostics necessary for safe operation or indispensable for the physics goals of the first operational phase OP 1.1 to take place in 2015, with the next operation phase OP 1.2 scheduled for 2016-2017. The following sections briefly summarize the main activities of the Diagnostics subdivision (DIA), which consists of three departments, "Edge and In-Vessel Diagnostics" (DIA-EIV), "Core Diagnostics" (DIA-COR), and "Diagnostic Engineering" (DIA-ENG).

9.1 Edge/Divertor and Magnetics Configuration Diagnostics

9.1.1 IR/visible Divertor Observation

The contract to build two long-pulse compatible IR/visible endoscopes for divertor temperature control and imaging has been awarded to the French company Thales-SESO early 2013. The development of these systems is progressing on schedule. Their installation on Wendelstein 7-X for OP 1.2 is foreseen in the second half of 2015. The contract for the two, fast infrared cameras for these endoscopes has been awarded to the company Infratec and they will be delivered in April 2014. A further set of 10 simplified IR/VIS systems, with IR micro-bolometer and visible cameras being installed directly behind the three observation windows at the plasma facing end of a 2 m long immersion tube with a rotating shutter, has been manufactured by the company TRINOS for limiter observation in OP 1.1 and the tendering for the high magnetic field compatible cameras (2.5 T) has been launched. Eight of these systems together with the two endoscopes from Thales-SESO will be used for divertor observation in OP 1.2. The 10 simplified systems will be installed on Wendelstein 7-X in summer 2014.

9.1.2 Video Diagnostic

During 2013 six of the ten front-end components of the video diagnostic have been installed in the plasma vessel. The video diagnostic camera systems developed by MTA WIGNER RMI, Budapest, Hungary, will be installed in the AEQ ports in all ten half modules of Wendelstein 7-X, and will enable the observation of almost all of the plasma facing first wall. In 2013 the main emphasis was put on the development and testing of the intelligent camera firmware and software. With the new firmware the camera can already record simultaneously movies of different regions of interest (ROIs) at different readout frequencies. The real-time event processing, directly within the EDICAM camera head, has also been improved considerably, and now works reliably to detect ROIs of several relevant kinds, such as hot spots. Demonstration tests are ongoing. A new software interface for camera control has also been developed, featuring both, a console and a GUI application.

9.1.3 Magnetic Diagnostics

The detailed design of all 126 Mirnov coils for the first operation phase, including cable routing, has been completed. In total 120 coils have already been assembled and calibrated, 90, of which have been mounted on the wall protection panels. 14 out of the 32 wall panels that include Mirnov coils have been installed in the machine. The design of the in-vessel magnetic diagnostics (Rogowski coils and diamagnetic loops) has been almost completed. The manufacturing of most and the integration of the major part of these diagnostics has been achieved in 2013. Tests with a prototype integrator and data acquisition module for the magnetic equilibrium diagnostics have been successfully completed.

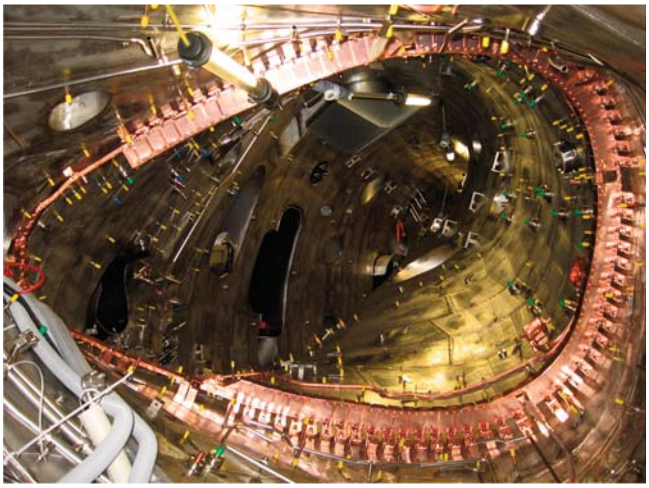

Figure 29: Diamagnetic loop with compensation coils. The sophisticated design, using a ceramic compound support structure and a common copper and steel housing, will provide shielding against microwave radiation and good thermal contact to the plasma vessel for quasi-continuous operation, without impairing the required time resolution of the compensation coils.

The placement of the electronic racks for the magnetic diagnostics within the torus hall has been fixed, and the necessary signal cables within the torus hall have been defined.

9.1.4 Flux Surface Mapping

The design of the diagnostic has been completed and manufacturing and procurement of the components started. The main components of the vacuum barrier, the inner support structure and the first actuator have been delivered. The installation of the in-vessel components and the welding of the fixing studs inside the ports are ongoing. The electron gun has been successfully tested within a magnetic field of 2.5 T.

9.1.5 Segmented PWI-target Fingers

16 modified exchangeable carbon divertor target fingers will be installed in the TDU as a plasma-wall interaction diagnostics in OP 1.2 to measure erosion of the divertor and to gain information on transport and re-deposition of the divertor and wall materials. The positions for 16 segmented fingers have been selected and the individual lengths been determined.

9.1.6 Target Integrated Flush Mounted Langmuir Probes for TDU Phase (OP 1.2)

All cable protection tubes as well as the cable connector unit have been mounted on the plasma vessel and inside the ports. The manufacturing of the cabling up to the connector plug has started.

9.1.7 Fast Reciprocating Probe System

The system will allow quantifying parallel plasma profiles and the flow characteristic in the scrape-off layer of the Wendelstein 7-X island divertor. The fast linear probe carrier has been developed at FZ Jülich as part of a multipurpose manipulator. This system will be located at the upstream position between the two versatile gas inlet locations used for the thermal helium beam and as divertor gas fuelling system. A principal solution for the support of the manipulator at Wendelstein 7-X has been found. In a Conceptual Design Review the overall design concept has been approved. The final development and the manufacturing drawing process have been started. The system is scheduled for implementation for OP 1.1.

9.1.8 Neutral Gas Pressure Gauges

Design, manufacturing drawings, and specifications for the six gauge systems have been finished and the tender for their manufacturing has been launched.

9.1.9 Thermal Helium Beam and Divertor Gas Fuelling System

Both gas manifolds including the entire gas feedthroughs and the vacuum adaptation systems were manufactured at FZ Jülich and delivered to IPP in December 2013, where the final UHV tests before their installation in Wendelstein 7-X are presently being performed. The control software for the piezo-valves has already been implemented by FZ Jülich. The control software for the periphery gas supply station will be developed by FZJ in 2014. A conceptual design of the gas supply station has been developed. It is planned to install both He-beam plug-ins at Wendelstein 7-X and build the gas bottle station by June 2014, so that the diagnostic can already be used in OP 1.1 as a fast fuelling system and for experiments on edge radiative cooling.

9.1.10 Thermal He-beam and Visible Spectroscopy Systems

FZ Jülich is developing optical endoscopes as versatile observation systems. A conceptual design has been made. The development of the optical setup has progressed and a proposed detailed design is available. The endoscopes will be used as observation systems for the thermal helium beam diagnostics, employing the versatile gas inlets, as well as for tomographic reconstruction of spectral line emission in the island divertor domain. The exploration of the emissivity and line strength using EMC3-Eirene is on-going. The conceptual design review will take place in the first quarter of 2014.

9.2 Microwave and Laser Based Diagnostics

9.2.1 Interferometry

The line-integrated density will be measured with a dispersion interferometer. This type of interferometer does not require a reference path, is inherently robust against mechanical vibrations and allows for an intermittent signal loss during long-pulse discharges. The mechanical support structure, consisting of vertically standing granite plates and an Al-support frame, has been set-up in the laboratory. This allowed for successful test operation of the vertical dispersion interferometer arrangement. This single channel dispersion interferometer is being prepared for operation in OP 1.1, while the first four channels of the multichannel dispersion interferometer are being prepared for OP 1.2.

9.2.2 Electron Cyclotron Emission (ECE)

The ECE system allows determination of the electron temperature from the blackbody cyclotron radiation emitted by the plasma with high time resolution and good spatial (radial) solution. A particular feature for Wendelstein 7-X is the high-field-side antenna, which allows a detection of non-thermalized electrons, e.g. related to ECR heating. This antenna is integrated into a carbon tile of the wall heat shield. Most of its in-vessel components, including the waveguides and the vacuum feed through, have been installed.

9.2.3 Reflectometry

Reflectometry measures plasma density profiles, density turbulence and its propagation velocity by microwave signals reflected from the cut-off layers in the plasma. Reflectometry for Wendelstein 7-X is embedded on the one hand within the framework of the Helmholtz Virtual Institute on Advanced Microwave Diagnostics, here with particular contributions from FZ Jülich and the IGVT Stuttgart, and on the other hand in a bilateral cooperation with CIEMAT in Spain. A diagnostic plug-in with a fast angular-scan Doppler antenna as K-spectrometer for turbulence measurements is prepared at IGVT. A correlation reflectometer including a plug-in with the required microwave antenna array will be provided by FZ-Jülich. The design of the versatile Gauss mirror optics has been completed together with IGVT. For the first operation this optics will be used for the Doppler reflectometer supplied by CIEMAT.

9.2.4 Thomson Scattering

The “Thomson Bridge” support structure has been completed and installed. The bridge serves as central support structure for the Thomson scattering diagnostic, supports the retroreflector of the single-channel interferometer, and provides access to the Wendelstein 7-X machine centre. All in-vessel components have been manufactured, qualified and assembled at Wendelstein 7-X.

9.3 Core Spectroscopy

9.3.1 RuDI-X, CXRS, NPA

The commissioning of the Russian Diagnostic Injector for Wendelstein 7-X (RuDI-X) and the high voltage power supply at a test stand outside the experimental hall has been completed and the system finally been accepted. The next steps before commissioning at Wendelstein 7-X will be the integration of Wendelstein 7-X requirements for control and safety and the assembly of the infrastructure inside experimental hall. RuDI-X provides an energetic beam of neutral particles required for active charge exchange recombination spectroscopy (CXRS) and charge exchange neutral particle analysis (CX-NPA). For the CXRS-system, the concept of the optical layout has been completed, and the quartz fibre bundles have been ordered. The immersion tube for the port AET41 has been manufactured by an external company. Presently, the leak and baking tests of this tube are being performed.

9.3.2 HEXOS

The VUV/EUV spectrometer system HEXOS was transferred from FZ-Jülich to Greifswald and has been successfully installed in the Wendelstein 7-X torus hall. The lines of sight were properly adjusted and the port flange vacuum barrier has been closed. It is planned to install the two HEXOS racks inside the torus hall early 2014.

9.3.3 X-ray Imaging Spectrometer

The high resolution X-ray imaging spectrometer (provided by FZ-Jülich) was included in the torus hall space reservation. Changes in the spectrometer support and modifications to the spectrometer vacuum system are foreseen to avoid a potential collision with the ECRH tower. The necessary design work packages are scheduled for the beginning of 2014. The beam line components, including required modifications to the port flange lid, for the installation of the spectrometer on the Wendelstein 7-X port have been designed and are being manufactured. A new type of imaging X-ray spectrometer (XICS) at Wendelstein 7-X will be supplied by PPPL (US).

9.3.4 Bolometer

Two bolometers will allow tomographic reconstruction of the total plasma radiation profiles in the triangular plane of the plasma vessel. The main components of the camera system have been manufactured. Assembly tests in the corresponding ports at Wendelstein 7-X have been successfully performed. The shutter tests at room temperature and in air for the vertical bolometer have been finished, the tests in vacuum at 150 °C are planned early 2014. For the horizontal bolometer system the manufacturing of the cooled front plate, containing the camera pinhole, and the manufacturing of the detector housing, as well as the redesign of the shutter, are ongoing.

9.3.5 Soft X-ray Tomography XMCTS

All mechanical components for the in-vessel soft X-ray multi-camera tomography system (XMCTS) have been manufactured. The assembly and installation drawings have been completed. The 4 port plug-ins have been manufactured and installed. The in-vessel pipe-work has been joined with the plug-in hoses, allowing for a later integration of the support frames with the cameras. Following the detection of a leakage in one of the hoses, a fast repair of the affected port plug-in could be conducted at the ITZ in Garching and the repaired plug-in was reinstalled. The assembly of the support frames was rescheduled for an installation prior to the start of OP 1.2.

9.3.6 X-ray Pulse Height Analysis (PHA) and Multi-foil Spectroscopy (MFS)

The main components for PHA-diagnostic have been manufactured and put together in the laboratory of the cooperation partner IPPLM in Warsaw. First tests of the filter changer with the wobble-stick mechanism have been successfully completed. The calibration sequence of the silicon drift diode detectors by x-ray fluorescence of material coated on the backside of the last aperture, which is illuminated by a mini X-ray tube, demonstrated the method of in-situ obtaining a calibration curve for the x-ray energy spectrum. The design of the MFS-diagnostic has been modified to allow direct mounting to the Wendelstein 7-X port. The manufacturing of the components is in progress.

9.3.7 Neutron Counters

The support structures for the two outer neutron monitors have been fixed on the cryostat vessel of Wendelstein 7-X, whereas the support structure for the central monitor is under construction by an external company. The main parts of neutron monitors themselves have been delivered and test-assembled by ITZ-Garching. The MCNP calculations as basis for the specification of the counting tubes have been finished by PTB Braunschweig and the ordering process has been started. In preparation of the in-situ calibration a space saving support system for the rails was developed. The cooperation contract with the PTB Braunschweig has been prolonged by two years. During OP 1.1 of Wendelstein 7-X only a single line-of-sight for Z_{eff} determination from visible Bremsstrahlung will be installed on the coaxial port pair AET40/AEZ40. Due to this arrangement the measurements will not be affected by any wall reflection since the opposite port serves as the viewing dump.

9.3.8 Coated Screws

All (≈31.000) TZM-screws for fixing the carbon tiles to the Wendelstein 7-X baffles and heat shields have been coated with an amorphous carbon layer to avoid erosion of TZM, which could have led to an influx of molybdenum into the plasma. The coating process at Fraunhofer IST had been accompanied by laboratory investigations at IPP for quality assessment.

9.4 Collaborations

FZ-Jülich, Germany: HEXOS, High resolution X-ray imaging spectrometer, thermal He-beam diagnostic, fast reciprocating probe
Budker Institute, Novosibirsk, Russia: RuDI-X
MTA WIGNER RMI, Budapest, Hungary: Video Diagnostic
IPPLM, Warsaw, Poland: PHA and MFS diagnostics
University of Opole, Poland: C/O monitor
Henryk Niewodniczanski Institute of Nuclear Physics (IFJ PAN): C/O monitor detectors
CIEMAT, Madrid, Spain: Interferometry
PTB Braunschweig, Germany: Neutron counters
IOFFE, St. Petersburg, Russia: CX-NPA
LANL, USA: Infrared cameras
Tech. U. Eindhoven, Netherlands: ECRH stray radiation detectors
PPPL, Princeton, US: XICS

10 Operations

This new sub-division was established in October 2013 in order to prepare the commissioning of Wendelstein-X. Also the CoDaC-department as a central service group belongs to this division.

10.1 Device Operation

The device operations department is preparing the integral commissioning of Wendelstein 7-X. In 2013 a task force under the lead of the chief engineer has prepared a master plan for commissioning, containing the sequence of the commissioning phases (see figure 30). These phases are now being detailed by the respective responsible officers of the systems, resulting in a work breakdown structure and a commissioning assurance template (CAT) for each single system. The CAT describes all the necessary steps to perform the integrated commission of a single system into the Wendelstein 7-X. A process instruction for the integrated commissioning of Wendelstein 7-X has been developed, including a definition of the necessary documentation.

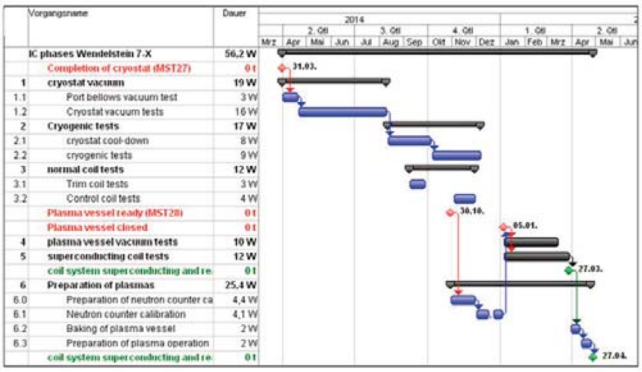

Figure 30: Master Plan for the Commissioning of Wendelstein 7-X.

The device safety group within this department plans, implements and leads the processes that are required to ensure safe operation of the Wendelstein 7-X device. In 2013, significant progress has been achieved in preparing the safety analyses of the main components and systems. In the process of performing the safety assessments, several additional technical and organizational measures to ensure safe operation have been proposed for implementation.

10.2 CoDaC

The department Control, Data Acquisition and Communication (CoDaC) has mainly worked on the preparation of the Wendelstein 7-X commissioning phase. This comprises the establishment of the required infrastructures, planning of the commission steps with respect to CoDaC components and the finalization of the software packages for the application during comissioning. Developments based on new requirements have been postponed to the operational phase of Wendelstein 7-X and the focus has been laid on the consolidation of the software packages. A strong prioritization of CoDaC work packages in compliance to the commision plan has been introduced.

10.2.1 IT/EDV

Essential for the operation of the experiment is a network infrastructure that is expandable and capable of streaming all the data with an estimated bandwidth of the order of 1 Tbit/s in the first years of operation. For a future-proof setup, exponential growth of data amount and rates has to be taken into account. Thus, Wendelstein 7-X CoDaC has installed a new data network that has a total routing capacity of 30 Tbit/s and could be even further expanded by reconfiguration into a spine-leaf architecture if necessary. Beside the new central network, a fast data link between the two sites, Garching and Greifswald, has been established. This link is to a significant fraction dedicated for the experiment data transfer to the RZG. It is part of the high performance storage system (HPSS), which moves data from the local parallel file system (GPFS) to the tape library in Garching and back, depending on the configured data policy. The mass storage system for the experiment data archive has been almost completed, and first test are expected for the beginning of 2014. The virtualization technology based on VMware products, which is already in use for the server systems, has been expanded towards desktop systems. The concept of virtual desktops meets the requirement to move the session on a personal computer between the control room and the office while keeping the actual session running. Each workplace is equipped with a generic zero client and the PC itself is running as a virtual machine on servers, which are equipped with high performance graphics cards. Virtual Desktops on the basis of VMware View 5.3 have been set up for preparation the roll out of such systems. A further requirement to make use of 3D graphics for scientific purposes and to use a mixed set of Windows and Linux computers as personal computers for data analysis/assessment in the control room could be easily fulfilled with these systems.

10.2.2 Control and Data Acquisition

10.2.2.1 Central Control and Frontend Systems

The developments have been mainly focused on the preparation of the commissioning phase. For this purpose, the hardware of the central control systems has been set up, which comprises the cubicles and visualization of the central safety system (cSS) and the central operational management (cOPM). A safety matrix system has been installed for the cSS for an efficient setup of the safety logic and for a proper structure in the implementation of this logic. A fast interlock system has been developed and implemented, that is required for plasma interlocks on time scales faster than the PLC cycle times (programmable logic controller). Beside the hardware installation of the cOPM, the implementation of the Wendelstein 7-X operational states has been started and is conducted by employing the programming language PCS7 for the Siemens PLC (S7-400).

Progress has been made in the implementation of the frontend systems and Interfaces to such systems. For the ECRH frontend system, the segment programming planning has been implemented into the experiment program editor, which required the development and embedding of so called component models. Such a model allows a convenient and aggregated programming of the set points of all gyrotrons. The cubicles of the flux surface measurement systems have been set up and prepared for tests. The diagnostic neutral beam injector (RuDIX) has been delivered and a local operational management (lOPM) system for cooling, cryo pumps and safety releases has been implemented. This setup has been used for the on-site acceptance tests of the injector. For the magnetic diagnostics of Wendelstein 7-X, a special version of the integrators with a very low drift and optimized for continuous operation has been developed and tested.

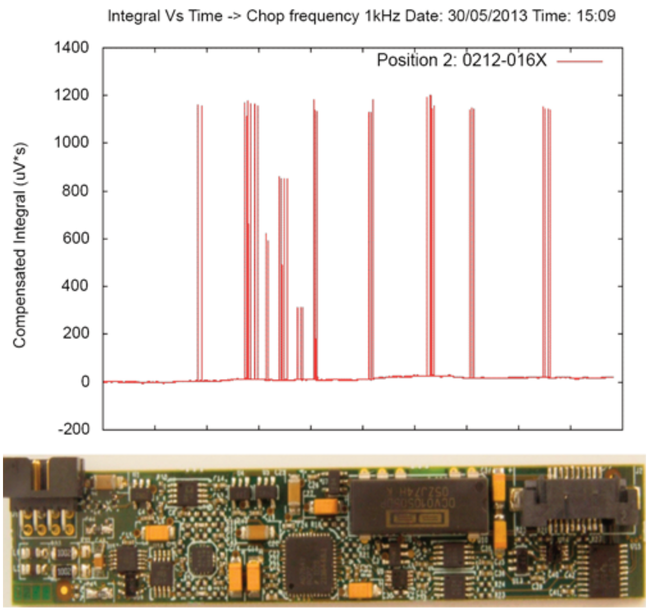

Figure 31: Top: Integrator long pulse test. Bottom: chopper integrator mezzanine module with galvanic isolation (dimensions ~ 100 mm × 20 mm).

Figure 31 shows a typical test case, in which the baseline reveals a low drift and the spikes simulate a signal corresponding to roughly 1 kA net plasma current in Wendelstein 7-X. It was also exactly verified, both, in the laboratory and directly at an experiment that the Integrators can be operated correctly in any position of the expected stray magnetic field of Wendelstein 7-X. The schematics and production files of the ATCA (advanced telecommunications computing architecture) boards, which can carry up to 32 integrator or ADCs, have been prepared. Beside the development of systems in the ATCA form factor, Wendelstein 7-X CoDaC also follows the new emerging MTCA.4 (micro TCA, smaller variant of ATCA) data acquisition (DAQ) standard.

These developments are strongly supported by DESY and first crates and FPGA (field programmable gate arrays) boards have been setup for tests and the final implementation of the dispersion interferometer DAQ system.

10.2.2.2 Software Projects

The CoDaC software stack has undergone a major refactoring with the purpose of consolidation and better maintenance capabilities. The direct objectives are to achieve a better testability for a higher reliability in productive mode and better internal code architecture for efficient expansions in the feature set. The configuration database project, that holds all the control station hardware configuration properties and segment programs, has almost accomplished the transition to a new database management system (DataNucleus/MongoDB) in order to get released from remaining dependencies on ObjectivityDB . Clear interfaces to the applications have been introduced like the CoDaStation (DAQ software), Xcontrol (session leader program), Xedit (experiment program editor), Confix (configuration database administration tool) and JosDaemon (application server for non-Java applications) for the real time control stations. The CoDaStation software in particular is accomplished in terms of a framework that allows the connection to data sources and sinks asynchronously or synchronously with transformation functions on the data streams in between. New interfaces have been implemented to the new archive and configuration databases. The CoDaStation is prepared for its first mission at Wendelstein 7-X to serve as a data collector of the engineering data generation by the operational management PLCs in 24/7 mode. The integration of the first video system, a Pixelfly camera, has been conducted with great success, i.e. collection and transformation of a video stream at low CPU load. For the dispersion interferometry, the network based connection to the FPGA module has been successfully implemented and tested.

10.2.2.3 ArchiveDB

The Wendelstein 7-X scientific and technical archive contains all acquired, analyzed and machine operation related data, and is therefore a crucial project. Activities continued to provide a portable and reliable data archive solution based on publicly available software and to replace the existing proprietary ObjectivityDB. The work has been carried out together with external contractors. A scalable storage system and a scalable network for the expected demands on data rates have been installed successfully. Performance tests have been conducted and write performance bottlenecks could be found and eliminated prior to productive operation. Read performance tests have been started, and a server distribution feature has been developed to support Wendelstein 7-X commissioning and initial operation OP 1.1. The storage of all experiment related parameters has been unified in order to keep the archive domain model agnostic for better maintainability. The backend software layer StreamAccess, designed for fast writing, has been implemented and successfully used during integration tests. The user friendly programming interface SignalAccess has been implemented for convenient reading and already applied for the DataBrowser application and some user applications. The implementation of a migration software for the existing productive data including consistency checks and the data migration of about 8 TB of data is ongoing.

10.2.2.4 Service Oriented Architecture/Databases

Progress has been made on the scientific analyses/modelling framework based on SOA (Service Oriented Architecture) and for the central experiment information databases. The SOA is now being used routinely and offers many services via the ESB (enterprise service bus) like VMEC2000, coil description database, field line tracing and a first prototype of an experiment archive access service. Web interfaces, also capable of 3D graphics, have been added for exploration of these function before integrating them in the user applications. The central Wendelstein 7-X information systems comprise so far a cable management and signal database. The cable management is used routinely for the setup of the Wendelstein 7-X periphery and has 4000 cables in the data set including information on the cable trays and their utilization. For the signal database, which holds information on the logical connections and system models for data analyses purpose, a database schema has been developed and the first prototype is under test.

10.2.3 External Contributions and Collaborations

CoDaC received contributions by the XDV group of the RZG, the University of Rostock for the lTTEv2 and TTE repeater development and for the testing the ATCA based ADC prototype by the Instituto Superior Téchnico (Portugal, Lisbon). The production of the ATCA boards is under procurement and licensed by the Instituto Superior Téchnico (Portugal, Lisbon).

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Princeton Plasma Physics Laboratory (PPPL), USA: T. Brown, B. Ellis, D. Gates, P. Heitzenroeder, K. Hill, S. Langish, S. Lazerson, M. Mardenfeld, D. Mikkelsen, H. Neilson, N. Pablant, A. Reiman, M. Zarnstorff.
Oak Ridge National Laboratory (ORNL), USA: M. Cole, J. H. Harris, A. Lumsdaine, D. A. Spong.
Los Alamos National Laboratory (LANL), Los Alamos, USA: G. Wurden.
Kyoto University, Japan: T. Mizuuchi, S. Murakami, F. Sano.
National Institute for Fusion Science (NIFS), Toki, Japan: T. Akijama, T. Funaba, T. Morizaki, M. Shoji, K. Toi, H. Yamada, M. Yokoyama.

Other Activities in Greifswald and Berlin

At WEGA experiments on plasma startup, OXB-heating and wall conditioning were performed. The major research objectives at VINETA have been studies of guide field effects in driven magnetic reconnection and the development of a high density helicon discharge. In the PAX/APEX project a test beamline for positron trapping has become operational. Work in electron spectroscopy focussed on a quantitative determination of the efficiency of the ICD process.

WEGA

Head: Dr. Matthias Otte

For the preparation of W7-X, plasma start-up using ECRH has been characterized and optimized. The 28 GHz ECRH system enables on- or off-axis heating at the 2nd harmonic in extra-ordinary mode (X2). The main purpose was to investigate which conditions in terms of power and neutral gas characteristics are required for reliable plasma start-up. To achieve this goal and to understand the main physical processes, both experiments and modeling need to be carried out in parallel. The following experiments were performed: i) a parametric study in heating power of 3-9 kW, neutral gas pressure of $0.4\text{-}2.4 \cdot 10^{-4}$ mbar, and a rotational transform $\iota/2\pi$=0.02-0.3, ii) a comparison between hydrogen and helium plasma start-up, iii) and finally on- and off-axis heating comparison. Fastest plasma start-up was obtained with high ECRH input power, low gas pressure and high rotational transform. Significant differences were observed between helium and hydrogen plasma, showing that helium is favorable to be used. A comparison between on- and off-axis heating showed that the initial process is 3D dependent. The experimental measurements are used to develop a model of the plasma start-up and will be compared with similar experiments recently performed on LHD and Heliotron-J. WEGA having the unique capability to be run also as a tokamak, comparative experiments to stellarator configurations were studied. A zero loop-voltage ECRH start-up scenario with small vertical field has been developed in tokamak magnetic field configuration. Further studies were carried out with the aid of microwave diagnostics in electron Bernstein wave heated plasmas with $n_e>10^{19}$ m^3 and a suprathermal electron component around the magnetic axis with energies up to 70 keV. These discharges are accompanied by a broadband microwave emission spectrum with radiation temperatures of the order of keV. Its source was finally identified as a parametric decay of the 28 GHz heating wave during the OXB-conversion process and has no connection to the suprathermal electron component. However, the resultant broadband microwave stray radiation was used for determining the OX-conversion efficiency of the optimized mirror system. The measured values are in good agreement with the theoretical calculations by the IPF Stuttgart. A connection to the suprathermal electrons via electron Bernstein wave emission could be excluded.

Radio frequency discharge conditioning (RF-DC) in both the ion and electron cyclotron frequencies (ICRF and ECRF) has been investigated as preparation for W7-X operation. For the stellarator configuration it is found that He-ICRF-DC (ICWC) for wall desaturation is at least one order of magnitude more efficient than He-ECRF-DC (ECWC). Also for isotopic exchange H2-ICWC is found to be more efficient although here the difference to ECWC is less pronounced. Typical characteristics of ECRF and ICRF discharge production in stellarator and pure toroidal (tokamak) magnetic field configurations could be distinguished via video images.

After more than 12 years of operation and 45.716 shots WEGA was finally switched off to free resources before the commissioning of W7-X.

Diagnostic Development

Work has continued on the development of the imaging MSE diagnostic, a new approach for measuring plasma current distribution in Tokamaks and Stellarators. A prototype IMSE system was constructed in Greifswald and installed at ASDEX Upgrade. Initial results show good agreement with the existing MSE diagnostic and where expected, agreement with modelling.

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) and the series of Coordinated Working Group Meetings has been continued. Joint experiments for the validation of neoclassical transport models have been analysed and documented (LHD, TJ-II, W7-AS). The results indicate for medium- to high density plasmas at high heating powers predominant neoclassical energy transport in the plasma core but differences of radial electric field measurements with ambipolar fields in LHD and TJ-II lead to follow-up studies. An activity has been initiated to develop the physics basis for steady-state discharge scenarios in view of Stellarator-Heliotron reactor operation schemes.

3D Effects in Tokamaks and Stellarators

Joint experiments within the ITPA Transport and Confinement group have been performed (ASDEX Upgrade, MAST, LHD) as well as data mining on DIII-D and KSTAR. Main focus of the research is to understand mechanism leading to so-called "pump-out" and transport changes due to resonant and non-resonant magnetic perturbations. At LHD a new helium beam diagnostic is being installed in order to study 3D structure of the plasma edge near the residual X-point.

Scientific Staff

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VINETA

Head: Dr. Olaf Grulke

Magnetic Reconnection

One major research focus of the studies of magnetic reconnection has been (i) the global evolution of the reconnecting fields and (ii) the development of micro-instabilities. Magnetic reconnection in VINETA is driven by an induced electric field along the X-line. The reconnection current is provided by a plasma gun. In addition to the ambient rf generated plasma ionization from the high energetic electrons in the current sheet cause strongly peaked plasma pressure profiles at the X-line. The associated steep plasma pressure gradients are found to play an important role in the force balance of the reconnection sheet. For small guide fields the current sheet gets strongly elongated along the separatrices due to the changes in magnetic pitch angle. Since the reconnection rate is generally observed to vary with the local reconnection current density, it is not expected to be constant along the plasma but to depend on the axial coordinate. The magnetic diagnostics is currently being upgraded to study the reconnection rates in three dimensions. For large reconnection current densities electromagnetic fluctuations are observed in the current sheet. The amplitudes of those fluctuations depend strongly on the local current density, as depicted in figure 1a, and no significant fluctuations are observed outside the sheet. The observed correlation lengths are short and the fluctuation spectrum is broad displaying a scaling with ion mass. Despite the different geometry and plasma parameter regime the observations are consistent with studies at the MRX reconnection experiment and support the proposed lower-hybrid drift instability as being the underlying instability mechanism.

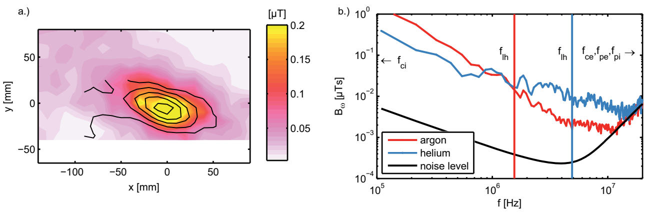

Figure 1: a.) Spatial distribution of high-frequency magnetic fluctuations in the azimuthal plane (color-coded) together with the reconnection current sheet (contour lines). b.) Spectra of magnetic fluctuations for two different ion species (Ar and He). Characteristic frequencies, especially the lower-hybrid frequency f_{lh}, are indicated.

High Density Helicon Discharge

Studies of high density helicon discharges continued. This research is embedded in the AWAKE project, an activity to develop a plasma-based wakefield accelerator using high-energy particle bunches to drive strong electric fields. The accelerating electric field amplitude predominantly depends on the plasma density. For AWAKE a nominal density of $n_{nom}=6\cdot 10^{20}$ m^{-3} is envisaged for a total discharge length of L=10 m. Helicon discharges have been proven as an extremely efficient plasma density source. However, basic power balance calculations indicate that unparalleled helicon wave power densities are required. For the present design of a cylindrical discharge with a diameter of 5 cm approx. 500 kW rf power is required for a 10 m discharge using a set of axially distributed helicon antennas to ensure axial plasma homogeneity. The present studies aim at a proof-of-principle experiment to demonstrate the required power coupling and plasma density. Presently, 24 kW of rf power are coupled into a quarz glass tube of 1 m length using two axially distributed m=+1 helicon antennas. The rf power system follows a strictly modular concept, i.e. each antenna is connected to identical, but individual rf generators and impedance matching networks. The achieved line-integrated central plasma densities as measured by a CO_2 laser interferometer reach approx. $1\cdot 10^{20}$ m^{-3} and its dependence on neutral gas pressure, figure 2a, is in basic agreement with the power balance calculations. The plasma density scales linearly with the ambient magnetic field strength, figure 2b, as expected from the helicon wave dispersion relation.

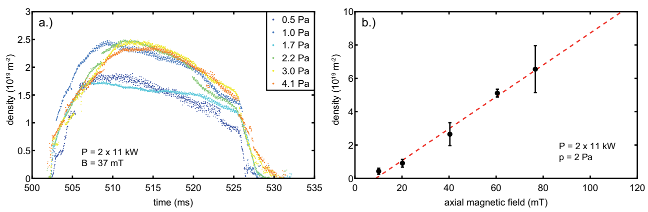

Figure 2: a.) Time evolution of the axial line-integrated plasma density as measured by a CO_2 interferometer over an rf pulse with a total power of 22 kW using 2 antennas. b.) Peak line-integrated plasma density over ambient magnetic field strength.

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PAX, APEX

Head: Prof. Dr. Thomas Sunn Pedersen

In this activity, technologies are being developed for the creation of a pair plasma, composed of an equal amount of positrons and electrons. Interest in laboratory experiments on such plasmas comes both from basic plasma science and from astrophysics. We have laid out a concept for the production of the first such plasma in a laboratory and are working on its implementation in both Greifswald and Garching. Experiments will be conducted at the world's most intense laboratory source for positrons, the NEPOMUC beamline at the FRM II neutron source. A cooperation agreement guaranteeing space for this activity in a new extension of the FRM II experimental area has been signed.

APEX

In 2013, we started prototype studies of *A P*ositron-*E*lectron E*x*periment (APEX) for the confinement of electron-positron plasmas. At its heart will be a superconducting, levitated current loop producing a dipole magnetic field. Effective transport of charged particles across magnetic surfaces is one of the essential issues, especially for positrons, where available beam currents are by far weaker than those of electrons. In the prototype experiment, we are focusing on the proof-of-principle experiments to test injection methods by using a small dipole field trap generated by a permanent magnet. We conducted a numerical analysis of the injection scheme in the dipole magnetic field overlaid with an external electric field (figure 3), and found that more than 80 % of the injected positrons can take long orbit lengths under optimized conditions. Based on these results, we started the construction of a prototype dipole field device with a strong neodymium magnet. The main infrastructure of the device is completed. In conjunction with the studies with electron plasmas, another method of positron injection by using positronium as intermediate particles will also be investigated in the prototype device.

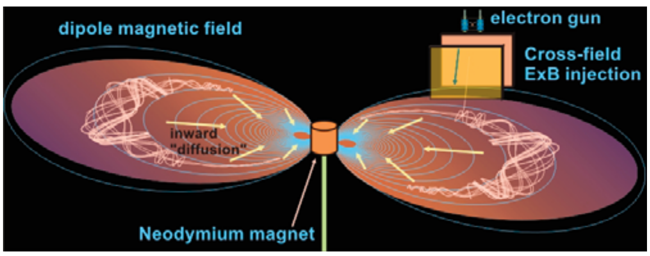

Figure 3: Numerical simulation of electron trajectories in the field of a magnetic dipole. A pair of plates creates an electric field in order to produce an E×B drift, which moves particles into a region of closed magnetic field lines.

PAX

In the *P*ositron *A*ccumulation E*x*periment (PAX) we aim to slow down, store and accumulate positrons, in order to increase the pair plasma density in the APEX experiment. These techniques are currently being developed in our Greifswald laboratory, in a collaboration with EMAU Greifswald (L. Schweikhard, G. Marx) and UC San Diego (C. Surko, J. Danielson). They will be mated with the experiment at NEPOMUC as soon as they are fully operational. In order to be able to do positron experiments in Greifswald, we have installed a source based on a ^{22}Na emitter, which is lead-shielded to background activity levels. Using these positrons, we have shown conduction of the beam through a positron trap, in which particles are cooled via inelastic collisions with a neutral, molecular buffer gas, then through a second trap providing accumulation of the cold positrons pulses. Deceleration ('moderation') of the positrons to beam temperatures of 1-2 eV has been accomplished. We have also measured the response of a fluorescent screen to the impact of the positron beam as a function of screen bias potential (figure 4). These data provide the so-called 'dead voltage', the (phosphor-dependent) bias potential, above which the quantum efficiency as a function of the screen potential becomes linear. This effect is well-documented for electrons, but not for positrons.

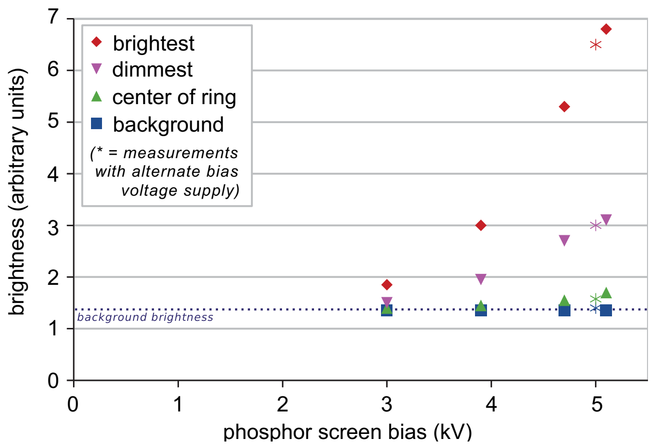

Figure 4: Brightness of different areas of the fluorescent screen as a function of the bias potential. Below a 'dead voltage' of approx. 3 kV, most positrons are absorbed without conversion of their kinetic energy into fluorescence photons.

Conference on the Physics of Positron-electron Plasmas

IPP Greifswald hosted an international expert meeting to identify targets for a first experimental campaign on electron-positron plasmas. Gyrokinetic simulations of turbulence in a pair plasma have been singled out as an attractive starting point to substantiate claims about the uniqueness of these systems. They will be compared to measurements of the actual confinement time in an experiment.

Scientific Staff

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Electron Spectroscopy

Head: Dr. Uwe Hergenhahn

The Electron Spectroscopy group is investigating excited state dynamics in molecules and weakly bonded aggregates, such as van-der-Waals clusters and liquids. An emphasis is on relaxation channels involving two or three different centers, like Intermolecular Coulombic Decay (ICD). These processes have become the subject of intense research in recent years, and the work on ICD is funded by the Deutsche Forschungsgemeinschaft within the research unit FOR1789.

Intermolecular Coulombic Decay

Projects studied in 2013 deal with ICD as a means of retrieving structural information, and with the efficiency of ICD. As a prototype systems for structured heteroclusters, we have studied noble gas clusters produced by expanding a mixture of neon and argon gas. From a thermodynamic viewpoint, it is plausible that clusters formed such are core-shell systems, with Ar forming the core. Our comparison of the electron spectra, comprised of the photoelectron lines and the features of Ne $2s^{-1}$ decaying via ICD into $(Ne^+)_2$ or Ne^+Ar^+ final states, with simulations corroborate this for small clusters. For larger clusters, a significant amount of Ne impurities within the Ar core is required to explain the data.

Although its dominance above other decay routes (fluorescence, nuclear dynamics) is an essential property of ICD, only in a single experiment the branching ratio of decays via ICD has been quantitatively determined. We have developed methods to extract the efficiency of ICD from a comparison of photoelectron-ICD electron coincidence rates to the non-coincident count rate of the photoelectrons. Applying this to ICD of Ne $2s^{-1}$ in Ne clusters leads to unit efficiency, as expected. Somewhat surprisingly, in water clusters ICD of $2a_1$ inner valence holes has an efficiency much lower than unity. This points to ultrafast proton transfer as a competing channel. Calculations to further characterize this point are underway.

Molecular Auger Decay in CF_4

Besides the work on ICD, we also carry out experiments on molecular Auger decay. In a molecular Auger spectrum information on the decaying state is implicitly ensemble-averaged. We use electron-electron coincidence spectroscopy to derive state-resolved information on the decay dynamics. This is particularly useful for molecules, in which either the core ionized or the doubly charged final state have a repulsive potential curve. For a repulsive core-ionized state, for example, contributions from all parts of its potential curve are superimposed in the Auger spectrum. Using carbon tetrafluoride (CF_4, tetrafluoromethane), we have demonstrated for the first time that these contributions can be disentangled by recording photoelectron-Auger electron coincidence spectra with high energy resolution. For the F K-VV spectrum of CF_4, there are significant differences in the Auger decay at different intermediate state (single core hole) geometries. With the help of calculations, we have shown that these differences result primarily from zero-point-fluctuations in the neutral molecular ground state, but are amplified by the nuclear dynamics during Auger decay.

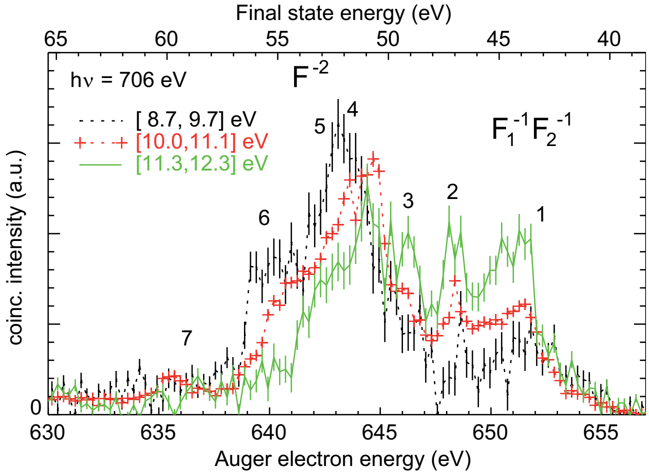

Figure 5: F K-VV Auger spectra of CF_4 for photoelectrons within three different kinetic energy intervals (see figure label).

In figure 5, Auger spectra pertaining to different parts (center, high and low kinetic energy flank) of the F 1s core level photoelectron line are shown. (These spectra have been recorded simultaneously and at a single photon energy.) The bigger part of the differences in these spectra can be traced back to differences in the C-F* bond length in the initial state (figure 6), with F* designating the atom that will become core ionized. The longer this bond, the higher the kinetic energy of the photoelectron (green arrow in figure 6), and the stronger is the population of delocalized final states, which lead to a higher Auger energy (green trace in figure 5).

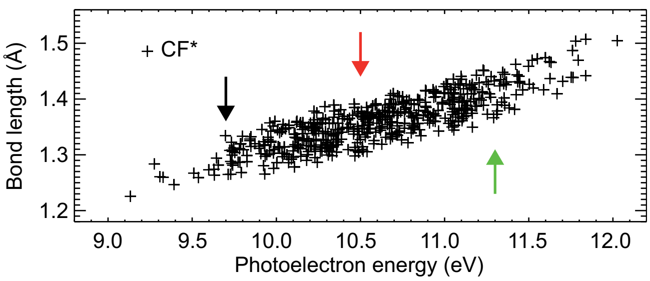

Figure 6: C-F bondlengths from a sample of 500 molecular dynamics snapshots of the CF_4 core ionized state, vs. photoelectron energy. Arrows mark the energies shown in figure 5.*

Scientific Staff

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ITER

ITER Cooperation Project

Head: Dr. Hans Meister

The IPP contributions to the ITER Project range from R&D for heating systems and diagnostics to the development of integrated control scenarios and theoretical modelling. In addition, IPP is playing a leading role in contributing to the ITER physics through 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

In 2013 the ITER cooperation project at IPP continued its efforts along the major contributions for the development of heating systems, diagnostics and plasma control as well as theoretical investigations. The test facility ELISE successfully investigated basic operation parameters and then started operation in Cs. It is accompanied by supporting investigations at smaller facilities and theoretical modelling. The contributions to the CYCLE consortium for the development of the ITER ICRF antenna and to the ECHUL consortium for the ECRH Upper Launcher continue. For the latter a performance analysis was made and demonstrated crucial operation parameters. Within the Framework Partnership Agreement (FPA) for the ITER Diagnostic Pressure Gauges work has been started by a detailed project planning and system analysis. The FPA on the development of the ITER bolometer diagnostic has finally been awarded to the ITERBolo consortium led by IPP. Meanwhile R&D efforts as part of a nationally funded project were concluded successfully. For the development of the Plasma Control System Simulation Platform for ITER the functional specifications of the main components have been detailed, an initial implementation generated and successfully demonstrated as prototype at ITER. Furthermore, IPP finalised a study on the effects of ELM on ITER performance and demonstrated that W erosion from the target under ITER controlled ELM conditions presents very little danger to the plasma. Additionally, IPP is leading several and contributing to many tasks within the EFDA Workprogramme and to the advancement of young scientists.

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 2013 with the first experimental period of the new ELISE test facility. Furthermore, the basic experiments as well as the diagnostic development at BATMAN and at the University of Augsburg (see chapter 12), accompanied by modelling of the processes leading to extraction of negative hydrogen ions and of electron suppression, have been continued.

After the successful commissioning, the first experimental period of ELISE started with the first plasma and beam pulses in March 2013, followed by a dedicated campaign without Cs for exploring basic tests of plasma generation and homogeneity, electron extraction and further conditioning of the grids. Due to the separate electron current measurement of the two extraction grid segments, a large vertical asymmetry of the electron extraction (factor 2) could be observed. Surprisingly, this asymmetry is not correlated with the source plasma asymmetry in 3 cm distance of the plasma grid, which is rather low (<10 %).

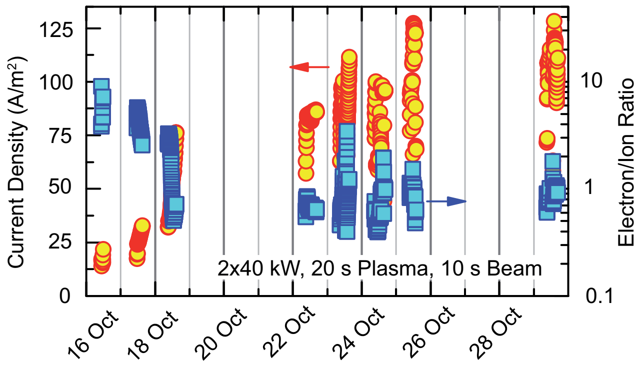

Figure 1: Improvement of the performance of ELISE after injection of Cs on 17/10/2013.

The experiments with Cs-based negative hydrogen ion production started in October 2013. Figure 1 shows the fast progress of the extracted current density and the electron/ion ratio during the first days of Cs operation within 10 s pulses. Current densities of 130 A/m^2 have been achieved, at the relevant source filling pressure of 0.3 Pa with an electron/ion ratio of 0.5, well below the required maximum value of one. In contrast to the small IPP prototype source at BATMAN, operation at filling pressures even below 0.3 Pa was possible, most probably due the larger gas flow per driver (factor 3-4) needed for ELISE (and for ITER NBI) because of the larger conductance of the extraction system. The extraction of electrons could be suppressed very effectively with a relatively low magnetic filter field, a factor of 2 lower than the design value. The achieved current densities are very encouraging for the low RF power (2×40 kW) presently applied due to risk mitigation. The pulse length could also be increased without loss of performance (figure 2). The experiments until the end of the F4E Service Contract in November 2014 aim at the demonstration of an ITER-relevant beam at the required parameters in hydrogen and deuterium for up to one hour.

The experiments at BATMAN continued on basic physics studies of the source performance, still with the emphasis on deuterium. A special request came from ITER to explore the effect of admixtures of deuterium to a hydrogen plasma on the performance, with the result that there is no effect for admixtures of up to 10 %. This is important for the operation of the diagnostic neutral beam injector (procured by India), as this system runs in hydrogen even for DT operation. A refurbishment program was started for BATMAN including the procurement of a new ITER-like grid system and a successful test of a solid state RF generator. This generator is presently discussed as an option for ITER as it is more robust than the actually designed tetrode-based generator and has a considerably larger efficiency.

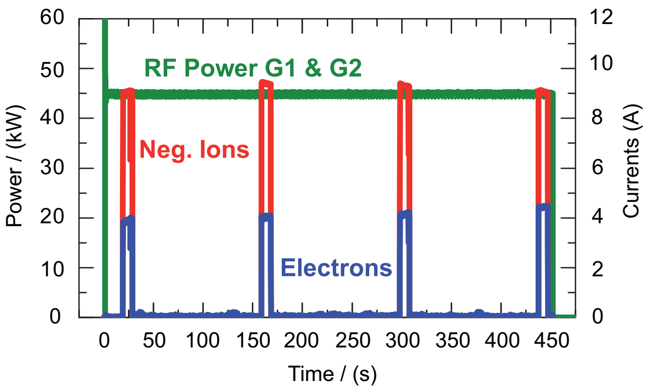

Figure 2: Long ELISE pulse at the required source pressure of 0.3 Pa. RF power was 45 kW per generator (G1 & G2). Pulsed extraction is only possible due to the technical limit of the IPP HV power supply.

The RF source modelling activities are still concentrated on electron suppression, Cs distribution and beam diagnostics, partly in collaboration with RFX Padova. The development of a full 3D PIC code for negative hydrogen ion and electron extraction – done within a two-year Alexander-von-Humboldt fellowship at IPP – made substantial progress: after a successful benchmark with beam trajectory codes, now full 3D magnetic field maps are included for more realistic simulations. A detailed assessment of the beam emission spectroscopy (BES) showed that the simple evaluation of beam divergence and homogeneity used since decades for small sources cannot be applied to large negative hydrogen ion sources. This is especially relevant for the ITER NBI system as BES is the main beam diagnostic. A beam trajectory code was developed for simulation of BES spectra. The final goal is to have a parameterisation of the BES spectrum for a variety of beam parameters, so that by including also other beam diagnostics (extracted currents, calorimeter) the full beam can be reconstructed.

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. The training of RFX personnel at the operation of the IPP test facilities and the tests of SPIDER and MITICA diagnostic tools together with RFX personnel was extended in 2013 with a total visiting time of about 17.5 personal-months. IPP personnel are also further involved in the tender and procurement of the SPIDER ion source.

Design of the ICRF antenna for ITER

The work carried out by the CYCLE consortium funded by F4E Grant 026 has now been completed. Final audits have been carried out, where required, and three period reports have been provided, as well as the final technical and management reports. The total manpower and cost claims towards F4E are within 6 % and 2 %, respectively, of the bids.

In negotiations between CYCLE, F4E and IO it was agreed that future work for the ITER antenna should be conducted within a framework contract. This work will concentrate on additionally required basic R&D, prototyping and integration, as well as operational testing. The CYCLE agreement was extended until December 2017 in order for the CYCLE consortium to be able to bid for a framework contract for the ITER ICRF Antenna. This bid was submitted in May 2013. It has been accepted by F4E and the partners in the consortium are in the final stage of signing the extension of the consortium contract and the power of attorney for CCFE to sign the framework contract on their behalf. IPP plans to continue its involvement in this work at the level of 1 ppy.

Upper Launcher for Electron Cyclotron Waves

The IPP is involved in the performance analysis of the upper electron cyclotron (EC) antenna being developed by the ECHUL-Consortium Agreement (involving KIT, CRPP, CNR-IFP, DIFFER) in the frame of F4E Grant 161. For the available beam parameters, the radial profiles of the driven current density are calculated employing beam tracing codes and the possibility of neoclassical-tearing-mode (NTM) suppression is assessed, through both simple stabilization criteria and through a direct solution of the Rutherford equation. The available power injected by EC launcher is found to satisfy with good margin the criteria for NTM stabilization during current flat-top. At the H-L transition, where according to scenario simulations the electron temperature drops on a shorter time scale than the density, the available power could become marginal, if the H-L transition occurs at the end of the flat-top phase, whereas if the transition happens later during current ramp-down (hence at lower values of the density) the negative impact of a lower temperature is drastically reduced. For a scenario at half magnetic field, the EC driven current does not change significantly with respect to the full-field scenario (similar temperature-to-density ratio, similar current drive efficiency), while the bootstrap current is smaller by about a factor of 2. As a consequence, the power required for NTM suppression drops by the same factor, reaching the 3 MW range.

These results have been obtained assuming perfect alignment between the peak of the EC profile and the rational surface, on which the NTM develops. Moreover, the EC profile is determined on the basis of the beam tracing results in a quiescent plasma, and neglecting the impact of multiple-beam superposition, of aberration and of the presence of the mode itself. The steering accuracy foreseen for ITER is found to be sufficient to keep deposition misalignment under control. An analysis of the effects related to plasma turbulence has been started (see sections on "Wave Physics and on Transport Analysis" in chapter 8). Turbulence can affect the EC profiles by either scattering the incoming beam before it is absorbed, or radially transporting the heated electrons before the current is generated. The first problem has been tackled in the frame of an approach based on the wave kinetic equation. First results suggest that a profile broadening due to beam scattering of a factor of two or more can be expected. The impact of turbulent transport is assessed by means of gyrokinetic simulations. First results suggest a marginal effect as compared to broadening due to beam scattering, at least for the q=3/2 surface.

Diagnostics

ITER Bolometer Diagnostic

After a lengthy negotiation procedure the Framework Partnership Agreement (FPA) for the R&D tasks on the ITER bolometer diagnostic has been awarded to IPP and its partners Wigner RCP, IMM, MTA EK and KIT in October 2013. The contract of the FPA was signed on 18.12.2013. The total estimated budget is ~10 M€, out of which 40 % will be funded by F4E. At the beginning of 2014 the first Specific Grants within this framework will be defined so that the envisaged work packages can start operation.

Meanwhile, the R&D activities for the ITER bolometer diagnostic at IPP were supported by national funding until the end of November. Further progress could be made in the areas detector development, prototype design and testing, and integration in ITER. The main focus of the investigations in 2013 was still 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). As previous efforts for adapting the geometry of the detector design to cope with the high temperature induced stresses did not improve the mechanical stability, the focus was set on investigating different material combinations as well as different designs for the support of the absorbers. To this aim processes were developed to deposit a gold absorber with large thickness using electroplating. Additionally, processes were investigated for using flexure hinges as support for a platinum absorber instead of membranes. In both cases pre-tests were successful and demonstrated a good adhesion of the absorber on its substrate. Now, the processes are being integrated to manufacture complete bolometer prototypes and submit them to thermal cycling tests.

The sensitivity calibration of bolometer prototypes performed in cooperation with the Physikalisch Technische Bundesanstalt has been fully evaluated. The results showed that the detectors tested are well capable of detecting radiation in the energy range from 50 eV up to 7 keV, the range of the dominating bremsstrahlung, with an efficiency close to 1. The detector with a 12 µm thick absorber could detect ~80 % of the incident photons at an energy of 20 keV. However, in the VUV and VIS range of the spectrum, the measured efficiency is strongly reduced. In this range improvements need to be found so that bolometer detectors in ITER will be able to give reliable radiation measurements also for plasma scenarios dominated by impurity radiation.

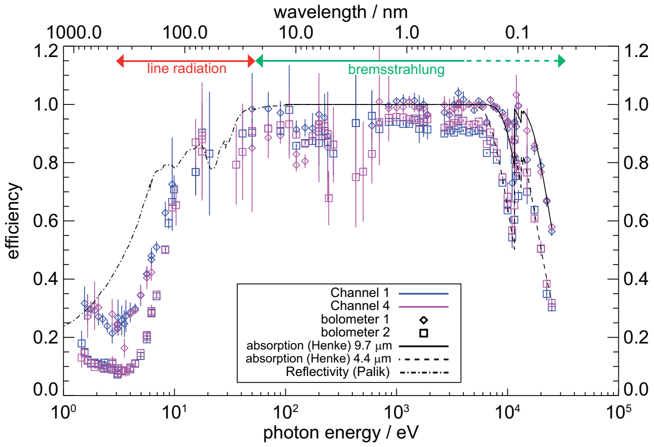

Figure 3: Efficiency calibration of 4 bolometer channels.

Several prototypes for collimator and mini-camera housing have been tested in the laboratory. Tests have been performed in cooperation with KRP Mechatec GbR to measure important material parameters used in the thermal simulations and to benchmark the corresponding finite-element-analysis (FEA). First, a mock-up made of two rods was tested to determine the thermal transfer coefficient (TCC) for various contact pressures and the different materials used for manufacturing the prototypes resulting in a TCC between 150 W/m^2K and 24.7 kW/m^2K (0–45 Mpa contact pressure). For a medium contact pressure in the order of 5 Mpa a TCC of 6 kW/m^2K was measured. Inserting a SIGRAFLEX® foil as heat conduction layer between the samples reproduced this value also for lower contact pressures and is thus the preferred method to enhance thermal transport for cases, in which the pretension provided by bolted contacts might be lost. Second, a mock-up of a bolted flange was tested demonstrating that the number and spacing of the bolts determines the average contact pressure, which in turn defines the TCC as measured by the first test set-up. Also for these tests, an additional heat conduction interlayer is beneficial. The third test with a complete bolometer camera was accompanied by FEA simulations, which used the previously determined values for the TCC as input (figure 4).

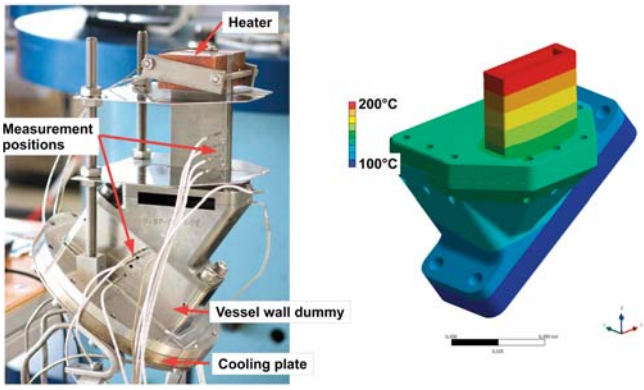

Figure 4: Prototype of a bolometer camera used for thermal tests (left) and corresponding FEA simulation result (right).

It could be demonstrated that these values reproduce the experimental results in the simulations very well.
The test facility IBOROB (ITERBolo robot) was further used to measure the transmission functions of various collimator prototypes and thus to improve their design. Additionally, it was set up in the vessel of ASDEX Upgrade for the first in situ measurement of bolometer cameras. A detailed discussion is given in chapter 17.
In September ITER held the conceptual design review of the bolometer diagnostic, which led to a well-accepted design concept based largely on the integration work performed within the ITERBolo project. In particular, most concepts and partly full designs for diagnostic components have been adopted by ITER and were endorsed by the review panel.

ITER Diagnostic Pressure Gauges

In July 2013 the kick-off meeting for the first two Specific Grants (SG01 and SG02) took place in Barcelona few weeks after contracts signature. SG02 establishes and runs for the entire duration of the FPA (48 months) the Coordination Support Office. It has the role of supporting the F4E technical responsible officer (TPO) and the supplier (IPP-Sgenia-KIT consortium) Technical Responsible Person (TRP) of each specific grant in several ordinary (document management, updates of schedule, configuration management and update of design baseline including all CAD drawings, etc …) and extraordinary (initiate special R&D services upon request of TRPs) tasks while coordinating the activities among the various SGs. It has an estimated total budget of 1.7686 M€ with a total of about 15 ppy of labour effort and a maximum F4E contribution of 749,945.20 €. As leading partner, the Coordination Support Office contract has been granted entirely to IPP. The second contract is named "SG01 Planning and urgent R&D" and had an original duration of 4 months. Mainly due to an underestimated work load, the contract was amended and extended to 8 months duration (ending now in February 2014) with about 17 % budget increase (due to scope increase) reaching an estimated total budget of 454.2 k€ (F4E contribution of 190.8 k€) and about 4 ppy divided over 13 managerial and technical professional figures. Activities foreseen in the work plan include: 1) revision and update of relevant documentation including DPG technical and measurement specifications, 2) preliminary interfaces specifications, 3) update of functional analysis provided by IO, 4) creation of the work breakdown structure (WBS) for the whole FPA including a very detailed description of activities (input, output, goals and objectives, work descriptions, etc …) to be included in the subsequent SGs, 5) resource loaded schedule for the whole FPA including an organisational structure for all subsequent SGs, 6) a complete prototype and test plan, 7) cost estimates for the hardware deliverables, prototyping, tests and man power for the whole FPA. The proposed project plan consists of 6 SGs allowing two iterative stages of design, engineering analysis, modelling and prototype testing in both laboratory and tokamak (AUG) environment.

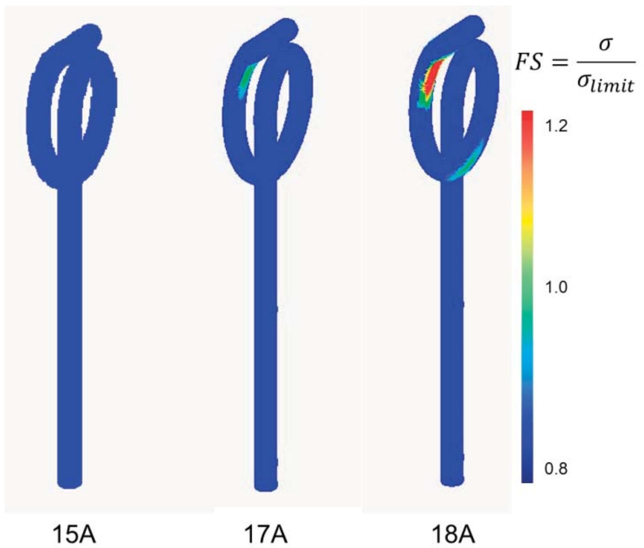

Figure 5: Linear FEM simulation of mechanical stress over plastic limit for a pure Tungsten filament under electric heating and J×B forces at 8 T. A current limit of 18 A in stationary condition is found before plastic deformation begins.

A minimum of technical R&D was included in the work plan of SG01. The present DPG design, based on the ASDEX pressure gauge, has been reviewed in order to identify outstanding issues and produce detailed CAD drawings of the gauge head. Linear FEM calculations aimed at checking the filament structural integrity against the higher magnetic field in ITER (up to 8 T) and the associated J×B forces. Using pure tungsten material properties (in absence of more relevant data for tungsten lanthanide oxide) the simulations identified a heating current limit (in stationary condition) of 18 A before exceeding the limit for plastic deformation (see figure 5). This heating current is marginal with respect to the typical operating conditions and thus an optimisation of the design will be needed to ensure the full performance. Accuracy requirements and the expected high radiation in ITER with an associated heating power to the components suggested the need to measure or control the temperature of the gauge head base plate. The associated R&D activities (feasibility and design) have been allocated to the future SGs to cope with this and other identified issues. The review of IO documentation resulted in an immediate request of design changes regarding the space allocation, cabling and number of foreseen gauges in the equatorial ports (increase from 2 to 4). An operation strategy has been proposed and it is currently under F4E and IO review. During the last phase of SG01 an initial optimisation of size, shape and position of the electrodes will be performed based on simple theoretical considerations. From the engineering point of view a pre-conceptual design study will define the DPG fixation options to be considered in future work packages. The next SG (SG03 "Basic design") is foreseen to start in spring 2014 and will last for about 12 months.

Control and Data Acquisition (CODAC)

The Plasma Control System Simulation Platform (PCSSP) for ITER is a joint project of IPP, CREATE / Univ. di Napoli (I) and General Atomics (US) as lead. In late 2012 the preliminary architecture for PCSSP was reviewed by IO, and further development released. In 2013 the functional specifications of the main components of PCSSP were detailed. These are the plant simulator modelling diagnostics, actuators and plasma behaviour, and the PCS simulator modelling plasma continuous control and plasma supervisory control. A further component is the event generator, which allows to stimulate changes in specific plasma and plant states and to trigger failure states in order to investigate the resulting system response. An initial implementation of these components was jointly developed, and a prototype successfully demonstrated at ITER in December 2013.

In February and October 2013 IO organized meetings to investigate modern real-time control framework concepts and their potential use for ITER. Prime candidates identified were the ASDEX Upgrade DCS, which is designed as a complete control environment capable of coordinating large distributed control tasks, and the MARTe System from IST Lisbon (with applications at JET, IPP/Prague, IST), which is optimized for subsystems with high-performance processing. IO expects to receive major input from IPP and IST in order to compile the requirements specification for the ITER real-time control framework.

During 2013 IPP assisted COSYLAB/Slovenia in the description and analysis of present Tokamak experiments' work flows and experimental configuration data as input to the design of the ITER work flow and pulse schedule. Learning from present best practices is a key to making ITER a device, which can be efficiently exploited by a distributed fusion community.

Simulation of the Effect of ELMs on ITER Performance

A large set of SOLPS simulations for D+T+He+Be+Ne+W for full and half field ITER scenarios were performed. In addition to cases with no W prompt re-deposition, the simple Dux model was implemented. With prompt re-deposition, W contamination of the core by a single ELM was found to be insignificant. The flux of W across the separatrix during the ELM cycle was used to perform coupled ASTRA-STRAHL calculations. A simple model used to calculate W re-deposition at the target for ITER controlled ELM conditions predicts a significant, factor 10^4, reduction in the net W erosion due to W re-deposition. This model however does not include effects of multiple W ionization and electric field force on the ions in the magnetic pre-sheath, which are very important under conditions investigated. A series of dedicated Monte Carlo simulations, aimed at establishing the role of these effects, was carried out. It was found that, with inclusion of all effects, the W re-deposition was not less, and under some divertor conditions, even greater than according to the simple model. Based on these results it was concluded that the net W erosion from the target under ITER controlled ELMs conditions presents very little danger of the plasma contamination with sputtered W. Also, it follows from these simulations that the avalanche effect, where W self-sputtering could lead to a run-away process of increasing W sputtering, can be ruled out.

Direct measurements of the impurity transport coefficients in the edge transport barrier (ETB) of H-mode plasmas were performed in ASDEX Upgrade. It was found that the transport between ELMs is in good agreement with neoclassical theory for all impurities up to argon. Thus, it can be assumed that tungsten transport in the ETB of ITER will be appropriately described by neoclassical theory. The neoclassical transport of W was studied for a large range of pedestal profiles of electron density and temperature at various values of plasma current and toroidal field.

A major finding of this study was that the radial convection velocity of tungsten is outward directed for a large part of the tested pedestal profiles. This is due to a combination of high pedestal temperatures and high separatrix densities making the outward directed temperature screening term to be the predominant contribution of the collisional convection. The high densities at the separatrix are needed to control the power exhaust in the divertor and the high pedestal temperatures are needed to achieve the performance goals of ITER. An achievement of the density and temperature profiles, which deliver optimum performance and power exhaust in ITER, also assures optimum collisional radial transport of tungsten promoting a hollow tungsten density profile in the edge transport barrier.

Combined ASTRA+STRAHL simulations of transport of impurities (with focus on W) in presence of ELMs of varying frequencies has been carried out for various ITER scenarios, using W ELM-driven sources as from SOLPS calculations. Both neoclassical and ad-hoc anomalous transport models have been included to simulate the evolution of the W profile in the pedestal region and in the core. The findings suggest that there is an optimal ELM frequency of 10-30 Hz for almost all scenarios, for which W accumulation due to the ELM-driven source is only moderately detrimental to the plasma performance. The lower limit in frequency is dictated by instantaneous radiation losses that would cause sudden H to L transitions, while the upper limit avoids too fast W accumulation before the natural W flush-out due to the found outwards-directed neoclassical pinch. Moreover, it has been found that tailoring of the pedestal density and temperature profile of the bulk ions is important to benefit from the outwards neoclassical pinch. Sensitivity studies carried out on the pedestal model and transport assumptions show that an ELM of diffusive type (which causes just flattening of pedestal profiles) is much more pessimistic than assuming an ELM that flushes out particles. This result pushes for more dedicated studies of ELM transport in particular in presence of hollow profiles as for the W predicted from neoclassical theory.
This study is now complete, and the final report has been accepted by ITER.

EFDA Tasks

IPP significantly supports the development of the physics basis for ITER and the definition of operating scenarios not only through the operation and scientific exploitation of its tokamak ASDEX Upgrade but also through dedicated tasks within the EFDA Workprogramme. These tasks – many of which are led by IPP and have contributions from several Associations – focus on special topics, which have been identified by the European Fusion Laboratories as being key issues for ITER, DEMO and the advancement of fusion in general. The scientific results achieved within these tasks are presented in various other chapters, mainly 1 (ASDEX Upgrade), 6 (DEMO), 7 (Plasma-facing Materials and Components), 8 (Theoretical Plasma Physics) and 10 (Energy and System Studies). The overall effort involved in the 51 tasks active in 2013 accumulated to 18.4 ppy, the maximum contribution by EFDA will be 673 k€.
At the end of 2013 the Contract of Associations was terminated. The corresponding activities will be continued through the newly set-up EUROFusion-Consortium with the funding being distributed through a project-oriented scheme. IPP was elected as the coordinator of this consortium and provides in 2014 the only mid-sizxmak in operation within Europe for experimental studies.

Advancement of Young Scientists

The FUSENET project, which started in October 2008, finished in October 2013. All milestones have been met and deliverables produced. The FUSENET association, a legal entity created to continue to advance the aims that the project pursued, will have its third yearly general assembly in February 2014. Negotiations are under way with the EC and the EUROFusion consortium to implement in the new environment the ways and means for and possibly further extend the role of FUSENET in the support of the education of scientists and engineers. IPP is strongly involved, among others through membership in the Board of Governors, and the Academic Council. In 2013, ten fellowships have been granted in the second cohort of the FUSION-DC funded project. Six of those are in one way or another connected with IPP (being through promotorship, co-promotorship or research stays at IPP).
The NIPEE (Negative Ion Physics and Engineering Expertise) programme was continued until November 2013 when the contract ended. The IPP trainee was strongly involved in the tests of an AC titanium pump for the W7-X neutral beam system (see chapter 3) and – during a 5 weeks stay at RFX Padova – in the conceptual design of the Cs-oven for the ITER NBI system.

Scientific Staff

ECRH: C. Angioni, F. Casson, O. Maj, E. Poli, H. Weber, H. Zohm; Members of ECHUL-CA and F4E Teams.
EFDA tasks: 70+ scientists.
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NNBI: S. Briefi, U. Fantz, P. Franzen, R. Friedl, M. Fröschle, B. Heinemann, W. Kraus, U. Kurutz, C. Martens, R. Nocentini, S. Obermayer, G. Orozco, R. Riedl, B. Ruf, L. Schiesko, P. Turba, C. Wimmer, D. Wünderlich; S. Mochalskyy (A.-v.-Humboldt fellow); F. Bonomo and 8 other scientists (RFX Padova); 5 scientists (University of Milan); S. Lishev (Bulgarian Academy of Science, Institute of Nuclear Research and Nuclear Energy).
Trainees: J.-M. Noterdaeme, H. Zohm (FUSENET and Fusion-DC coordinators); G. Orozco (NIPEE trainee).

DEMO

DEMO Design Activities

Head: Prof. Dr. Hartmut Zohm

The 'DEMO Design Activities' project focuses on aspects of physics and technology relevant for both tokamak and stellarator designs, in line with the unique position of IPP, which follows both lines. Many of the activities are carried out under the EFDA PPP&T Work Programme, where substantial collaborations within the EU exist. On the national level, the German DEMO Working Group joining scientists from FZJ, IPP and KIT serves to strengthen collaboration and strategic planning.

Exhaust Studies for a Tokamak DEMO

Exhaust continues to be a very important subject for DEMO design, with strong implications on the overall operational parameters. The global criteria for exhaust in DEMO have been tentatively set as $P_{sep}/R < 15$ MW/m, compatible with both the assumption used for ITER to ensure an at least partially detached divertor as well as the requirement to stay in H-mode, $P_{sep} > P_{HL}$. Prescribing P_{sep}, the power crossing the separatrix in charged particles, means that for given $P_{tot} = P_{fus} + P_{AUX}$, effectively the core radiation is prescribed. While for ITER, the above assumption leads to $P_{rad,core}/P_{tot} = 25$ %, well in line with present day experimental conditions, for DEMO this number will have to increase dramatically up to 70-80 %. Experiments on ASDEX Upgrade demonstrating such high core radiation with good plasma performance by adding a mix of seed impurities are reported in chapter 1, section 7.8. Based on these results, different impurity mixes have been assessed in order to clarify their suitability to the DEMO core.

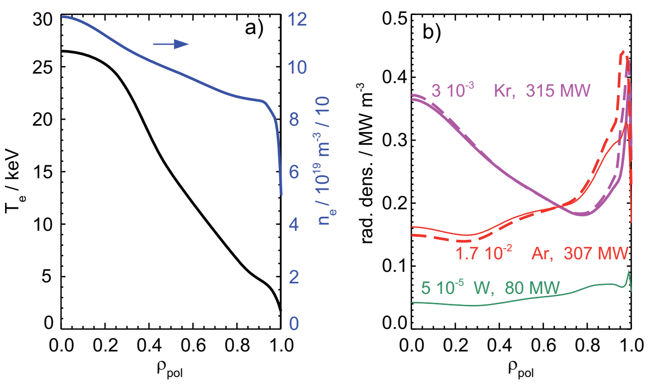

Figure 1: Assumed plasma profiles (left) and radiation profile modelled for the EU conservative DEMO.

Figure 1 shows two examples. On the left, the assumed plasma profiles, corresponding to the EU conservative DEMO design under the assumption of peaked density profiles, are shown. The right part shows the radial distribution of core radiation from W (assumed as 'intrinsic' impurity) and cases using Ar or Kr as seed impurity Both can give rise to the desired core radiation level of around 300 MW in this case, but Ar has a more favourable profile, with less radiation in the centre so that one may expect a lower impact on confinement. On the other hand, the contribution to Z_{eff} and dilution may be quite high and a combination of seed impurities may be required to obtain the optimum radial profile with minimum impact on plasma performance. A set of transport simulations to assess this has shown that dilution is the strongest constraint, while the effect of core radiation on confinement is limited. As such, the higher Z impurities are favoured (Kr, Xe), with Xe behaving practically as W (high radiatiation and negligible dilution). On the other hand Kr, Xe are not strong SOL/divertor radiators, and so another impurity with different temperature characteristics such as Ne or N will have to be used in addition. Finally, we note that for SOL and divertor radiation, another impurity with different temperature characteristics such as Ne or N will have to be used in addition.

Heating and Current Drive

The assessment of the H&CD capabilities for different tokamak DEMO designs was continued. Further to the assessment of the capabilities of the different systems to replace the ohmic current component presented last year, a study of the application of ECCD for the stabilisation of NTMs was undertaken for the 'conservative' EU DEMO design point. These modes are expected to be potentially unstable in a conservative DEMO at the q=2 and q=3/2 surface due to the unfavourable ρ^*-scaling of the onset β. The analysis used the beam geometry from the global current drive study i.e. an unfocused beam of width 4.6 cm (1/e2 power width) at the launch point, leading to a width of the driven current profile of the order of 10 cm at the q=2 surface and 20 cm at the q=3/2 surface.

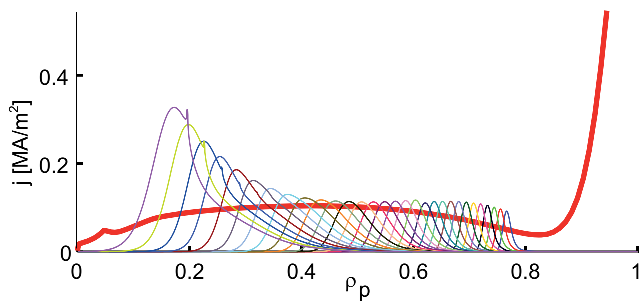

Figure 2: Profiles of ECCD driven current compared to the bootstrap current density. For a power of 4.5 MW in an individual beam, the criterion $j_{ECCD}/j_{bs} > 1.2$ is fulfilled over a wide radial range, in particular also at $\rho_p = 0.4$ (q=1.5) and $\rho_p = 0.6$ (q=2).

Figure 2 shows a plot of driven current profiles, generated with 4.5 MW each, where the deposition location is varied by a scan of the toroidal and poloidal launch angles. For comparison, also the bootstrap current density for the conservative DEMO is shown. Contrary to the situation predicted for ITER, the radial width of the driven current profile will be much larger than the marginal island width, to which the NTM has to be reduced before it decays on its own, due to the use of unfocused beams. In this case a modulation of the ECCD power in phase with the magnetic islands due to the NTM will be required. On the other hand, the current drive efficiency is quite high compared to ITER due to the combination of higher temperature and higher gyrotron frequency of 280 GHz so that the power required to exceed the stabilisation criterion for modulated stabilisation, $j_{ECCD}/j_{bs}>1.2$, is already met at an injected power of roughly 5 MW. Hence, the power requirement seems very modest and NTM stabilisation by ECCD should be foreseen in the 'conservative' DEMO. This study used beam steering for control of the deposition location, as is foreseen for ITER. However, in the harsh DEMO environment, it might be prudent to avoid movable parts close to the plasma and hence, a future study will address if instead, frequency step-tuning of gyrotrons will be adequate for deposition control without the need to move the beam. We will also study the effect of beam focusing with the aim to explore if the need to modulate the gyrotron power in phase with the NTM can be removed by making the ratio of width of driven current and marginal island width small enough.

Stellarator DEMO Studies

For the stellarator design, detailed analysis continues to focus on technological elements that may be different or more complex than in tokamaks to assess in a timely manner the related challenges. A study of the effect of the use of ferritic steel in blanket modules showed that while a change of the total iota profile is expected, there is no significant generation of unwanted helical components that could destroy the flux surface topology. Hence, while these effects have to be incorporated in the design from the beginning, they do not provide an additional challenge. Furthermore, studies are ongoing to assess the aspects of maintainability of the blanket modules in a HELIAS type stellarator. Concerning the conceptual design of a 'HELIAS-ITER' (see AR 2012), we transferred the methodology of dimensionless size and heating power, defined in a way that contours of constant dimensionless parameters ρ^*, β, ν^* can be expressed as function of these two variables if the density is constrained in addition, from tokamaks to stellarators. Since this requires an assumption on energy confinement, we used an adapted version of the ISS confinement scaling to locate such a device in the corresponding map. Figure 3 shows the plot for tokamaks (left) and stellarators (right). It can be seen that a HELIAS stellarator based on the W7-X design capable of achieving Q=10, i.e. equivalent to the self-heating fraction in ITER, would sit in roughly a similar position as ITER on the tokamak path to DEMO. The reactor points shown in the stellarator map are for HELIAS designs with 4 periods (H4/18) and 5 periods (HELIAS 5-B). The latter would have a major radius of 22 m while the Q=10 point is positioned at 14 m. Finally, an effort is put into the development of a stellarator systems code that can be used for scoping studies. Here, we have started to incorporate stellarator specific modules into the PROCESS code developed at CCFE, UK such that this code, which is widely used in the EU tokamak DEMO design studies, can also be applied to stellarators, thus allowing a direct comparison of power plant characteristics of the tokamak and the stellarator concept. First achievements are a consistent description of the plasma geometry, an island divertor and the coil system for PROCESS, and work is ongoing to develop a module describing the energy confinement. This whole work is part of the ongoing effort to incorporate the stellarator in fusion roadmaps in parallel to the tokamak, which is a strategic goal of IPP given its unique position to combine tokamak and stellarator expertise with two world-leading experiments and a strong corresponding theory effort.

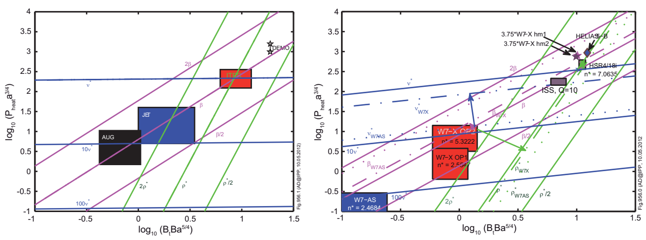

Figure 3: Map of dimensionless size and heating power for tokamaks (left) and stellarators (right). Two HELIAS reactor design points are shown (HSR 4/18i and HSR5-B) together with a Q=10 HELIAS based on W7-X.

DEMO Technology Studies

As pointed out in the DEMO current drive analysis (see last year's Annual Report), substantial auxiliary current drive may be required for a realistic steady-state DEMO tokamak. Hence, not only the plasma current drive efficiency, but also the wall-plug efficiency of auxiliary CD systems needs to be developed further. For Neutral Beam Injection, a major gain is expected from increasing the neutralizer efficiency. A promising candidate is laser detachment, and a first experiment was installed at the University of Augsburg (see chapter 12). Other activities aim at an increase of the reliability of the RF system by investigating new highly efficient coupling schemes with first promising tests of Helicon coupling in Hydrogen and the identification of alternatives to Cs for negative hydrogen ion production. Furthermore, the assessment of the reliability, availability, maintainability and inspectability (RAMI) of a possible NBI system for DEMO has been continued.

Scientific Staff

C. Beidler, S. Briefi, L. Casali, A. Dinklage, E. Fable, U. Fantz, P. Franzen, T. Hartmann, A. Kallenbach, W. Kraus, K. Lackner, E. Poli, F. Schauer, G. Tardini, M. Wischmeier, F. Warmer, C. Wimmer, R. Wolf, H. Zohm.

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

Ion Chemistry in H_2-Ar Low Temperature Plasmas

For fusion devices with a full-W divertor, such as ASDEX Upgrade and JET, impurity seeding is necessary for radiative power dissipation. Nitrogen and argon are presently foreseen as seeding gases. Therefore, plasma-chemical reactions in H_2 plasmas with admixtures of small amounts of argon and nitrogen are of relevance for processes in the boundary plasma. To some extent these processes can be studied in low-temperature laboratory plasmas. In a first step, inductively coupled low-temperature H_2-Ar plasmas at 1.0 Pa ($n_e \approx 3\times10^{16}$ m^{-3}, Te≈3-5 eV) were thoroughly characterised by a wide variety of plasma diagnostic methods. Absolute ion densities were determined with an energy dispersive mass spectrometer. Results were compared to the results of a semi-empirical rate equation model. The model includes electron-induced ionisation and dissociation processes and ion-molecule reactions in the plasma volume. The model requires input of some measured plasma parameters such as electron density, hydrogen dissociation degree, and gas temperature. The calculated model results show the identical trends and are by and large in quantitative agreement with the experimentally determined ion densities of all ion species (H^+, H_2^+, H_3^+, Ar^+, and ArH^+). In pure hydrogen plasmas the dominant ion species is H_3^+. In argon admixed plasmas ArH^+ is dominant. The derived model allows a detailed view on the ongoing plasma-chemistry. Primary ions H_2^+ and Ar^+, which are produced by electron-induced ionisation of the background gas, are efficiently converted to the secondary ions H_3^+ and ArH^+ by ion-molecule reactions. In the next step comparable investigations of H_2-Ar-N_2 mixtures will be performed.

Three-dimensional Hydrogen Isotopes Microscopy in Tungsten

The SNAKE microprobe facility operated by the Technical University Munich was used for 3D microscopy of hydrogen in 25 µm thick tungsten foils using incident protons with energies between 17 and 25 MeV. In SNAKE recoiling protons from the sample and scattered protons from the beam are detected in coincidence in transmission through the foil. The lateral resolution of the method is a few µm and the depth resolution is of comparable magnitude. First experiments have shown that the method is sensitive enough to resolve the surface hydrogen contamination (probably by adsorption of water from the atmosphere) of a crack through a tungsten foil (figure 1). The investigated tungsten foil has been recrystallized in order to create grains considerably larger than the spatial resolution of the method, thus allowing investigating the role of grain boundaries as possible hydrogen traps. The possibility for deuterium microscopy was tested by analyzing a 25 µm thick deuterium-implanted tungsten foil with a deuterium beam. Resolution and sensitivity of deuterium microscopy are roughly comparable to hydrogen microscopy.

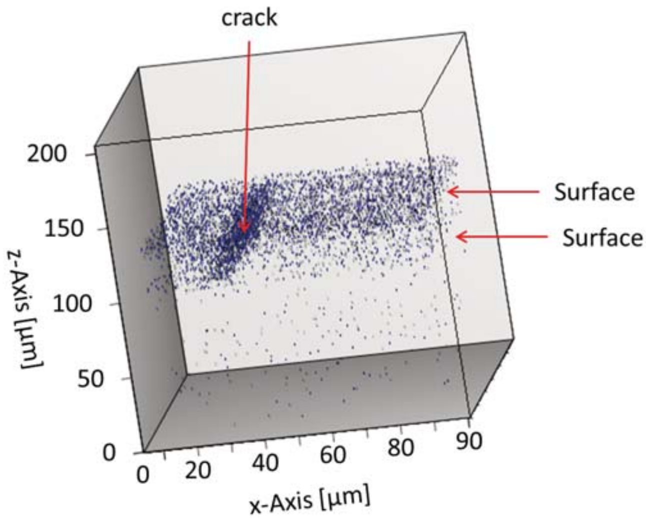

Figure 1: 3-dimensional map of hydrogen in a 25 µm thick tungsten foil. H atoms are indicated by blue dots. The z-axis is stretched by a factor of 8 compared to the x-axis. The top and back surfaces are discernible by a slightly higher H signal most probably due to adsorbed water. The sensitivity for H on the back side of the foil is lower than on the front side. A region of enhanced H signal is attributed to water adsorption in a crack.

Strongly Reduced Penetration of Low-energetic Deuterium in Radiation-damaged Tungsten at High Fluxes

Tungsten samples were damaged by 12.3 MeV W^{4+} ions at the IPP tandem accelerator to a maximum damage level of 0.45 displacements per atom (dpa). The damage extends to a depth of about 1.5 µm below the surface. The damaged samples were subsequently exposed to low-energy deuterium plasmas with an ion energy of roughly 5 eV at high ion fluxes of about 10^{24} D-ions/m^2s at the plasma generator Pilot-PSI in collaboration with FOM DIFFER. Deuterium depth profiles and the total deuterium inventory were measured by nuclear reaction analysis and thermal desorption spectroscopy. The diffusion process was modelled using the TMAP 7 code.

It was observed that the fraction of deuterium that penetrates into the material is only 10^{-5}-10^{-7} of the incident plasma flux and therefore orders of magnitude lower than expected on the basis of the direct reflection. The penetrating flux fraction depends strongly on the local surface temperature and shows an Arrhenius-like behaviour. It was proposed that deuterium does not directly penetrate bulk tungsten at these conditions, but that it thermalizes at the surface, where it forms a protective chemisorbed layer. An energy barrier of 1-2 eV between the surface and the bulk is observed, causing the reduced influx of deuterium and leading to slow filling of traps in the damaged layer.

Migration of Materials in Fusion Devices

Erosion of P92 Steel and Tungsten in the Main Chamber of ASDEX Upgrade

A number of P92 steel-coated tiles were exposed to plasma at the inner heat-shield region of ASDEX Upgrade during the 2012-2013 experimental campaign. The campaign-integrated erosion/deposition profiles of the tiles were determined using Rutherford Backscattering Spectroscopy (RBS). For several tiles small net erosion (50-100 nm) was measured, particularly for the ones located above the inner midplane. To supplement these results, a full poloidal set of upper-divertor tiles with W and Ni marker stripes were exposed to plasma during the first half of the 2012-2013 campaign. The RBS data measured from the tiles showed that the top parts of the ASDEX Upgrade vessel are net-deposition regions for W and the deposition is slightly stronger at the inner than at the outer side. In contrast, for Ni net erosion (50-100 nm) was observed on all the analyzed tiles, excluding the region close to the secondary separatrix where large erosion and deposition peaks alternated. Finally, erosion at the outer midplane was investigated with the help of a marker probe that was exposed to four low-power H-mode shots in ASDEX Upgrade. Net erosion of around 1 nm was measured for the W marker and 10 nm for the Ni marker during the 25-s-long experiment. It can be concluded that material is predominantly deposited at the inner side of the ASDEX Upgrade main chamber, especially on the heat shield and the inner divertor. The outer divertor is a strong net-erosion region and the same holds for limiter structures at the outer midplane. Steel can be safely used in the heat-shield region while W seems to be the only option at the outer midplane and in the divertor.

Experiments and Modelling on the Nitrogen Migration in ASDEX Upgrade

Nitrogen is routinely used in ASDEX Upgrade to control the heat flux on the divertor target plates. It has been observed that part of the nitrogen that is puffed during a discharge is retained in the vessel and released in subsequent discharges. It is not yet clear, whether the retention is mainly caused by the formation of WN_x by the implantation of N into W, by co-deposition or whether a significant amount is adsorbed on surfaces in the form of ammonia. Also the mechanism leading to the release of nitrogen in the subsequent discharges has yet to be clarified.
We therefore started comprehensive studies, including well defined laboratory experiments, experiments in ASDEX Upgrade and computer simulations. For the experiments at ASDEX Upgrade, N was puffed into well-characterized L-mode plasma. Using the divertor manipulator system, W samples were exposed at the outer target plate. Post-exposure ion beam analysis of the samples revealed that the W-surfaces become saturated with N within one discharge and that nitrogen accumulation intricately depends on the local plasma temperature through the implantation depth and re-erosion. Spectroscopic analysis of nitrogen line emission reveals position (i.e. exposure condition) dependent rise and decay times of the local nitrogen re-erosion flux.
Using these data as boundary condition, N transport and redistribution in the plasma were studied by computer simulations. The modelling of mixed-material formation requires an integrated approach that self-consistently links plasma transport with surface evolution. To that end the WallDYN code has been developed in 2010. For the simulations N transport was pre-computed by DIVIMP using plasma background models from SOLPS simulations. For the simulation of nitrogen the WallDYN model was upgraded to include the saturation of nitrogen in tungsten, the loss of nitrogen to the pumping system and time-dependent ion energies and nitrogen puff.
The dynamic change of the N erosion source at plasma exposed W surfaces was then computed by WallDYN using a W-N surface model that has been benchmarked against laboratory experiments. First simulations show, in agreement with the experiment, a strong rise of the N re-erosion flux within the first second. A further rise is predicted for longer time scales. Virtual diagnostics were implemented in DIVIMP for subsequent direct comparison with spectroscopic measurements. By this procedure, the experimental results from sample analysis, spectroscopy and N pumped by the vacuum system can be interpreted for the first time within a unified self-consistent model.

Tritium Inventory – Understanding and Control

Evolution of Deuterium Depth Profiles in Self-damaged Tungsten

Numerous experiments over the last years have shown that self-damaged tungsten has substantially larger hydrogen isotope retention as compared to undamaged tungsten. However, little attention has been paid to the amount of hydrogen necessary to fill the damage zone and no conclusive results can be found in literature regarding hydrogen retention as a function of the initial damage level. Although some studies postulate unlimited increase of retention with increasing damage level, in most cases saturation is observed between damage levels ranging from 0.2 to 0.9 dpa. In recent experiments, the evolution of deuterium depth profiles was studied in addition to the total retention to determine the onset of saturation in self-damaged tungsten. Recrystallized, polycrystalline tungsten was damaged by 20 MeV W^{6+} implantation at room temperature. Damaging fluence was varied from 3.2×10^{15} W/m^2 to 1.6×10^{19} W/m^2 corresponding to peak damage levels of 0.002 to 10 dpa.

Available trap sites were decorated with deuterium by exposing the targets to low temperature plasma. The energy of the impinging ions was kept below 15 eV. The deuterium fluence was varied from 0.1 to 3.4×10^{25} D/m^2 to observe the filling of the damaged zone until saturation. A sample temperature of 450 K was used to avoid any defect annealing during D decoration. The deuterium depth profiles within the top 7 µm were derived applying ^{3}He nuclear reaction analysis (NRA). Temperature programmed desorption (TPD) was applied to determine the total D retention. TPD and NRA results coincide very well, both showing that D retention increases proportionally with damaging fluence at the lowest damage levels, but starts to deviate already above 0.01 dpa. Up to a peak damage level of 0.5 dpa D depth profiles show a maximum at a depth of 1.3 µm similarly to the damage profile calculated by SRIM. Also the measured maximum range of D of 2 µm coincides with the expected damage range. However in all cases the maximum of the calculated damage profile is more pronounced than the measured D depth profile. Above 0.5 dpa D starts to fill up the region between the surface and the damage maximum and the profiles level off indicating the onset of saturation at a local D concentration around 1.4 at.%. For higher damage levels also the total retained D amount shows saturation. Substantial damage propagation beyond the damage zone can therefore be excluded.

Permeation of Deuterium through Tungsten

In order to investigate deuterium transport in radiation damaged tungsten permeation measurements were performed. Radiation defects were created by irradiation with 20 MeV W-ions up to a maximum of 0.5 dpa, subsequently the samples were exposed to deuterium ions at 200 and 1000 eV. The permeation flux through the sample was detected by a quadrupole mass spectrometer. The permeation break through time increases by at least one order of magnitude compared to undamaged tungsten. The experimental results were modeled using the TESSIM code, and good agreement with the experimental data could be achieved. The energy of traps created by heavy ion irradiation was determined as 1.75 eV from the model.

Reduced Deuterium Retention in Self-damaged Tungsten at High Surface Temperatures

The effect of surface temperature during irradiation by high-flux deuterium plasmas on deuterium retention in self-damaged tungsten was studied in collaboration with FOM DIFFER. The samples were pre-damaged by 12.3 MeV W^{4+} ions at room temperature to different damaging fluences. The deuterium retention within the top 6 µm of the sample saturates at a W^{4+} fluence of about 3×10^{17} m^{-2} (corresponding to a peak damage level of about 0.2 displacements per atom (dpa)) at all investigated temperatures. Retention is strongly reduced by almost one order of magnitude at high temperatures of 800-1200 K as compared to 470-525 K. A combination of nuclear reaction analysis, temperature programmed desorption and positron annihilation Doppler broadening was used to investigate the reduction in deuterium retention. Positron annihilation Doppler broadening measurements suggest that during plasma exposure at elevated temperatures defects are mobile and cluster into larger clusters containing up to a few tens of vacancies.

Materials and Components

Tungsten Fibre Reinforced Tungsten Composites

A severe problem for the use of tungsten in a future fusion reactor is its inherent brittleness and its further embrittlement during operation. Reinforcement of tungsten with drawn tungsten wire was proposed as a possible solution by the PFMC group in recent years. This tungsten fibre-reinforced tungsten (W_f/W) composite utilizes the so called extrinsic toughening which is well known from ceramic fibre-reinforced ceramics. Here mechanisms such as fibre bridging or fibre pull-out allow local energy dissipation and therefore increase crack resistance and thus toughness.

These mechanisms were shown to work on model systems containing a single fibre. Using a chemical deposition technique bulk W_f/W was successfully manufactured for the first time. A fibrous preform consisting of tungsten wires was infiltrated with gaseous precursors (WF_6 and H_2). In a surface reaction WF_6 is reduced by H_2 to deposit solid tungsten on the wire surfaces. Compared to the classical manufacturing route by powder metallurgy, the chemical process allows low processing temperatures (<600 °C) and a force-less fabrication. Therefore, the composite structure and interface integrity could be preserved which is essential for the toughening mechanism to work. A cross section of bulk W_f/W produced this way is shown in the picture below.

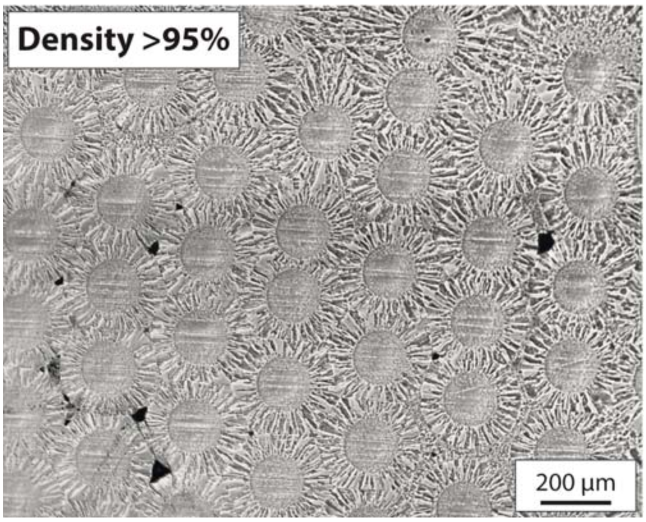

Figure 2: Cross section of bulk W_f/W. Circular structures indicate the tungsten fibres embedded into the chemically deposited matrix.

With this technique several samples containing 100 fibres each (volume fraction 0.3) were produced and tested in cooperation with the Erich-Schmid-Institute in Leoben to investigate the fracture behaviour of W_f/W. Three point bending tests were conducted on notched samples. During the test the sample surface was observed by an electron microscope to monitor the crack propagation. Several toughening mechanisms leading to controlled crack propagation could be identified. The samples showed increased fracture toughness compared with the non-reinforced counterpart. The toughness was more than doubled by using the composite concept. These tests show, that extrinsic toughening works for tungsten. The next step is now to optimize the manufacturing process and produce a larger database on mechanical properties.

High Heat Flux Facility GLADIS

In the high heat flux facility GLADIS fusion-relevant combined heat and particle loads can be applied to specimen ranging from small test samples to complete actively cooled components. The applicable power density ranges from 0.5 to 45 MW/m² at particle fluxes of typically several 10^{21} $m^{-2}s^{-1}$. In 2013 this high flexibility facilitated the following investigations and experiments:

- Qualification of the manufactured HHF divertor target elements and tests of specialised targets for the test divertor unit of Wendelstein 7-X
- Performance tests of tungsten monoblock chains delivered by F4E for the divertor of ITER
- Experimental determination of the transient heat absorption of W divertor materials for infrared thermography on JET and ASDEX Upgrade
- Materials qualification and divertor component development in the frame of the EFDA PPP&T high heat flux materials programme in collaboration with KIT and FZ Jülich
- Investigation of EAST divertor materials and components in the frame of a Sino-German Collaboration
- Investigation of the gas retention and erosion behaviour of actively cooled tungsten targets under high heat load and combined H and He particle load
- Start of construction of a high pressure and hot-water cooling loop to meet the expected cooling conditions of ITER and water-cooled DEMO components.

For Wendelstein 7-X the qualification of the series manufacturing of the HHF targets was continued. The result of the statistical assessment of about 10 % of the delivered elements confirms the stable industrial manufacturing process without any indications of degradation of the thermal performance (see Wendelstein 7-X, section 4.1).

Tests of ITER divertor mock-ups were conducted to investigate the performance of the W material under HHF loading resulting in 1500 °C surface temperature. This causes recrystallisation and grain growth. The experiments were conducted in collaboration with the ITER Organisation, FZ Jülich, and DIFFER.

The purpose of the experimental determination of the transient heat absorption of W divertor materials was the validation of the computer code and input parameters used to determine local power fluxes on divertor targets from infrared thermography. These experiments have been performed in support of the JET ITER-like Wall programme as well as the ASDEX Upgrade programme.

In the frame of the PPP&T High Heat Flux Materials programme samples designed and manufactured by KIT were tested in GLADIS. The surface modifications after hydrogen loading at 10 MW/m² of newly developed tungsten materials produced by powder injection moulding at KIT were investigated. Water-cooled divertor component mock-ups designed by KIT were tested successfully up to 6 MW/m².

Actively Cooled Tungsten Targets under H/He Heat Flux: Gas Retention and Erosion

In terms of physical sputtering tungsten is considered to be the material, which will yield the maximal lifetime of plasma-facing components in future fusion reactors. It is, however, well known that exposure of tungsten surfaces to He can lead to the formation of very distinct surface and near-surface features. Therefore the surface morphology modification of actively cooled tungsten components under bombardment with H/He mixtures relevant for a reactor divertor was investigated in GLADIS. Mock-ups were exposed to simultaneous loading with a high power density and high particle flux consisting of a H beam with an admixture of He in the range of a few percent. The admixture of He into the beam has a distinct effect on the morphology, which forms during bombardment. Above 600 °C the near-surface layer contains bubbles with sizes in the range nm to µm. It had already been reported that this influences the erosion behaviour of tungsten. For 6 % He admixture the erosion exceeds the prediction by physical sputtering data by roughly a factor of 2.

In 2013 the experiments were continued by employing H beams with 1 at.% He. In the investigated fluence range between 1×10^{24} and 1×10^{26} m^{-2} no dependence of the morphology development was observed. Even for the lowest investigated fluences scanning electron microscopy showed a bubble layer with a thickness, which is presumably the result of a dynamic equilibrium of morphology formation and material erosion. This thickness depends on the He concentration in the beam.

Temperature programmed desorption (TPD) was performed on a set of samples after GLADIS exposure using a linear temperature ramp of 5 °C/min up to a temperature of 1080 °C. During the heating phase both, H and He showed a distinct structure in the desorption signal. While the amount of desorbing He decreased significantly in a subsequent 80 minutes hold phase at 1080 °C, the H signal decayed only very slowly. Therefore a long time desorption was performed holding the sample at 1080 °C for nearly 30 hours. Apart from the features observed during ramping up, a very slow decay of the amount of desorbing H was found in the hold phase.

This behaviour is consistent with model expectations about the diffusion of H in tungsten, which is slowed down in the presence of traps. The experimental results were compared to the desorption curve computed from a diffusion-trapping model. The aim was to investigate if the slow decay of the H desorption signal is compatible with the result of a diffusion trapping model. For simplicity a constant trap concentration of 2×10^{-5} was assumed throughout the sample with a single binding energy of 2 eV. Furthermore, it was assumed that all traps were filled prior to the TPD ramp. The comparison is shown in figure 3. As can be seen the experimentally observed long time desorption behaviour at constant temperature can be satisfactorily described by a diffusion trapping model.

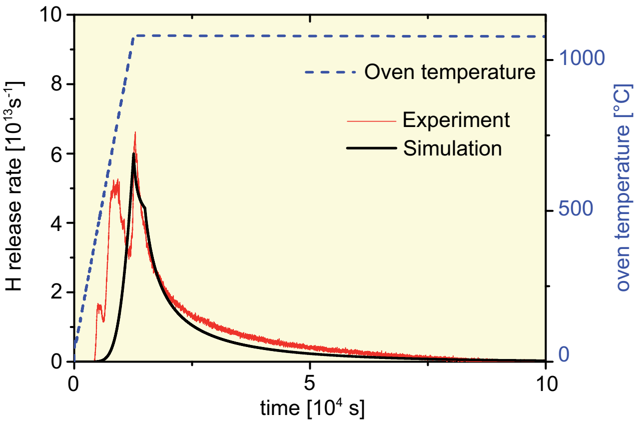

Figure 3: Investigation of the long-term hydrogen release from a tungsten sample exposed in GLADIS. The red line is the hydrogen release rate and the blue dashed line the oven temperature. The black line is a numerical simulation from a diffusion-trapping model.

Integration of and Collaboration in EU Programs

EU Task Force on Plasma-wall Interaction

The project continues to support the EU PWI Task Force on Plasma-Wall Interaction. Members of the PFMC project act as TF leader and as project leaders for “Fuel Retention” and “Formation and re-erosion dynamics of ITER-relevant mixed materials”. Furthermore, the project provides input to a variety of tasks in numerous individual projects. Many of these tasks are carried out in close cooperation with other EURATOM Associations. Further contributions have been made to projects coordinated under the EU Topical Group “Materials” on W materials development and high heat flux investigations as well as on steel as PFM. Within the EFDA Fusion Programme the Project provides two mid-size facilities – the High-Heat-Flux Test Facility GLADIS and the Integrated PWI Facility – and supports the PWI-relevant investigations at ASDEX Upgrade.

EFDA PPP&T Task “Bare Steel Wall”

Within the EFDA work programme 2013 on Power Exhaust IPP continued its participation in the task agreement “Bare Steel Wall” as the coordinating partner. Together with five European Fusion associations as partners the investigations on the direct applicability of uncoated low-activation steel as plasma-facing material were extended.

Within the PFMC project at IPP three main activities were pursued:

Based on a finite element analysis it has been decided to install two full toroidal rows of the ferromagnetic steel P92 on the central column of ASDEX Upgrade. The installation of these steel tiles was completed in 2013.

The second activity consists of laboratory measurements on the erosion behaviour of the low-activation steel EUROFER 97. To achieve high erosion fluences this was performed using deuterium plasma exposure in the high-flux linear plasma device PISCES in collaboration with the University of California in San Diego. On the other hand energy- and species-resolved measurements of the erosion yield were performed using IPP’s high current ion source. In both cases a reduction of the erosion yield with fluence was observed. By ion beam analysis this was attributed to preferential sputtering of the lighter elements and the corresponding enrichment of W. Preliminary experiments indicated that the reduction of the erosion yield is diminished at elevated temperatures.

The third activity was a numerical study of the steel erosion behaviour using the code SDTrimSP. The energy-resolved erosion measurements mentioned above were used to benchmark the code results. This activity is important since a well-benchmarked code is the only tool, which can be used to make predictions for application in a DEMO reactor.

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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.

Microscopic Investigation of Radiation Damage in Tungsten and its Influence on Deuterium Retention

Hydrogen isotope retention in radiation damage produced in plasma-facing components by fast neutron bombardment is important for both ITER & DEMO due to plasma performance and due to safety limitations by the accumulation of tritium in the damaged material. Tungsten samples were irradiated by 20 MeV W^{6+} ions in order to create radiation-induced damage as proxy for radiation damage by neutrons at different damage levels and at different temperatures. The samples were made of polycrystalline tungsten manufactured by Plansee AG with grains elongated perpendicular to the surface (ITER-grade W). They were mechanically polished to a mirror-like finish and recrystallized at 2200 K for 10 minutes. Accumulation and recovery of radiation defects under/after self-ion irradiation were investigated by decoration with deuterium and by scanning transmission electron microscopy (STEM). Self-ion irradiation leads to a rather high D retention (≥0.1 at.%) in W even at high temperatures (≥700 K) due to the formation of defects with high de-trapping energy for deuterium. The annealing of defects with low trapping energy for D occurs in the temperature range between 300 and 700 K. Radiation-induced defects with high de-trapping energy are thermally stable at least up to 1100 K. This conclusion was supported by the scanning transmission electron microscopy data.

In-situ Deuterium Depth Profiling in Tungsten during Interaction of Atomic Deuterium with Undamaged and Self-ion Damaged Tungsten

Tungsten samples were irradiated by 20 MeV W^{6+} ions at room temperature in order to create radiation-induced damage. The undamaged and damaged samples were then exposed to an atomic deuterium beam at sample temperatures from 500 to 900 K. Comparison of in-situ NRA at JSI in Slovenia and ex-situ NRA at IPP shows reasonable agreement for the D concentrations in the damaged area, indicating trapping of D at radiation-induced defects. A considerably higher D concentration was found by in-situ NRA analysis compared to ex-situ NRA in the undamaged area at depths >3 µm, indicating either some dynamics of D retention in solution and in weak traps or the creation of additional traps by the analyzing He beam.

Deuterium Retention in TiC and TaC Doped Tungsten at High Temperatures

Deuterium retention in tungsten doped with 1.1 wt% TiC and 3.3 wt% TaC (manufactured at Tohoku University, Japan) was investigated by irradiation with 38 eV/D ions at 800 K to fluences up to 1.8×10^{25} D/m^2 or exposed to D_2 gas at a pressure of 100 kPa at 800-963 K for 24 hours. The retention was studied by nuclear reaction analysis and thermal desorption spectroscopy. In the case of irradiation at 800 K, deuterium retention in W-3.3TaC was comparable to that in as-received W, while the retention in W-1.1TiC was several times higher. In the case of exposure to D_2 gas, at all used temperatures the bulk deuterium concentration in W-1.1TiC was more than one order of magnitude higher than that in W-3.3TaC or in pure tungsten. The highest deuterium bulk concentration in W-1.1TiC was observed in the case of exposure at 800 K and was about an order of magnitude higher than that after irradiation at 800 K.

Deuterium Retention in Undamaged and Damaged Rusfer

The deuterium retention in damaged and undamaged reduced-activation ferritic-martensitic steels (RAFMs) was investigated under exposure to deuterium gas. RAFM Rusfer (EK-181) samples were damaged by 20 MeV W^{6+} ions to a maximum damaging fluence of 0.89 dpa (1.4×10^{18} ions/m^2) for the simulation of damage by neutron irradiation, by pulse heat loads in the QSPA-T facility with 10 pulses of 0.5 MJ/m^2 with a duration of 0.5 ms, and by low-temperature plasma irradiation in the LENTA facility at 320 and 600 K to a fluence of 10^{25} H/m^2. The deuterium retention was investigated in the temperature range of RT-773 K at a pressure of 10^4 Pa. Deuterium depth profiles were measured by nuclear reaction analysis (NRA) to a depth of about 8 µm. Deuterium retention in damaged and undamaged Rusfer in the temperature range of 300-600 K has a maximum at about 500 K for all investigated damage types. Typical values of deuterium bulk concentrations are of the order of 10^{-3} at.%. Irradiation by W ions results in an increase of the deuterium retention by a factor of about two, irradiation of Rusfer with high heat fluxes or high-flux irradiation with a low temperature plasma at elevated temperature leads to a decrease of the retention in Rusfer.

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Plasma Theory

Theoretical Plasma Physics

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

The project "Theoretical Plasma Physic" is devoted to first-principle based model development with emphasis on magnetic confinement. It combines the efforts of the divisions Tokamak Physics, Stellarator Theory and Numerical Methods in Plasma Physics, of a Junior Research Group and of the HLST Core Team of the EFDA HPC Initiative. It is also a major partner in the Max Planck Princeton Center for Plasma Physics.

Tokamak Physics Division

Head: Prof. Dr. Karl Lackner

Tokamak Edge Physics

Significant effort went into supporting and developing the SOLPS package. During controlled ELMs in ITER very high electron temperatures (>100 eV) and densities (>10^{21} m^{-3}) at the outer target can be reached, as follows from SOLPS code modelling. Monte-Carlo simulations of sputtered tungsten (W) redeposition during such ELMs were performed. Under these conditions, sputtered W can undergo multiple charge ionizations during the first gyro-motions. High T_e near the target also implies rather high electric potential variations across the widths of order of W ion Larmor radii. The potential variation, in turn, is related to density variation in the magnetic pre-sheath (MPS). All these effects (multiple charge ionizations, potential and density variations) were included in the simulations. It was shown that the probability of W redeposition is very close to 100 % (non-redeposition fraction below 10^{-4}) for expected ITER controlled ELM conditions. Even for significantly lower temperatures (~10 eV) and lower densities (~10^{20} m^{-3}) the redeposition probability remains close to 100 %, implying small amounts of originally sputtered W penetrating into the main plasma. It was also shown that there is a significant safety margin against a possible W self-sputtering avalanche, the process, in which circulation of W in the MPS and Debye sheath would lead to progressively higher W energies above those, for which the self-sputtering yield equals 1. Results of simulations are applicable to a wide range of plasma conditions at the target plates that can be encountered in various magnetic confinement fusion devices.

A 3D turbulence code called GRILLIX is developed, which is aimed on simulating the region around the separatrix, treating both open and closed flux surfaces on the same footing. The main ingredient of the code is a grid consisting of a few poloidal planes and a flux surface independent Cartesian grid within each poloidal plane. With this approach the dynamics around the X-point is resolved most naturally. Simple standard finite difference methods within a plane can be applied for perpendicular operators. Parallel operators are discretised via a field line tracing procedure and an interpolation within the neighbouring poloidal planes (field line map). With this approach the toroidal resolution can be reduced drastically (in practice 2-16 poloidal planes). For the parallel diffusion operator it has been shown, that the numerical diffusion arising due to the interpolation process can be brought below a negligible limit by using the support operator method. The first target model is the Hasegawa-Wakatani equations. It has been shown that in the cylindrical limit GRILLIX yields the same results as obtained with flux tube codes, which make use of a field aligned grid but cannot be used around the separatrix. Zonal flows, which are n=0, m=0 radially sheared flows, are obtained correctly with GRILLIX (figure 1), showing indeed that numerical diffusion due to the field line mapping procedure does not introduce any significant errors. First preliminary results for geometries with shaped flux surfaces and with an X-point have been obtained and work towards this direction is being further pursued.

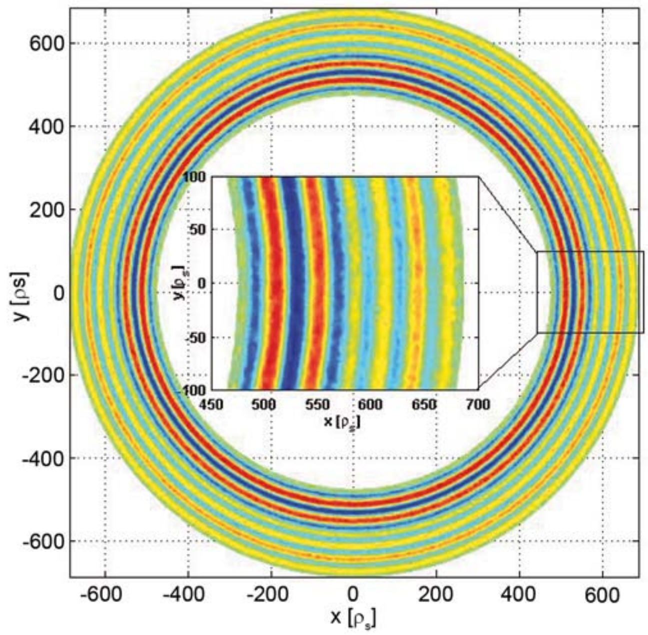

Figure 1: Snapshot of a GRILLIX 3D turbulence simulation in saturated state. The electrostatic potential on the first poloidal plane (toroidal angle φ=0) is shown. Zonal Flows are not damped away spuriously by numerical diffusion but are obtained correctly.

MHD Theory

Equilibrium Calculation and Stability Analysis

The axisymmetry of tokamak equilibria may be violated by external perturbation fields, asymmetrically placed Test Blanket Modules (TBMs), formation of a helical core, etc. Therefore, three-dimensional ideal MHD tokamak equilibria were computed with the code NEMEC, and their stability properties were investigated with the code CAS3DN, which is a linear ideal MHD code. These computations were performed for AUG-type equilibria perturbed by Resonant Magnetic Perturbation (RMP) fields, and for an ITER scenario taking into account the toroidal field ripple and perturbation fields caused by TBMs. The introduction of a measure of the corrugation of the flux surfaces allowed the quantification of the surface deformation. Contour plots of the corrugation, and its Fourier decomposition in magnetic coordinates revealed kink-type structures, which were correlated with the q-profile and the periodicity of the plasma equilibrium. 3D tokamak equilibrium calculations are numerically very demanding. An adequate choice of the numerical parameters (e.g. number of harmonics, radial surfaces, etc.) is essential. To decide whether the number of iterations was sufficient or not, it was very important to study the development of the corrugation in dependence of the number of iterations. Further studies demonstrated the influence of the corrugation on the stability properties. Both, stabilizing and destabilizing effects of the RMP fields, and an influence of the TBMs on the stability properties were observed. For numerical reasons only low-n modes ($n \leq 4$) were considered, but one would expect similar effects for higher mode numbers. Therefore, the effect of RMP fields on the ELM behaviour observed in several tokamaks might be partly caused by the modified stability properties of the deformed equilibrium. That is, ELM mitigation might not only be a resonance phenomenon.

Non-linear MHD

The nonlinear growth of the internal kink mode is studied numerically using reduced MHD equa-tions in cylinder geometry. For a low Lundquist number, $S<10^7$, usual sawtooth reconnection is seen as before: a m/n=1/1 magnetic island grows while the original core shrinks, where m and n are the poloidal and toroidal mode numbers, respectively. For higher S values, however, the mode growth is found to be qualitatively different and to have three phases: (1) Linear and earlier nonlinear phase: The m/n=1/1 island grows and a plasma current sheet forms at the resonant surface; (2) Nonlinear phase: The current sheet is broken up and the secondary island grows; (3) Tearing mode phase: The 1/1 and the secondary island changes in the tearing mode time scale. The reconnection time in phase 1 and 2 is much shorter than that predicted by Kadomtsev's model, while the secondary island in phase 3 prevents fast complete reconnection. Compared with the results from reduced MHD equations, a much faster sawtooth crash, with the crash time about 50 μs, is found from two-fluid equations for typical ASDEX Upgrade parameters, in agreement with experimental observations. The electron pressure gradient in the generalized Ohm's law is the dominant effect (finite ion sound Larmor radius effects). In the framework of two-fluid equations, local shear plasma flow is driven by the internal kink mode. The driven plasma flow is in the counter (co-) current direction inside (outside) the q=1 surface in the linear phase and propagates towards the magnetic axis during the nonlinear mode growth. After the sawtooth crash, the driven plasma rotation is in the co- (counter-) current direction inside (outside) the q=1 surface, in agreement with TCV experimental observations.

Benchmarking for plasma edge instabilities between the non-linear MHD code JOREK and the linear MHD code CASTOR has been started. When completed, this will help to profit better from the complementary approaches: While the linear model is better suited to access a large number of different cases or parameters and high resolutions, the non-linear approach is required to investigate ELM sizes, heat flux patterns, or other intrinsically non-linear phenomena.

In previous non-linear MHD simulations of edge localized modes in ASDEX Upgrade the non-linear drive of low-n toroidal harmonics, particularly n=1, by quadratic mode coupling has been demonstrated. Those simulations were focussed on the early non-linear phase up to the onset of non-linear mode saturation. Now first simulations of full ELM crashes have been carried out for realistic ASDEX Upgrade configurations including a large number of toroidal harmonics ($0 \leq n \leq 22$). In these simulations components with low toroidal mode numbers play an important role also during the fully non-linear state.

The resistive wall model given by the coupled code JOREK-STARWALL was successfully benchmarked for vertical displacement events of an ITER-like X-point plasma. While previous simulations of vertical displacement events and resistive wall modes performed with JOREK-STARWALL took into account the vacuum response only for a single toroidal harmonic, the implementation was extended now to correctly treat the vacuum response of several toroidal harmonics.

Energetic Particle Physics

The numerical investigation of global instabilities excited by energetic particles with the nonlinear gyrokinetic code NEMORB was continued. NEMORB is the electro-magnetic, multi-species version of the global PIC code ORB5, previously used mainly for turbulence studies. As a first step we have focused on the benchmark for Geodesic Acoustic Modes (GAM) against analytical theory in the absence of energetic particles. Linear electrostatic global simulations of GAMs with equilibrium profiles compatible with those in ASDEX Upgrade have been performed and compared with results of LIGKA, showing a good agreement and opening the way to realistic tokamak modelling. A shifted-Maxwellian fast particle distribution function has been implemented in NEMORB, and energetic-particle induced GAMs (EGAMs) have been investigated. The EGAM frequency and the growth rates calculated with NEMORB agree with the predicted theoretical values. Numerical benchmarks of EGAMs have been performed against the gyrokinetic semi-Lagrangian code GYSELA. Electromagnetic simulations of GAMs and EGAMs with NEMORB for low beta proved the capability to deal with the problem.

First scalings for Alfvén oscillations have been obtained with NEMORB and compared with analytical theory. The linear gyrokinetic code LIGKA was used to study EGAMs in off-axis beam-driven ASDEX Upgrade scenarios. At low temperature these modes can be excited together with BAEs (beta-induced Alfvén eigenmodes). Basic dependencies on temperature, density, safety factor and magnetic shear profile were investigated in order to understand linear existence criteria in preparation for non-linear multi-mode studies.

The nonlinear hybrid HAGIS model was further adapted to study energetic particle (EP) transport and losses in realistic ASDEX Upgrade scenarios. As a crucial new element a consistent ICRH-generated EP distribution function has been implemented into HAGIS. Together with previous extensions for obtaining the perturbation structures, frequencies and damping rates as obtained from the gyrokinetic eigenvalue solver LIGKA, we obtained a HAGIS version that could successfully be applied to experimental scenarios. The simulated losses' phase space pattern coincides very well with the measurements of the fast ion loss detector in an ASDEX Upgrade reference discharge. The simulations show the high prediction capability of the code package and they reveal interesting physics: in these scenarios a linearly subdominant mode becomes dominant in the late nonlinear phase. A resonant and a stochastic transport regime could be identified and the EP losses could be classified as prompt, resonant or stochastic (diffusive). The multi-mode character of the scenario (e.g. the role of subdominant modes) was found to be crucial for losses in the lower energy range. Only with the most realistic modelling of the eigenfunction the experimentally observed losses at very low energies could be reproduced numerically.

Kinetic Theory and Wave Physics

A temperature anisotropy of the main ion species can compete with the plasma rotation in causing poloidal asymmetries of the high-Z impurity density, and a natural way of inducing temperature anisotropies of the ions is ICRF heating. The TORIC-SSFPQL package has been used to estimate these ICRF-induced temperature anisotropies in AUG discharges, which were designed to show evidence of in-out poloidal asymmetry of tungsten. This application together with the interest for the impact of ICRF heated (energetic) species on Alfvénic activity motivated the extension of the SSFPQL model to include trapping effects: development and implementation of these effects have been pursed during the year with preliminary results. A major technical change in the TORIC-SSFPQL has been the parallelization, which now is done for the loop over toroidal modes. Within the ITM activity a cross-code benchmark effort has been started and coordinated, and first results have been obtained and documented. In particular, scans over the concentration of the minority species have shown that already at low concentration of He3 (~3 %) it is possible to achieve good performances of minority heating in full-field ITER-like discharges.

The new code WKBeam that solves the wave kinetic equation for high-frequency waves has been developed. It is based on a phase-space treatment that allows a consistent description of caustics and wave scattering from small-scale density fluctuations, which cannot be treated in a standard ray/beam tracing scheme. The code retains diffraction effects, a general form of the scattering operator (derived in a perturbative approach), the control of mode-to-mode scattering, full tokamak geometry and it allows the determination of the absorption profile. Analytic and numerical results indicate that scattering of electron cyclotron waves from turbulent density fluctuations is not diffusive in AUG but will be diffusive in ITER. For beams injected from the ITER upper launcher, a broadening of the deposition profile by a factor of two or more should be expected for realistic turbulence parameters.

Gyrokinetic simulations for a magnetic island have been performed with the code GKW, with the goal of isolating the contribution of the polarization current, in planar and toroidal geometry. Slab-geometry runs with low magnetic shear have been found to be prone to Kelvin-Helmholtz instability and lead to solutions different from analytic predictions. In toroidal geometry, the polarization current is mixed with, and often dominated by, other physical effects related to the dynamics developing across the island separatrix, thus changing the related picture of tearing mode stability. For further results on this topic, see the section Collaboration with University of Bayreuth.

The studies of the neoclassical transport of low-Z impurities in the pedestal region of a Tokamak H-mode plasma were continued. For some ASDEX Upgrade discharges, simulations with input data from the experiment were performed. The results for poloidal and parallel impurity velocities helped explaining the measurements. The parallel force balance shows that the friction between impurities and main ions causes the strong poloidal density asymmetry. The ratio v/D between the pinch velocity and the diffusion coefficient scales linearly with the ion charge as in the analytic neoclassical theory.

The current flow between two electrodes in a low-temperature plasma confined by a cusp magnetic field was studied with PIC simulations resolving the full gyro-motion. A current across the magnetic field produces a j×B force, which imparts momentum onto the plasma. The goal is to find out where the current is flowing and how much momentum can be transferred. This should contribute to the understanding of plasma dynamo (and related) experiments. A slab model was devised with two electrodes floating in the plasma with a given potential difference between them. First results show the importance of a strong plasma source for keeping up the current in case of an electron emitting cathode.

Transport Analysis

Research activities have been mainly dedicated to different aspects of particle and impurity transport. Theoretical developments performed over the previous years in order to obtain a complete description of heavy, highly charged, impurity transport in the presence of strong rotation have been applied to specific modelling of W transport in JET discharges. The results of the modelling and the combined experimental analysis are presented in the section on JET collaborations. From a theoretical perspective, this work has highlighted the importance of correctly taking into account the neoclassical transport enhancement produced by centrifugal effects. This implies that turbulent transport becomes relatively less effective in offsetting the neoclassical pinch in highly rotating plasmas. This result has also motivated the extension of the modelling tools in order to include the effect of poloidal asymmetries caused by the presence of fast ion populations, which are produced by auxiliary heating systems, like ion cyclotron resonance heating (ICRH) and neutral beam injection (NBI).

Quasi-neutrality implies that the poloidal inhomogeneity of fast ion populations is accompanied by the development of a background electrostatic potential. This can strongly impact the poloidal inhomogeneity of highly charged impurities. In order to properly compute these effects on turbulent transport, fast ion populations, like ICRH minority ions, have been included in the code GKW in the form of a bi-Maxwellian distribution, which can be taken into account by the equilibrium quasi-neutrality solver. From the standpoint of neoclassical transport previously published analytical studies have been extended in order to also compute the effects of this type of impurity density asymmetries. It is found that neoclassical transport of heavy impurities is strongly enhanced not only by strong out-in asymmetries, like in the presence of centrifugal effects, but also by strong opposite in-out asymmetries. In contrast, transport can be reduced in case the in-out asymmetry is sufficiently weak.

Nonlinear local electromagnetic gyrokinetic turbulence simulations of the ITER standard scenario have been performed with parameters at the q=3/2 surface in order to investigate the electron transport in that regions of the velocity space characteristic of electrons carrying the current generated by electron cyclotron waves. Electromagnetic fluctuations and subdominant microtearing modes are found to contribute significantly to the transport in these regions of the velocity space, even though they have only a small impact on the transport of bulk species. For nominal parameters, the predicted particle diffusivities are small enough to imply minimal broadening of the current drive and heating profiles. However, a high sensitivity of the transport level to an increase of beta has also been found, which can lead to more significant broadening effects in high beta scenarios.

Turbulence Theory

Theoretical understanding of mesoscale and microscale turbulence is required for developing a predictive capability of heat, particle and momentum transport in tokamaks and stellarators. In recent years, the global particle-in-cell gyrokinetic code ORB5 has been upgraded with intra- and inter-species Landau collision operators for ions and electrons. In addition to this, electromagnetic perturbations have been included in the model allowing for a complete self-consistent and fully kinetic treatment of finite beta effects. More recently, the model has been extended to include new 3D diagnostics, allowing for measurements of electromagnetic potentials and relevant fluid quantities (density, temperature, vorticity) as well as turbulence spectral analysis. Those diagnostics have been successfully applied to the study of electrostatic (adiabatic electrons) ion temperature gradient (ITG) driven turbulence, focusing in particular on the convergence properties of the different spectra and on the role of the plasma shape. The new 3D diagnostics were applied to the case of ITG driven turbulence in the presence of a finite beta and trapped electron dynamics. Local and global spectra reconstructed from the 3D diagnostics showed that finite beta effects and kinetic trapped electrons have little influence on the fluctuations spectra of ITG modes, despite their strong influence on the level heat transport.

Various representations of the plasma model within gyrokinetic theory were developed to increase understanding of some of the issues involved in the interplay between polarisation and higher order drifts. By using the canonical toroidal momentum rather than the canonical parallel momentum as a coordinate, all of the effects of magnetic curvature are removed from the parallel phase space bracket and included among the spatial drifts. While the penalties in terms of velocity space resolution are large (the unperturbed parallel energy becomes proportional to the square of the toroidal major radius), this has been found very useful to gyrofluid theory since the benefits remain after the details of velocity space are integrated away. Momentum conservation satisfies the same equation in both the gyrokinetic and gyrofluid representations. The rearrangement of geometric factors leaves both pieces of the nonlinear parallel gradient (perturbed and unperturbed, according to the dependence upon the non-equilibrium magnetic potential) in exactly the same form they have in fully nonlinear reduced MHD (low beta, moderate aspect ratio). It follows that the equations cover all aspects of nonlinear reduced MHD, hence most of the large-scale, nonlinear magnetic dynamics expected in large tokamaks. A numerical model under construction intended to investigate the self consistent interplay between magnetic equilibrium, global MHD, turbulence, and rotation will be thoroughly tested against existing MHD results.

We continued our collaboration with the research group “Complex Systems” at the University of Innsbruck. Study of the effect resonant magnetic perturbations (RMPs) on edge turbulence was continued this year to focus on Edge Localised Modes (ELMs), which are thought to be due to a breakout phase of an MHD instability in the steep gradient region. Edge turbulence computations with the GEMR code (electromagnetic gyrofluid with global geometry variation) were augmented with an external perturbation given by a parallel magnetic potential with zero current satisfying the boundary conditions, which then gives rise to the Resonant Magnetic Perturbation (RMP) magnetic field. In the linear and nonlinear phases of the instability the electron screening of the RMP is still effective, so that the magnetic flutter transport (parallel motion, radially on perturbed field lines) is not significantly changed from the non-RMP control case. Even for large RMP amplitudes the radial transport is still dominated by turbulent E×B advection, while formation of stationary convective structures leads to edge profile degradation. In modelling using single bursts, the RMP causes resonant mode locking and destabilisation. Analysis of the combination between an RMP and oscillatory E×B flows shows the tendency to take energy out of the flows. However, results of this sort should only be used for experimental modelling when the control case is a successful self consistent capture of the H-mode state, and this lies in the future.

Collaboration with Princeton Plasma Physics Laboratory continues on two projects: plasma micro-turbulence and edge plasma simulation.

EFDA Task Force 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 (Core and Edge Transport, Turbulence), and one deputy project leader (Software Infrastructure). Development work was performed as a collaborative activity between LSPM-CNRS (Paris) and IPP on SOLPS to support the generation of grids extending to the main chamber wall, and then the use of these by B2. The work on coupling SOLPS to the ITM core transport code “ETS” was continued and simulations for ITER (with D, T, He, Be, Ne, W) have been performed. Further ITM contributions have been made in the areas of turbulence and heating. Much of the ITM activity was centred around two-week “Code Camps” in Garching, Madrid, Helsinki, Ljubljana, and Lisbon with significant IPP attendance. TOK together with significant input from the RZG has successfully provided the 256 core Gateway Cluster to EFDA for use by the ITM.

MAPPER Project

IPP was one of the partners involved in the EU FP7 project MAPPER (Multiscale APPlications on European e-infRastructures), started in 2010 and completed in 2013. Using MAPPER tools, the physics of simulating plasmas on the transport time-scale taking into account plasma turbulence phenomena was addressed by coupling equilibrium, transport and turbulence codes. The equilibrium code provides metric coefficients for both the transport and turbulence codes based on the plasma profiles provided by the transport code; the turbulence code then calculates the transport coefficients needed by the transport code based on the metric coefficients (from the equilibrium code) and the plasma profiles (from the transport code); the transport code then updates the plasma profiles. This is performed within a time loop where the turbulence code runs for a short time (order micro-seconds), and the transport code uses a time-step of 1 ms – 100 ms.

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Global Gyrokinetic Simulation of Linear ITG Instability

The PIC code EUTERPE has been applied to the numerical modelling of linear ITG instabilities in W7-X and LHD. A systematic scan of temperature and density gradients was done to obtain results for the linear growth rates of ITG modes in stellarator geometry. EUTERPE runs are routinely based on pre-processed equilibrium data, e.g. from the VMEC equilibrium code, and the recent results were obtained for a 3D equilibrium at β=2 % for W7-X and β =1.5 % for LHD. Realistic plasma pressures and densities were chosen, but the simulations were done in the linear, electrostatic approximation, with Boltzmann-distributed electrons in fixed magnetic equilibria. The resulting growth rates for W7-X (which are similar to those in LHD) are summarised in the stability diagram (figure 2) showing a clear onset of linear ITG instability for $\eta=L_n/L_T\geq 1$. A "blind test" on a reduced set of the data exhibited excellent agreement between these global simulations and full-flux-surface results from the local code GENE (figure 3).

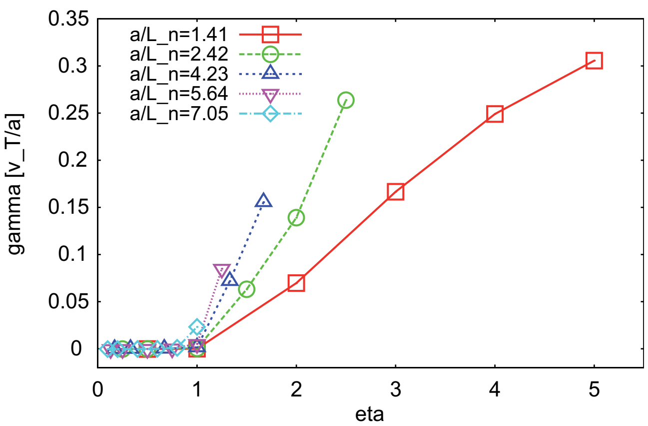

Figure 2: Linear ITG instability growth rates $\gamma=v_T/a$ in W7-X vs. stability parameter $\eta=L_n/L_T$ for a hydrogen plasma with β=2 % and T(s=0.5)=1 keV with different density gradients a/L_n.

Gyrokinetic Simulations on a Magnetic Surface

The GENE code has been used to calculate the structure of ion-temperature-gradient-driven turbulence over W7-X flux surfaces, which exhibits interesting differences compared with tokamaks. The turbulence is localised to narrow bands on the outboard side of the torus in regions of unfavourable magnetic curvature. These bands are so narrow in the poloidal direction that the turbulent transport depends on the normalised gyroradius ρ^* although the code employs a local approximation in the radial direction. It appears that this circumstance causes the transport to be less "stiff" than typically observed in tokamaks.

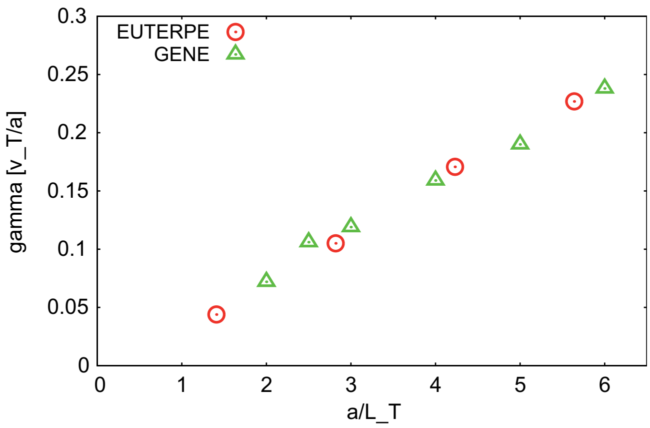

Figure 3: Linear ITG instability growth rates $\gamma=v_T/a$ in W7-X vs. temperature gradient a/L_T for a hydrogen plasma with β=2 % and T(s=0.5)=1 keV as obtained with EUTERPE (global) and GENE (local/full flux surface version).

Global Gyrokinetic Simulations

Until recently, the global gyrokinetic PIC code EUTERPE used various approximations in the set of gyrokinetic equations for numerical convenience. A long-wavelength approximation in the field equation for the electrostatic potential restricted its applicability to perturbations with kρ<1. This approximation is not admissible for trapped-electron modes, and could be a problem even for electrostatic ion-temperature-gradient modes in Wendelstein 7-X. In order to overcome this restriction, a Padé approximation has been introduced in the field equation resulting in a very good approximation to the full operator, thus extending the applicability of the code into the region kρ>>1. The direction perpendicular to the field lines was approximated by planes of constant toroidal angle both in the field equations and in the gyro-averaging operations. Additionally, the term resulting from an interchange of the gradient and gyro averaging operators was not exact. These limitations have now been removed by implementing the exact expressions resulting in a better global energy conservation of the code. In addition, an extensive comparison for linear and nonlinear tearing modes in a slab using a gyrokinetic and a four-field gyrofluid model was completed. The results showed that, over a wide range of parameters, the models agree very well. As a prerequisite for studying forced magnetic reconnection, inhomogeneous boundary conditions have been implemented.

Landau Damping of Turbulence

Dissipation is a key problem in plasma turbulence. It can affect mode saturation, it shapes the spectrum of fluctuations, and it sets the resolution requirements to correctly simulate the turbulence. The classical dissipation mechanism in turbulence involves the nonlinear transfer of energy to small scales where viscosity acts. However, another possible mechanism in a weakly collisional plasma is linear Landau damping.

In this context, it is not understood whether one dissipation mechanism should be more important than the other. Recent work has now uncovered a novel effect whereby linear Landau damping can be suppressed in a turbulent setting. The forced Vlasov equation was studied to model how a single linearly damped plasma mode will reach a quasi-steady-state sustained by nonlinear interactions with a turbulent bath. As the characteristic frequency of the source exceeds that of linear phase mixing, the damping rate tends to zero super-algebraically (figure 4). In other words "frequency detuning" causes the effective damping rate to be "zero at all orders" in the frequency ratio. It is also shown that, under the right circumstances, the opposite can occur: a linearly damped wave can act as a source of energy for the turbulence. This "nonlinear instability" could give rise to turbulence below the linear instability threshold.

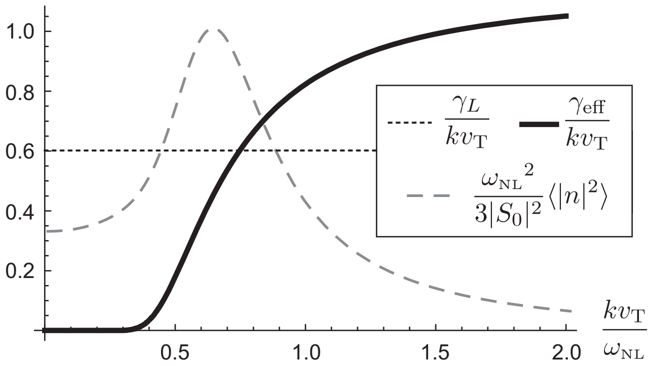

Figure 4: Super-algebraic falloff of effective damping rate γ_{eff} under detuning of the forcing frequency ω_{NL}. The expected Landau damping rate (γ_L) is shown for comparison. Frequencies are normalized to the linear rate of phase mixing kv_{th} and S_0 is the amplitude of forcing.

Numerical Confirmation of Enhanced Microstability in Quasi-isodynamic Stellarators

It has previously been shown that magnetic configurations where the second adiabatic invariant J decreases with plasma radius, so-called maximum-J configurations, are stable against conventional trapped-electron modes (TEM) and lower-frequency trapped-particle modes in large regions of parameter space. Quasi-isodynamic stellarators, for example W7-X at high plasma pressure, fulfil this property approximately. In order to assess whether stability also holds in only approximately quasi-isodynamic configurations, extensive numerical studies were carried out. The DIII-D tokamak, the quasi-axisymmetric stellarator NCSX, Wendelstein 7-X, and a more quasi-isodynamic configuration were investigated by means of electrostatic flux-tube simulations using the gyrokinetic code GENE. While DIII-D and NCSX showed similar growth rates for both ion-temperature gradient modes (ITGs) with adiabatic and kinetic electrons and TEMs, the growth rates were significantly lower in both W7-X and QIPC in all simulations that included kinetic electrons. This enhanced stability is due to the fact that these electrons draw electrostatic energy from the instabilities, as predicted by the analytical theory.

Neoclassical Impurity Transport

Extensive calculations of neoclassical impurity transport have been performed including Φ_1, the part of the electrostatic potential that varies over magnetic surfaces. Extending previous studies where Φ_1 was set as an input provided by the code GSRAKE, the gyrokinetic code EUTERPE has now been used to calculate both Φ_1 and the neoclassical transport fluxes. These simulations have confirmed that Φ_1 can affect the transport significantly. This influence on the impurity transport has been found to be inherent to the non-stellarator-symmetric character of Φ_1. In particular, a correlation of larger amplitude $\sin\vartheta$ component of Φ_1 (where ϑ denotes the poloidal Boozer angle) with larger departure from the standard neoclassical prediction has been found, see figure 5. The presence of such $\sin\vartheta$ components in Φ_1 is understood by the fact that Φ_1 inherits these from the part of the distribution function of the bulk species responsible for its transport in stellarator symmetric equilibria. These conclusions are of special relevance to LHD and TJ-II, whereas for Wendelstein 7-X the amplitude of Φ_1 is not large enough to affect the impurity particle transport appreciably.

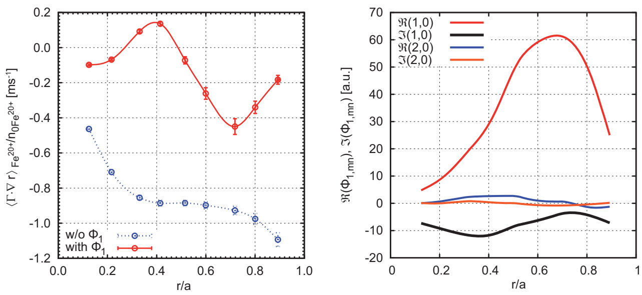

Figure 5: Left: Normalized particle flux density of Fe^{20+} as a function of the effective radius at LHD including Φ_1 (solid) and neglecting it (dotted). Right: Amplitudes of the real and imaginary parts of the Fourier coefficients of Φ_1 for the modes with larger amplitude.

Further developments of EUTERPE on the neoclassical side include the implementation of a collision operator conserving particle, parallel momentum and energy. A benchmark of the non-local neoclassical version is planned against the code FORTEC-3D.

Fast Energetic Particles and Alfvén Eigenmodes

To describe the interaction between fast particles and otherwise stable Alfvén eigenmodes, a fully kinetic description is necessary. In many cases, it is possible to restrict the kinetic description to the fast particles and describe the bulk plasma as a fluid.

Recently, the three-dimensional ideal-MHD eigenvalue solver CKA has been coupled to the gyrokinetic particle-in-cell code EUTERPE. In this hybrid model the growth rate can be inferred from the energy transfer from the energetic particles to the MHD mode. This model has been extended to work in the non-linear regime keeping the spatial structure of the MHD mode fixed but allowing the amplitude and phase to change in time according to the calculated energy transfer from the fast particle component. The necessary equations relying on the energy transfer between the wave and the particles have been derived and an energy theorem could be formulated. In a tokamak, the saturation level of the perturbations has been calculated (figure 6). A secular growth of the perturbation is observed when no damping mechanism for the wave is present. This finding is in agreement with those of other groups.

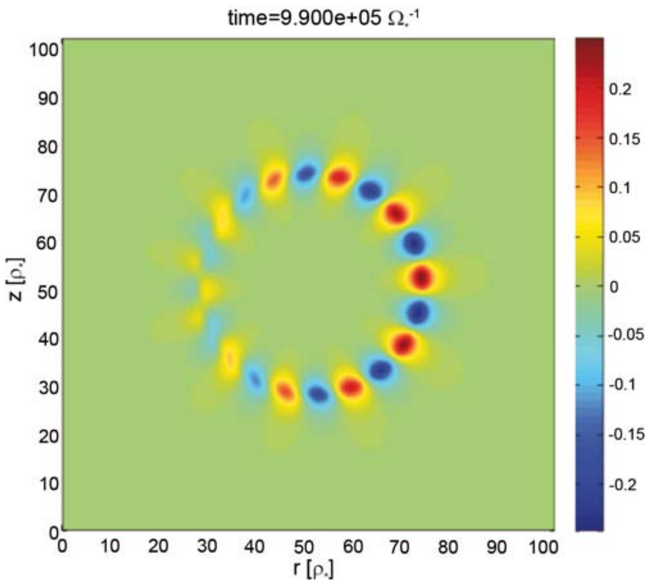

Figure 6: Saturated electrostatic potential with an external damping of $2.5 \cdot 10^{-3}\ s^{-1}$.

Furthermore, the effects of finite fast-ion orbit width (FOW) and Larmor radius (FLR), the role of the equilibrium radial electric field, as well as the effect of anisotropic fast-particle distribution functions on have been studied in W7-X geometry. In addition, a preliminary stability analysis of a HELIAS reactor configuration has been undertaken. FOW and FLR stabilisation effects are important in W7-X but are found to be much weaker in the reactor. An effect of the equilibrium radial electric field, which is stabilizing in the electron-root regime, may be attributed to a modification of the fast-ion drift orbits. The effect of anisotropy in the background fast-ion distribution function has been considered in the cases of a "loss-cone" and an "ICRH-type" distribution function. The latter type of anisotropy may inhibit AE mode destabilisation since most of the fast-ion energy is concentrated in the perpendicular particle motion. In the reactor plasma, the stability properties were considered under plasma conditions predicted by transport modelling. An unstable HAE mode was found with large growth rate, $\gamma/\omega \approx 4$ %, but it must be borne in mind that only the drive and damping directly related to the fast ions have been studied so far. The damping mechanisms associated with the bulk plasma (collisional, continuum and radiative damping) have been ignored. Nevertheless, the calculation shows that Alfvén eigenmodes could be driven unstable by alpha particles in a stellarator reactor.

Ideal MHD

The CAS3D code can be used to calculate the effect of finite plasma pressure on stellarator equilibria. A recent application involves determining the change of the internal 5/6 island width in W7-X with increasing plasma-beta. In parallel, the CAS3D code development was continued further on the perturbed-equilibrium line. The code now makes it possible to calculate effects arising in finite-plasma-beta equilibria due to a change in the plasma pressure or an external field perturbation. Within an ITPA collaboration, the ideal MHD equilibrium code VMEC has been used to determine the corrugation of the plasma edge due to resonant magnetic perturbations (RMPs) in three ITER single-null baseline cases. With a number of n=4 and n=3 RMP patterns, generated by the active ELM-control coils foreseen in the ITER design, edge displacements of up to 5 cm (2.5 % of the minor radius) have been observed.

MHD Stability of Plasmas without Nested Flux Surfaces

Existing numerical tools for calculating the MHD stability of magnetically confined plasmas generally assume the existence of nested flux surfaces. These tools are therefore not immediately applicable to configurations with magnetic islands or regions with chaotic magnetic field lines. However, in practice these islands or chaotic regions are usually small, and their effect on MHD stability can then be evaluated using a newly developed perturbation theory. This procedure allows the effect of the broken magnetic topology on the stability of each eigenmode to be calculated without requiring any knowledge about the perturbed eigenfunctions. All that is needed to numerically evaluate volume integrals of quantities that are known from existing numerical codes, namely, the unperturbed eigenfunctions and the field perturbations.

Density Control in Wendelstein 7-X by Pellet Injection

Plasma fuelling and density control are challenging problems in fusion experiments. The lack of a neoclassical particle-pinch makes the problem even more complex in stellarators. Neoclassical thermo-diffusion in case of strong central electron cyclotron resonance heating (ECRH) leads to hollow density profiles that can provoke the creation of a neoclassical particle transport barrier and finally the loss of density control. Hollow density profiles have been observed in many discharges in LHD experiments with clear indication of its neoclassical nature. To effectively control the plasma density, central particle fuelling is necessary in large stellarators and can be provided by pellet injection if the pellets can be made to penetrate sufficiently far into the plasma. In tokamaks, the pellets launched from the high-field side (HFS) of the magnetic field penetrate much deeper into the plasma as compared to the low-field side (LFS) injection due to the grad-B-induced E×B-polarization drift of the ablatant. In stellarators, the grad-B-drift changes its direction depending on the position along the magnetic field line and thus the expanding ablation cloud does not necessarily drift towards the plasma centre as a whole. Different pellet injection scenarios in W7-X have been studied with the HPI2 code. It was found that the particle deposition profile in case of LFS pellet injection (pellet size 2 mm, velocity 300 m/s) is localised within the outer third of the plasma minor radius. The same pellet injected from the HFS penetrates deeper; the resulting deposition profile extends from a quarter of the minor radius to the plasma boundary. On the basis of such simulations, the density control scenarios of ECR-heated plasma have been studied using 1-D predictive transport modelling. The ECR heating position, the strength of the pellet source and its position were used as control parameters, and particular attention was paid to conditions for which the injected pellet increases the plasma density beyond the ECRH cut-off density. It was found that the off-axis fuelling scenario also requires off-axis heating that creates a positive electron-temperature gradient in the central portion of the plasma and thus inward thermo-diffusion of electrons that reduces the total particle flux.

Selective ECR Heating of Trapped/Passing Electrons in W7-X

Numerical simulations of ECRH scenarios in W7-X have been performed with selective heating of trapped / passing electrons by the X3-mode (140 GHz) launched near the "triangular" plane where the magnetic field strength is the smallest. The X3-heating is supported by X2-heating at 105 GHz. The calculations were performed by coupled transport and ray-tracing codes. It was found that the power fraction absorbed by trapped electrons is very sensitive to the launch conditions. For example, if the launch angle of the X3 heating beam is varied by 15 degrees, the power fraction absorbed by the trapped electrons increases from 15 % to 94 %. The power density absorbed by particles trapped in toroidal ripples is increased by a factor of about five due to geometrical effects, implying that quasilinear (or even nonlinear) effects in the cyclotron interaction may take place. These predictions could be explored in experiments with power absorption by ripple-trapped electrons, leading to an additional convective contribution to the radial transport. Since the current drive is roughly proportional to the power fraction deposited into the passing electrons, the change of the driven current could be used as a diagnostic tool.

Ray-tracing Code TRAVIS: New Options

In the TRAVIS code for ray tracing in stellarator plasmas, the initial conditions for the rays have been redefined in such a way that the asymptotic shape of the beam in the Fraunhofer zone becomes identical to that calculated by Gaussian optics. This makes it possible to specify the beam geometry in exactly the same way as required by beam tracing techniques, making ray-tracing calculations without strong focussing yield results very similar to the corresponding calculations using beam tracing. Additionally, the initial conditions for the ray-tracing calculations have been generalised to allow for an elliptical cross-section of the beam with possible astigmatism. In collaboration with the Institute for Applied Physics of the Russian Academy of Sciences, a preliminary version of quasi-optical modelling has been implemented and tested in TRAVIS. The module solves the parabolic wave-equation along the reference ray taken from ray-tracing, and thus calculates the detailed distribution of wave power within the beam.

Stellarator Optimisation

The code ROSE (ROSE Optimises Stellarator Equilibria) written for the purpose of configuration optimisation was extended by a massively parallel optimisation algorithm seeking estimates of both first and second derivatives of the target function. In the framework of EFDA activities preparing the physics base for a HELIAS demonstration reactor, ROSE was used to obtain a new quasi-isodynamic equilibrium exhibiting very small effective ripple and significantly improved confinement of fast particles (figure 7). Finding such configurations with small bootstrap current remains a challenge and topic for ongoing research.

Figure 7: Plasma boundary of an optimised HELIAS configuration.

3D Edge Modelling and Divertor Physics

The EMC3 code has been improved in many aspects. Ad hoc boundary conditions for intrinsic impurities at the SOL-core interface have been removed by implicit coupling to a 1D core model. The general solution for the 1D model is pre-calculated by standard finite difference methods, independently of the neighbouring scrape-off layers (SOLs) and divertors, and then processed into surface quantities that provide definite boundary conditions on the SOL-core interface for the EMC3 code. The coupling between the 1D core and the 3D SOL model is implicit and SOL-core iteration is therefore not needed. The SOL-core coupling not only removes the boundary conditions at the more or less artificial SOL-core interface, but also provides a framework for the integrated modelling of impurity transport throughout the plasma from the centre all the way to the divertor targets. Additionally, the code has been extended to allow for non-uniform cross-field transport coefficients. Mathematically, this is implemented by switching the stochastic integral from Ito calculus to a generalized Stratonovich definition, and is technically realized by a two-step method. This method has been benchmarked against simple models by assuming different shapes and combinations of the cross-field transport coefficients.

A particle splitting technique developed for specific ITER applications has been standardised as a general method for improving the Monte Carlo statistic in low-temperature ranges of most interest. Domain splitting, which was earlier possible for the toroidal direction only, is now feasible for all three directions, facilitating mesh optimisation for any specific divertor configuration. Stellarator-specific constraints on mesh construction have been removed, aiming at developing the code toward a general, device-independent 3D tool. Axisymmetric neutral-facing components, which were previously approximated by a large number of triangles in Cartesian coordinates, are now represented in cylindrical coordinates, leading to a great speed-up of neutral-particle tracing for tokamaks. With these features, a new code version was released at the end of 2013, which has been delivered to all EMC3-Eirene users worldwide.

Scientific Staff

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Numerical Methods in Plasma Physics

Head: Prof. Dr. Eric Sonnendrücker

The division "Numerical Methods in Plasma Physics" is devoted to the development of efficient and robust computational methods and algorithms for applications in plasma physics and more specifically for the models and problems of interest to other divisions of IPP.

Structure of the Division

The emphasis of the division lies on the development, optimization and analysis of numerical methods and is tightly coupled with the group "Numerical Methods in Plasma Physics" at the Mathematics Center of the TU Munich. In addition to inventing some new methods specifically for the problem at hand, the division aims to maintain a knowledge of state of the art methods in the general area of numerical mathematics and scientific computing in order to be able to adapt them where needed to plasma physics problems. The division consists of four research groups: Kinetic Modelling and Simulation, Fluid Modelling and Simulation, Plasma-Material Modelling and Foundations, Zonal Flows and Structure Formation in Turbulent Plasmas. Moreover the EFDA High Level Support Team (HLST) is attached to the division.

Kinetic Modelling and Simulation

Variance Reduction Techniques for Collisional PIC Codes

The δf gyrokinetic PIC method implemented at IPP in the tokamak code NEMORB and the stellarator code EUTERPE has proven very efficient in the collisionless regime. However the particle weights that are needed in δf simulations and that stay constant in the absence of collisions tend to drift apart too much when collisions are added making the noise reduction benefit of the δf method, which is normally quite important in the collisionless case, not so interesting anymore.
Using a splitting scheme between the transport and collision operators, we could focus on the collision part only. Putting the method in the framework of stochastic differential equations, we could find out that the weight growth is inherent to the model (even without numerical discretisation) and can be completely avoided in the collisional part by choosing the control variate as a steady state of the collision operator (i.e. a local Maxwellian). In this case the weights stay constant for the collision phase and this removes a large part of the weight growth problem. However, there is still a small weight growth coming from the transport part, and this is not reduced by the collision part even though this latter brings the distribution function closer to the local Maxwellian control variate. This is because of the weight mixing that occurs during the collision part, which has the effect of augmenting the variance of the weights locally in any phase space region. In order to reduce this, an additional ingredient like coarse graining or resampling is necessary.

Variational Integrators for Plasma Physics

New variational integrators have been developed for the Vlasov-Poisson system in 1D as well as for ideal and reduced magnetohydrodynamics (MHD) in 2D. The new schemes respect important conservation laws like energy conservation with errors as small as the machine accuracy. The Vlasov-Poisson scheme shows better stability properties than previous integrators, conserving the L2 norm of the distribution function in addition to the total particle number, momentum and energy. The new scheme does not need to be stabilised by the insertion of artificial dissipation or viscosity terms and by itself shows no dissipation in the important physical quantities. The schemes for MHD conserve energy and cross helicity as well as magnetic field line topology. Reconnection processes occur only if electron inertia or resistivity terms are added to the equations. This is a major advantage of our variational schemes over conventional numerical schemes, for which most often reconnection of field lines is observed even in the ideal case due to numerical resistivity. Ongoing work concentrates on the generalization of our schemes to higher dimensions, the implementation of fast solvers, and rigorous proofs of the discrete conservation laws by Noether's theorem.

Extension of GENE to 3D Magnetic Configuration

We are developing a global version of the Gyrokinetic Electromagnetic Numerical Experiment (GENE) code. The following elements have been implemented within the GENE code: a grid-point representation of the distribution function and its spatial derivatives, in addition to the previous Fourier based representation, and a more general treatment of the sparse matrices appearing in the gyro-average operator, which is required to handle the two-dimensional grid-point representation.

Discontinuous Galerkin Approximation of the Vlasov-Poisson Equation

We are investigating the use of a Discontinuous Galerkin (DG) finite element formulation for the approximation of the Vlasov-Poisson equation in phase space. Within the framework of a master thesis, a modified version of a previously available DG formulation for the Vlasov-Poisson equation has been obtained, ensuring exact energy conservation for the discrete problem. This formulation has then been implemented and validated on a set of one-dimensional and two-dimensional test cases.

Specific Methods for High-dimensional Problems

A major challenge in simulations of the Vlasov equation stems from the fact that the problem is posed in a six-dimensional phase space. On the other hand, there are classes of methods that are especially designed to efficiently solve high-dimensional problems. We have been investigating the use of such methods for the Vlasov-Poisson equation.

The idea of the so-called sparse grid method is to sparsify the high-dimensional mesh in a systematic way such that functions of bounded mixed-derivatives are represented in an economic way. Since the solution of the Vlasov equation contains small filaments, this assumption is not appropriate for the Vlasov equation. However, the sparse grid method might be useful in a hybrid approach to cover the smooth part of the solution. Efficiency of the sparse grid interpolation has been addressed and improved for a semi-Lagrangian solver of the Vlasov equation.
A more recent and less mature technique for high-dimensional problems is the tensor train method. In this method, a high-dimensional function is represented by a nested sum of tensor products. As opposed to the sparse grid method, the compression is not fixed but adapted to the solution. We have seen for the nonlinear Landau test case in two and four dimensions that growth and damping rates of the solution can be well recovered also when the solution is compressed to some percentages of the amount of data on the full underlying mesh. This gives hope that a compression of the solution in tensor train format is suitable for the Vlasov equation. However, further work needs to be done to improve the computational complexity of the algorithms in tensor train format.

Extension of Semi-Lagrangian Methods

The GYSELA code, developed at CEA Cadarache in France, is based on a mesh in polar coordinate of an annulus in the poloidal plane. In collaboration with CEA we have started investigating using arbitrary shape magnetic configurations and also including the centre of the tokamak and the edge region. To this aim we developed a semi-Lagrangian method using a general multi-patch mesh. The mapping on each patch is defined with Non Uniform Rational B-Splines (NURBS). Specific issues concerning conservativity, free stream preservation and patch-crossing have been investigated.

Development of a Kinetic Library

The division is involved in the development of the SELALIB library for kinetic and gyrokinetic simulations in collaboration with Inria in France. The library is written in object-oriented Fortran 2003. Its aim is to provide building blocks for physics codes as well as to provide a test bed for comparing different methods. Part of this year's work has been to think about interfaces, especially for the advection, which is fundamental component that was missing in the library. We have found some solutions for 1D and 2D advections, thanks to some abstract concepts of Fortran 2003. Several simulations have then been implemented in this framework: cartesian semi-Lagrangian 2D guiding center sequential simulation tested on periodic Kelvin Helmholtz instability, polar semi-Lagrangian 2D guiding center sequential simulation tested on the diocotron instability, general curvilinear semi-Lagrangian 2D guiding center sequential simulation (first results, but still in progress), cartesian semi-Lagrangian 2D Vlasov-Poisson parallel simulation with high order time splitting tested on Landau damping, bump on tail, two stream instability, beam and KEEN waves, cartesian semi-Lagrangian 2D Vlasov-Poisson sequential simulation without time splitting tested on beam problems, cartesian semi-Lagrangian 4D Vlasov-Poisson parallel simulation on cartesian grids with high order time splitting tested on Landau damping, polar semi-Lagrangian 4D drift kinetic parallel simulation tested on a simple ITG instability.
Classical methods, as first working implementations are used. Some new methods have also already been incorporated: high order splitting in time with new coefficients optimized for the Vlasov-Poisson equation, conservative non uniform cubic splines with application to KEEN waves. Other new methods, that have been developed recently, still need to be implemented in this framework. This is for CSL1D and the new CSL2D, which are conservative versions (CSL is for Conservative Semi-Lagrangian) of the classical backward semi-Lagrangian (BSL) method.

Fluid Modelling and Simulation

Implicit Time Stepping for the Reduced MHD Code JOREK

JOREK implements the nonlinear resistive reduced MHD equations. It is discretized in space using a small amount of Fourier modes in the toroidal direction and Finite Elements in the poloidal plane. This yields a nonlinear system of differential equations in time. Instead of using an implicit discretisation of the linearized equations as was originally done, we solve directly the nonlinear equation resulting from an implicit time discretisation of the system using an inexact Newton method, which uses a GMRES solver for the internal linear system. An adaptive time stepping has been implemented based on the number of iterations of the Newton solver: when the number of iterations increases compared to the last time step, the time step is decreased, else the time step is increased. This method is very robust and the solver converges with a reasonably large time step for all models that have been tested. An energy stability analysis of the model has also been performed.

Plasma-Material Interaction Modelling and Foundations

Lattice Trap-diffusion Models

In future fusion devices the amount of tritium retained in plasma-facing components has to be minimized to stay below safety regulation limits and to allow for an economic tritium management. Here tungsten with its low equilibrium solubility for hydrogen isotopes has a clear advantage compared to most other materials considered as potential first-wall material candidates. However, defects caused by irradiation of tungsten with neutrons or charge exchange neutrals can act as traps for hydrogen isotopes, thus increasing the concentration of retained hydrogen by orders of magnitude above the concentration given by the equilibrium solubility. The evolution of concentration profiles of retained hydrogen under simultaneous irradiation is typically simulated by continuum based diffusion-trapping models under the assumption of a thermally activated de-trapping process without memory. However, results of isotope exchange experiments at IPP point towards the presence of a non-thermal release mechanism, whose precise nature is still unclear. A new lattice trap-diffusion code has been developed to enable the flexible and efficient simulation of various release models. Since the new code can simulate the time-evolution of a whole thermal-desorption cycles it can also be used as virtual diagnostic for TDS measurements. Based on the present results two candidates for the non-thermal release process appear the most likely ones: Either a kinetic-energy assisted release (i.e. phonon-assisted) or a reduction of the release energy by locally present hydrogen.

Prediction of SOLPS data with the Gaussian Process Method

The simulation of plasma-wall interactions of fusion plasmas is extremely costly in computer power and time – the running time for a single parameter setting is easily in the order of weeks or months. Up to now a data base of about 1500 entries in different parameter regimes has been acquired by groups in the TOK department. Based on these already gathered results our approach is to predict the outcome of parametric studies within the high dimensional parameter space. Particularly useful for such tasks with various numbers of dimensions for input data or target function is the Gaussian process method, which we utilize within the Bayesian framework. Uncertainties of the predictions are provided, which point the way to parameter settings of further (expensive) simulations.

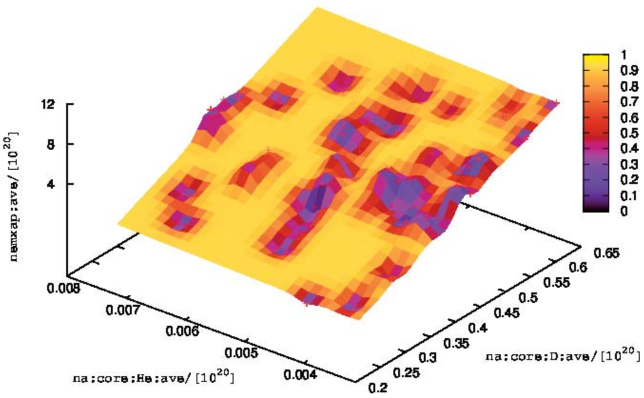

Figure 8: Predictive mean for the maximum electron density at the outboard divertor as the target function and the core densities of deuterium and helium as two-dimensional input. Only data from the SOLPS database with ELM set to False and densities for deuterium above 10^{19} m^{-3} and helium above $3.1 \cdot 10^{17}$ m^{-3} are considered making a data pool of 76 entries.

Figure 8 shows a first result, where, to keep it instructive, we restrict ourselves to the two-dimensional space for the input data (the core densities of deuterium and helium) and one-dimensional target function (maximum electron density at the outboard divertor). The expectation value of the target function plotted together with its variance (normalized colour code) depicts those parameter regions (in yellow) in input space where further (expensive) computations should take place to enforce the reliability of the outcome.

Zonal Flows and Structure Formation in Turbulent Plasmas

Turbulence Advection Schemes

The so-called essentially non-oscillatory (ENO) and weighted ENO (WENO) schemes have been implemented and tested up to approximation order 9 for their suitability to be applied to turbulence and shock simulations. For approximation orders above 3 spurious oscillations were found.

Zonal Flows

Work has continued on the turbulence driven slab zonal flows with increased resolution and more detailed parameter scans. We have started to study the effect of magnetic islands on turbulence induced geodesic acoustic modes (GAM). So far stable Islands have successfully been set up, and local profile flattening due to enhanced turbulence in the island has been observed, while the GAMs are confined outside the island.

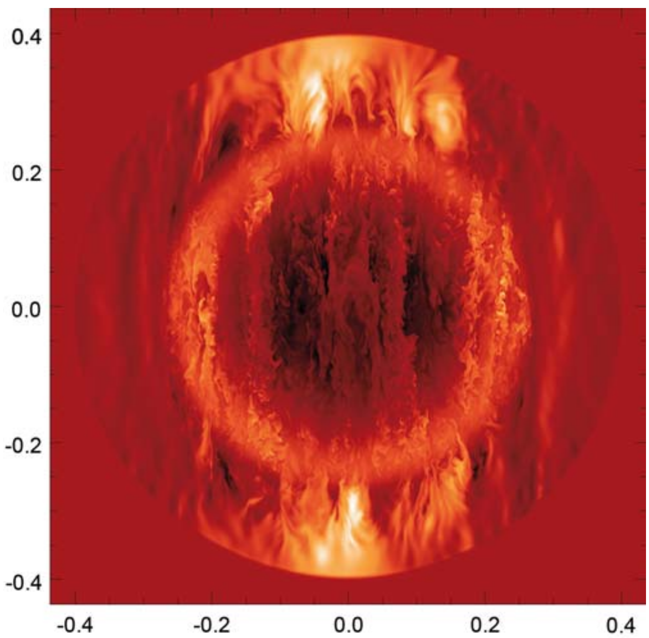

Figure 9: Entropy fluctuations in a polar cross section of the anelastic turbulence code simulated on a 1024^3 grid. The inner circle marks the boundary of an unstable region of increasing entropy with depth; outside the circle only gravity waves exist. Note how the Taylor Proudman constraint causes an elongation of all structures along the axis of rotation in the polar cross section.

For comparison with hydrodynamic zonal flows in planetary atmospheres, an anelastic massively parallel Cartesian code has been developed for the solution of the Navier Stokes equation including a nonlinear viscosity along the lines of large eddy simulations. The Cartesian grid places no effective restriction on the maximum resolution, as does the use of spherical harmonics. Smooth structures, such as the zonal flows or entropy profile modulations are resolved well enough to be damped only negligibly. Figure 9 shows a characteristic turbulence pattern obtained with the code.

Workshop on Numerical Methods for Kinetic Equations (NumKin 13)

A workshop devoted to Numerical Methods for the Kinetic Equations of Plasma Physic was organized by the division together with Francis Filbet of the University of Lyon in France. It was hosted on the IPP site from October 2-6, 2013. It involved around 50 mathematicians and physicists interested in numerical methods for different kinetic models such as Vlasov, Boltzmann, Fokker-Planck-Landau as well as reduced models and also gyrokinetic models with or without collisions. Different numerical methods including Particle-In-Cell, and several semi-Lagrangian and Eulerian techniques were considered.

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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 HELIOS supercomputer system at the Computational Simulation Centre of International Fusion Energy Research Centre (IFERC-CSC), Aomori, Japan. The HLST consists of a core team based at IPP Garching and of staff members provided by the Associates. At present, the former has six members and the latter contributes with an additional four scientists. This year the HLST core team was involved in nine different projects submitted by scientists from all over Europe. By way of example, we present here an overview of the work being done for three projects.

BELIGHTHO Project

The BELIGHTHO project is explicitly providing support on different levels for the European scientists who use the Helios machine. HLST has access via the trouble ticket system of CSC to most of the tickets submitted by the European users. This gives the flexibility to pick up special concerns of users whenever necessary. In addition, the BELIGHTO project investigates topics, which are of general interest such as checking and improving the documentation provided by CSC. Especially this year we helped CSC to reconfigure the whole procedure for threads and task pinning on Helios, and the corresponding documentation was updated accordingly. This is especially of interest when OpenMP is used within a shared memory node.

The main contribution of this year was the continuation of the extensive evaluation of the MPI libraries available on the Helios machine. We found out that both Bull and Intel MPI libraries require a large amount of time when initializing a so-called ALL_TO_ALL operation and we have strongly contributed to reduce the effort in collaboration with the CSC support team and Bull. Some alternative implementations have been thoroughly tested on several supercomputers. These alternatives basically consist of reducing the number of communicating MPI tasks during the communication operation. The outcome of this study was presented at an international conference on parallel computing (ParCo2013). The results of this study are interesting as they show that a distributed matrix transposition on 64k cores with one MPI task per core is possible. Runs of simple applications revealed several issues on large numbers of cores, which are now fixed or about to be fixed. Consequently, the whole user community of Helios will benefit from this experience.

PARFS Project

The main goal of the PARFS project was to adapt the HYMAGYC code to support resolutions up to ITER-like configurations. HYMAGYC is being used to study linear and nonlinear dynamics of Alfénic type modes in Tokamaks in the presence of energetic particle populations. It is a hybrid simulation code that features both Particle-In-Cell (PIC) and Magnetohydrodynamic (MHD) components. While the PIC module could scale up to several hundreds of processes, the field solver's computational core (the linear solver) was bound to be serial, using an own ad hoc implementation. Hence, the serial sparse linear solver was a bottleneck to the scalability of HYMAGYC.

Initial activities included changes for portability and standards compliance. With our collaboration, the project coordinator made the necessary changes in HYMAGYC to allow the use of parallel solvers. In this context, the best solver we have been able to identify was MUMPS-4.10. A strong scaling test based on the MUMPS solver has been performed on the Helios machine from a minimum allowed (for memory reasons) of four nodes/MPI tasks to a maximum of sixteen nodes/256 MPI tasks for the most relevant case (ITER sized, with $1.4 \cdot 10^6$ equations and $5.5 \cdot 10^8$ nonzeroes). The scalability properties of this solution are a mere factor of two for the LU factorization part, and a factor of six for the more time critical "backsolve" part. This showed that the problem under consideration is quite demanding for direct solvers as they require an excessive amount of memory for the LU factorization. Therefore, iterative solvers might be more appropriate as long as their convergence rate is satisfactory. Nevertheless, the present project has enabled HYMAGYC to handle ITER sized cases. As a consequence of the solver-related code being now parallel, further solvers could be easily tested in the future.

TOPOX Project

Modern tokamaks have strongly shaped diverted magnetic structures, in which the last closed flux surface is a separatrix with an X-point. This leads to high magnetic shear near the X-point region, whose effect on drift-wave turbulence is believed to be severe. A complete numerical demonstration of this is yet to be made due to the outstanding challenge of resolving all the relevant space scales involved. This constitutes the framework within which project TOPOX was devised. In particular, the objective is the extension of a Poisson solver based on a method developed by Sadourny et al. This method is currently being used in the Grad-Shafranov equilibrium solver GKMHD, built on a triangular grid in RZ-space, with the points arranged along flux surfaces, which are topologically treated as hexagons.

The goal of the project was to extend such scheme beyond the magnetic separatrix into the SOL, including the X-point. The first part of the work consisted in getting acquainted with the tools already available, namely the GKMHD code and its underlying solver algorithm. An appropriate standalone test-case was implemented using both Sadourny's method with the IBM WSMP library and an alternative finite-differences pseudo-spectral solver. The comparison of both methods demonstrated both the correctness of the former's implementation, as well as its advantages over the latter in terms of discretization efficiency.

The second part of the work was devoted to devising the extension of the Sadourny's method beyond the X-point, into the SOL. The solution found consists of setting an artificial boundary between the X-point and a grid node in the outermost SOL flux surface that is topologically treated as a hexagon. Everything outside this domain is discarded, meaning that the divertor itself is not included. However, the necessary magnetic structure, namely the SOL, the private flux region and the X-point are kept together with the hexagonal topology of the closed field line region grid. This means that Sadourny's method can be directly applied to the open field-line region with only minor modifications.

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"Turbulence in Laboratory and Astrophysical Plasmas"

Head: Prof. Dr. Frank Jenko

The main goal of our research efforts is to better understand the important unsolved problem of plasma turbulence in the context of magnetic confinement fusion science as well as astrophysics. 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. Below, three examples of current projects are briefly described. For a more complete overview and details, please see the citations below or visit the website http://www.ipp.mpg.de/~fsj.

Validation of Gyrokinetic Turbulence Simulations for Tokamak L-mode Discharges

Given the impressive progress in nonlinear gyrokinetic simulation over the last decade or so, computations characterized by a remarkable level of realism have become feasible, allowing for direct quantitative comparisons with experimental measurements. While some successful examples can be found in the existing literature, recent simulations for the outer-core region of L-mode discharges were reported to display a shortfall, i.e., a significant underprediction of the heat transport level. These claims have been reviewed with the help of GENE in two different ways. First, a dedicated series of simulations based on the original DIII-D shortfall discharge has been carried out. Second, extensive simulation studies (using about 15 million core-hours) were performed for similar ASDEX Upgrade discharges and carefully benchmarked with the GKW code [1]. Both investigations demonstrated ion heat flux matching within the experimental error bars of the temperature profiles, failing to confirm the notion of a systematic transport shortfall for L-mode pulses.

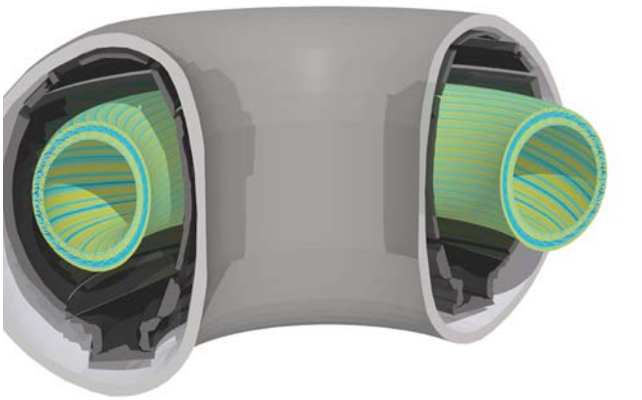

Figure 10: Snapshot of turbulent fluctuations simulated for an ASDEX Upgrade discharge with the nonlinear gyrokinetic code GENE.

[1] *D. Told, F. Jenko, T. Görler, F. J. Casson, E. Fable, and the ASDEX Upgrade Team, Physics of Plasmas* ***20****, 122312 (2013).*

Nonlinear Stabilization of Tokamak Turbulence by Fast Ions

Another set of direct quantitative comparisons between nonlinear gyrokinetic simulations and experimental observations has been carried out in the attempt to interpret JET discharges with reduced ion temperature profile stiffness. Previously, those recent observations had been linked to the simul

taneous occurrence of both low magnetic shear and strong toroidal rotation, but could initially not be reconciled with gyrokinetic simulation results. By means of highly comprehensive gyrokinetic simulations using the GENE code, this issue was revisited, retaining in particular electromagnetic effects, as well as two separate particle species for the fast ions introduced by ICRH and NBI heating. While it had been known for several years that electromagnetic effects can have a strongly stabilizing effect on ITG turbulence, the new simulations showed that this stabilization is strongly enhanced in presence of fast ions, reducing transport levels by up to an order of magnitude and thus explaining the improved confinement seen in JET [2]. This fast-ion induced stabilization may be expected to have a favourable effect in future reactor plasmas, which will naturally contain a significant fraction of fusion-generated alpha particles.

Development of a New Class of Reduced Turbulence Models

In the light of several severe shortcomings of traditional quasilinear models of turbulent transport, we have started the search for novel classes of reduced turbulence models, retaining important non-linear effects without introducing many free parameters. In this context we have applied the Large Eddy Simulation (LES) approach – solving numerically the large scales of a turbulent system and accounting for the small-scale influence through a model – to nonlinear gyrokinetic systems that are driven by a number of different micro-instabilities. Through a process known as "dynamic procedure," one can enforce self-consistency within the resolved range of phase space scales. In first applications to the calculation of density fluctuation spectra as measured in ASDEX Upgrade via Doppler reflectometry it is found that savings of more than an order of magnitude can be achieved while retaining full accuracy.

Scientific Staff

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[2] *J. Citrin, F. Jenko, P. Mantica, D. Told et al., Physical Review Letters* ***111****, 155001 (2013).*

Max Planck Princeton Cooperation

Max Planck Princeton Research Center for Plasma Physics

Head: Prof. Dr. Sibylle Günter

In its second year of existence, the MPPC held two scientific workshops, one at Garching in January and one at Princeton in October, each with more than 70 participants. Collaborative work has also been fostered by short-term and long-term visits. A large number of projects on fundamental aspects of experimental and theoretical plasma physics based on cross-Atlantic collaborations has been launched, and first common publications are appearing.

Magnetic Reconnection

The newly built linear reconnection device VINETA II is fully operational now. The axial conductors have been modified to allow for a fully symmetric reconnection drive. One pair of conductors generating the X-point topology in the azimuthal plane is driven with a current from a pulse forming network, which allows for a constant current regime over the timescale of the reconnection. The ratio of the reconnecting field to guide field strengths can be varied in the range of $B_{rec}/B_g=10^{-2}\ldots1$. The second pair of conductors being energized by a sinusoidal current drives the magnetic reconnection. The drive frequency is in the range of f_{drive}=50-100 kHz, which is faster than the typical timescale for resistive diffusion of the magnetic field through the current layer. The axial plasma current that flows in response to the reconnection process is provided by a plasma gun located at one end of the X-line. The plasma generation is by radiofrequency heating and resulting peak plasma densities can be controlled via the discharge mechanism. The main diagnostic tools are induction probes, which are used to measure the in-plane magnetic field topology, to reconstruct the current sheet, and study the evolution of high-frequency electromagnetic fluctuations. Plasma profiles are diagnosed using triple Langmuir probes. The experimental program has focused on two main objectives: (i) guide-field dependence of magnetic reconnection and (ii) electromagnetic fluctuations within the current sheet. The ratio B_{rec}/B_g together with the localized current source leads to a change of the magnetic pitch angle and to a distortion of the current sheet along the axial direction. It is observed that for small ratios the current sheet is localized at the X-line, whereas for large ratios the sheet is strongly elongated along the separatrices. The azimuthal current sheet profile agrees well with field line calculations, mapping the aperture of the plasma gun along the magnetic field to the measurement area. The resulting change in the local current density at the X-line leads to a variation of the reconnection rate, which gets smaller for increased ratios. So far no signatures of Hall-MHD reconnection at low guide fields have been observed. A detailed 3D characterization of the reconnection rate along the axial direction is ongoing. The geometrical change of the current sheet affects also the distribution of electromagnetic fluctuations, which are observed during magnetic reconnection. The amplitude of those fluctuations correlates with the local current density, which point at current-driven instabilities. A dedicated campaign at the MRX experiment (PPPL, Princeton) revealed that despite the different reconnection geometry and plasma parameter regimes, the fluctuations display very similar features: broadband, incoherent fluctuations around the lower-hybrid frequency with short correlation lengths. The fluctuations spectra show a scaling with ion mass towards higher frequencies, in agreement with lower-hybrid-type instabilities. The detailed characterization of the nature of the fluctuations and how they affect the reconnection process will be a major research objective in the upcoming campaign.

Investigation of the sawteeth crashes and neoclassical tearing mode (NTM) formation in ASDEX Upgrade allows to study magnetic reconnection in a strong guide field. Analysis of the sawteeth crashes show fast and incomplete reconnection, which can be explained only in the frame of two-fluid theory. At the same time, NTM formation can be relatively slow, with conversion from dominantly ideal into the resistive instability. Both problems are complex and require careful analysis with two fluid non-linear MHD codes, which is foreseen for the next years.

Energetic Particles

The results from the initial study of passive runaway electron supression in tokamak disruptions was published this year [H. M. Smith et al., Phys. Plasmas 20, 072505 (2013)]. The main idea is to shape the vessel in such a way that the large toroidal electric field in the disruption drives helical currents in the wall. The resulting magnetic fluctuations in the plasma can cause enhanced runaways losses. It was found that it is difficult to ergodise the central plasma where the runaway beam usually forms. However, if the primary runaway generation is reduced by other means (e.g. by increasing the electron density) the final runaway current profile becomes more peaked and the ergodised region moves closer to the centre. The ergodisation is also likely to cause MHD instabilities that could enhance the runaway losses further.

As observed at several experiments, global magnetic fluctuations in the Alfvén frequency range can modify substantially the evolution of the runaway current in the current quench phase of a tokamak discharge. In order to investigate and quantify this interaction, the nonlinear hybrid codes HAGIS has been extended to allow for relativistic particle energies. The new code has been successfully benchmarked with the ANTS code for a large range of particle energies and orbit types. Using distribution functions for relativistic electrons as given by sophisticated runaway-generation codes, the nonlinear evolution of relativistic electrons in the presence of global electromagnetic perturbations will be investigated.

Based on a well-documented ASDEX Upgrade discharge with 2D-ECE imaging data, a code benchmark and validation study of several IPP and PPPL codes has been started. So far, CASTOR, LIGKA, NOVA and M3D-K were employed to compare successfully the real mode frequency and eigenstructure of reversed shear Alfvén eigenmodes (RSAE). Good agreement for the fluid codes has been obtained. Kinetic effects modify the linear properties in certain limits, especially when steep background gradients at the shear reversal point are present. Further benchmarks (damping, non-linear evolution), also for other codes (NEMORB, GTS, GKM, HAGIS) and mode types (EGAMs) are in preparation.

Plasma Turbulence

In addition to projects dealing with the role of turbulence in the context of magnetic reconnection, the magneto-rotational instability, and the acceleration and transport of energetic particles, there are also several projects directly dedicated to plasma turbulence, being pursued in close collaborations between groups at PPPL, Princeton University, MPA, MPS, and IPP. In this context, the gyrokinetic core turbulence code GENE is being further extended from a flux-surface global to a fully global code for non-axisymmetric configurations like stellarators or tokamaks with symmetry breaking magnetic perturbations (e.g., to control Edge Localized Modes), and the novel gyrokinetic edge turbulence code Gkeyll – based on Discontinuous Galerkin methods – is being developed. While GENE has been used to investigate the nature of ITG turbulence in W7-X geometry, a 1D1V version of Gkeyll has successfully reproduced Alfvénic dispersion relations.

GENE has also been employed to study the basic physics of plasma turbulence and use this knowledge to construct accurate reduced models of turbulent transport. It was shown that for sufficient drive strength and low collisionality, there is a transition from a state with dominant dissipation at large scales in all five phase space dimensions to another state, which is characterized by a strong cascade in perpendicular wavenumber and velocity space [D. R. Hatch et al., Phys. Rev. Lett. 111, 175001 (2013)]. The latter regime is expected to apply to ITER discharges and will require high numerical resolution or novel modeling techniques. Insights from these investigations have been used to develop Large Eddy Simulation techniques – widely used in fluid dynamics – for nonlinear gyrokinetics. This way, the ratio between accuracy and effort could be improved by more than an order of magnitude for several experimentally relevant cases. Moreover, the origin of nonuniversal power laws in density fluctuation spectra could be examined, and an analytical model based on a modified Kuramoto-Sivashinsky equation was used to explain the simulation results [V. Bratanov et al., Phys. Rev. Lett. 111, 075001 (2013)].

Magneto-rotational Instability

The magneto-rotational instability (MRI) is of central astrophysical importance for the process of accreting matter on a central gravitating object such as a black hole or a newly forming proto-star.

In the respective topical group of the MPPC, two projects associated with IPP are investigating this phenomenon. Experiment-oriented numerical simulations are conducted to improve theoretical understanding of the liquid-metal MRI experiment conducted at PPPL, to help to analyze existing measurements and to guide further experimental investigations. In this context, two computational tools are being employed, the finite-difference code HERACLES and the finite-element code SFEMaNS. The latter allows for a particularly realistic treatment of the boundary conditions for the magnetic field at every point on the cylindrical surface of the experiment.

The astrophysical importance of the MRI is mainly due to its nonlinearly saturated state: turbulence. Similar to the common observation in experiments for magnetically-confined fusion, MRI turbulence in accretion disks is expected to enhance the outward transport of angular momentum necessary for astronomically observed accretion rates. The investigation of the statistical properties of MRI turbulence is conducted by the plasma astrophysics group at the TU Berlin, in collaboration with their partners at Princeton. The computational tool, the KT code, which has been previously developed by the group for the purpose of the simulation of trans- and supersonic (magneto-)hydrodynamic turbulent flows, is based on a higher-order extension of the Lax-Friedrichs scheme including constrained transport for the divergence-free magnetic field evolution. This approach, although numerically less expensive than commonly used Riemann solvers, comes at the cost of increased numerical dissipation. During last year the order of the numerical approximations used by the KT code has been increased throughout from third to fourth order in 2013. The KT code is now expected to yield a numerical performance, which allows for benchmarking with the Athena code used by the collaborating Princeton group.

Scientific Staff

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Supercomputing

Computer Center Garching

Head: Dipl.-Inf. Stefan Heinzel

Introduction

The RZG supports optimization of complex applications from plasma physics, astrophysics, materials science and other disciplines for supercomputers and offers data management services and infrastructure. Moreover, the RZG provides data visualization services for the exploration and quantitative analysis of simulation results and plays a leading role in several large MPG, national and international projects in collaboration with other scientific institutions.

The Rechenzentrum Garching (RZG) 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 long-term storage services are provided for large sets of experimental data, supercomputer simulation data, and data from the humanities for many Max Planck Institutes. 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 new supercomputer named "Hydra". In October 2012 an Intel Sandy Bridge based initial system with a peak performance of about 200 TFlop/s was put into operation. In autumn 2013 the system was expanded to a Petaflop system with Intel Ivy Bridge processors and Mellanox InfiniBand FDR14 technology. 338 compute nodes have been equipped with 676 NVidia Kepler K20X GPUs, 12 with 24 Intel Xeon Phi cards. Immediately after operational readiness the system achieved 90 % application usage. Furthermore, a series of different mid-range Linux clusters are operated for the IPP and further Max Planck Institutes. Since the beginning of 2013 the new EFDA ITM gateway computer is operated by the RZG for the European fusion research community. Based on a dedicated Linux cluster with powerful graphics hardware the RZG provides interactive remote visualization services to scientists of the Max Planck Society. The scratch file system of the supercomputers is accessible from the visualization nodes.
In April, a new RZG tape library was installed at the LRZ (Leibniz Rechenzentrum). This tape library holds the second copy of RZG's data archive. It has a capacity of about 5000 tapes, expandable to 20,000. The library is connected to a new Linux server, also at the LRZ, which exchanges data with the rest of the servers in the HPSS archive system at the RZG through a dedicated 10 Gb/s network link. While the RZG uses HPSS for archive data, it uses TSM (Tivoli Storage Manager) for backups. The TSM server machines, which have been in operation for the last five years are being replaced with new hardware. As the TSM server databases cannot be transferred from the old AIX-based machines to the new Linux-based machines, all backups must be made fresh or copied from the old to the new servers, a long process, which has been running for the last months and will take some more time to finish.

High-performance Computing

Support in the field of high-performance computing (HPC) is a central mission of the RZG. Major tasks are the optimization of codes and participation in visualization and graphical preparation of data, also for computer architectures and systems, which are not running at the RZG, but at other institutes and computing centres world-wide. In the following selected projects are presented in more detail.

VMEC Code

The Variational Moments Equilibrium Code, VMEC, is the main workhorse for computing three-dimensional MHD equilibria in stellarator experiments such as Wendelstein 7-X (W7-X). There is a great interest in the community for significantly reducing the runtimes of individual VMEC simulations which, for typical setups, can range up to hours of computing time on modern processors. In particular, the ability to enter the regime of "real-time" diagnostics during the operation of the W7-X machine is considered highly desirable. Based on representative setups provided by the department of Prof. Helander a detailed assessment and prototypical optimization of the computational performance of VMEC was performed at the RZG, and a strategy for adapting the serial code to modern multicore-processor architectures was proposed (for details, see IPP-Report R/48, 2013). By eliminating legacy program structures and by adding an OpenMP parallelization of the relevant subroutines, speedups by a factor of 10 on a modern Intel Xeon processor with ten cores are achieved compared to the original code executed on the same hardware. On top of these optimizations a second level of restructuring has been proposed, which is based on a transposed data layout for the three-dimensional physical domain. This will open up the possibility to implement a hybrid MPI/OpenMP parallelization, which allows to distribute a VMEC run across multiple nodes of a compute cluster and thus to gain another order of magnitude in computational performance. Depending on the setup this will allow to utilize approximately some hundred processor cores with high parallel efficiency, thus enabling VMEC runs with significantly shorter computation times (up to two orders of magnitude are in reach) or with correspondingly larger resolution.

GENE Code

GENE is one of the leading codes for gyrokinetic plasma turbulence simulations. GENE is widely used for different physics applications and runs on all major supercomputer platforms. The code is still under active development with regard to extending it to new physics, including more efficient numerical algorithms, and also improving the computational performance. In 2013, the performance of the GPU version developed at the RZG was analysed with the roofline model and strategies for improving the performance were developed. For the DFG-funded SPPEXA program support for compilation and execution of the GENE code on different HPC platforms was provided in the EXAHD project.

LINMOD Code

The LINMOD code, which has been developed at the Max Planck Institute for Solar System Research (Group of Prof. J. Büchner) is employed for three-dimensional, time-dependent simulations of the solar corona in the framework of resistive magnetohydrodynamics (MHD). Starting from a serial FORTRAN 90 code version an MPI-based, two-dimensional domain decomposition with width-1 halo exchange and an OpenMP parallelization within the individual, "pencil"-shaped domains was implemented at the RZG. The hybrid code has been demonstrated to scale up to more than 30,000 processor cores for a grid size of 2048^3 and shows very good weak scalability from 20 cores (1 node) for a 256^3 grid to more than 20,000 cores (1000 nodes) for a 2048^3 grid on the new IBM HPC cluster "Hydra".

ELPA, a Library of Scalable Eigenvalue Solvers

In the BMBF project ELPA highly-scalable direct eigenvalue solvers for symmetric matrices had been developed under participation of the RZG. The software was made publicly available under an LGPL license and has meanwhile been employed in different simulation software packages worldwide. ELPA was further optimized, especially through vectorization for AVX exploitation on new Intel processors and by a mixed OpenMP/MPI parallelization scheme, and maintained in the git repository for public use.

GPU and Many-core Computing Technologies for HPC Applications

With GPUs and Intel's Many Integrated Cores (MIC) technology two new, conceptually similar architectures have been established in the high-performance computing landscape. Both architectures are characterized by a large number of "lightweight" processor cores with comparably low clock frequencies, and are thus able to combine significant compute performance (in the order of 1 TeraFlop/s per card for double-precision floating-point arithmetic) with high energy efficiency (in the order of 5 GigaFlop/s/Watt). The RZG has recently deployed a significant resource of this type as part of the new high-performance computer of the Max Planck Society and the IPP. It comprises 338 GPU nodes (676 Nvidia „Kepler" K20x GPUs) and 12 MIC nodes (24 Xeon Phi 5110p coprocessors) and provides a nominal peak performance in the order of 1 PetaFlop/s. This system part is, on the one hand, a competitive computing resource, which is already used by several Max Planck research groups for running production applications, for example with classical molecular dynamics codes like GROMACS, NAMD, LAMMPS, ACEMD. On the other hand, it serves as a development platform for porting and developing new simulation codes for the new architectures with "lightweight" cores, which are expected to get prevalent in future high-performance computing systems. So far, the RZG has ported the codes GENE (plasma micro-turbulence code, IPP), VERTEX (type-II Supernova simulations, Max Planck Institute for Astrophysics), MNDO (semi-empirical quantum chemistry code, Max Planck Institute for Coal Research), and ELPA (scalable direct eigenvalue solver library developed by a multidisciplinary consortium led by the RZG) to GPUs and/or the MIC architecture.

PRACE

The RZG continued as Tier-1 partner together with the Gauss Centre for Supercomputing (GCS) EU FP7 PRACE-IP projects where many European supercomputing centres collaborate for the support of excellent simulation projects from all over Europe. MPG scientists are meanwhile mainly engaged in Tier-0 projects. The RZG was also involved in organization and conduction of the international "HPC Summer School in Computational Sciences", which was held in June 2013 in New York City for European, American and Japanese postgraduate students and postdocs with PRACE financing the European participants.

Scientific Visualization

A central software and hardware infrastructure for the Max Planck Society and the IPP is operated at the RZG, which is dedicated to quantitative analysis and visualization of simulation data. It enables scientists to efficiently perform interactive remote visualization of large data sets generated at the supercomputer "Hydra" or at the Linux clusters, in particular without the need to transfer the data to local workstations. The RZG supports scientists with the use of these resources and also takes over concrete visualization projects by itself.
As a recent example for project support the visualization of data from comprehensive three-dimensional supernova simulations shall be mentioned, which are carried out in the group of H.-Th. Janka, MPI for Astrophysics in the framework of a PRACE Tier-0 project on large European supercomputers. The figure shows a snapshot of the temporal evolution of the innermost about 500 km of the simulation domain. The entropy per baryon (as a common measure for the heating of the stellar material by neutrinos) is illustrated with different shades of red

and yellow. The bluish gleaming outer sheath marks the position of the supernova shock wave. The clearly visible large-scale deviations from the spherical symmetry play a decisive role in the understanding of the neutrino-driven explosion mechanism. In the inner the juvenile neutron star can be identified as small ball. The project was awarded the second prize in the MPG competition “Max Planck Award 2013 – Hidden Treasures?”.

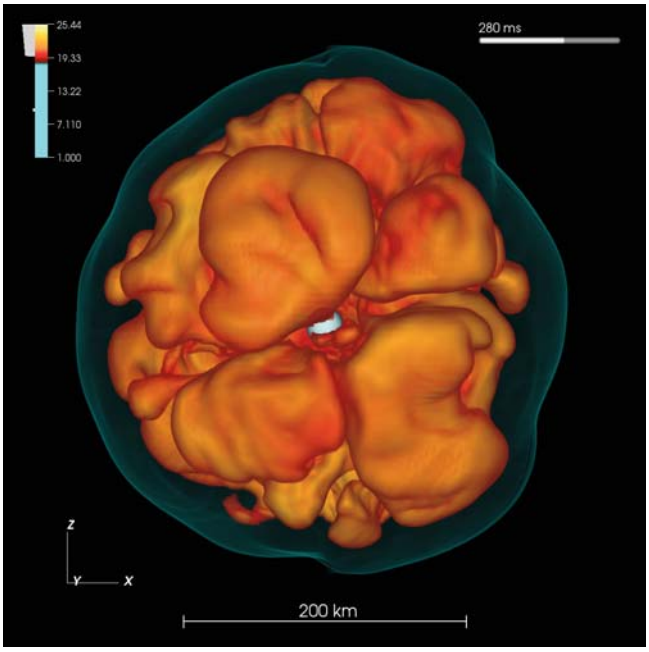

Figure: Frame from an animation, which illustrates the evolution of a type-II supernova explosion. (Data: Max Planck Institute for Astrophysics; Visualization: Elena Erastova and Markus Rampp, RZG).

Data Services

Data services are of growing importance for various science disciplines. This has been addressed by the RZG with a new data service group taking care of the different data-oriented support needs of the different communities. Selected examples of the activities of this group are presented.

High Performance Storage System (HPSS)

After the installation of the new archive system HPSS in late 2011, all data from the previous archive system had to be copied to HPSS. The copying of data, which had been archived by HPC users (about 3 Petabytes) was finished in December 2013. The copying of data archived under AFS is still on-going, but will likely be finished within a month or two.
HPSS, through its various interfaces, especially GHI, which allows data migration between GPFS and HPSS, is in use not only for HPC and AFS data, but increasingly for other data areas, including data from RZG European projects like EUDAT and from diverse Max Planck Institutes across Germany. For some data-oriented projects, it was decided to use dedicated GPFS file systems with GHI. Apart from the original GHI system in use for HPC archives, the RZG has installed a second GHI system for the MPI for Biochemistry and is in the process of installing a third GHI system for use by the W7-X fusion experiment. It is likely that still more GHI systems will be installed in the future.

Oracle Databases

The RZG, in support of several Max Planck Institutes, provides support for various Oracle databases and Oracle applications. This service includes the deployment of the appropriate database versions, the deployment of Oracle clients on various operating systems, user support, and the backup of the database resources in case of disaster (database failure).
During 2013 the RZG deployed two Oracle applications for IPP projects. A user front-end application was deployed for the ASDEX Upgrade project where Oracle FORMS services and the associated Web-Logic environment were required. Oracle FORMS is a product, which allows users to create forms, or screens, which simplify the interaction with the Oracle database. Additionally a project management suite, Primavera P6, was deployed for the ITER Diagnostics project at the IPP. In addition to these activities at IPP Garching support is provided to IPP Greifswald in the form of consulting and aiding with service coverage during vacations.

Support for Data-intensive Projects

Some of RZG’s data projects are about supporting and developing technologies to manage data in a global, collaborative context. In the Galformod project for instance the RZG together with the MPI for Astrophysics provides web access for the astrophysics community to workflows acting on data resulting from model simulations of galaxy formation. In the Replix project on the other hand the RZG together with the MPI for Psycholinguistics in Nijmegen handles the management of linguistic data from “The Language Archive (TLA)” using the “integrated Rule-Oriented Data System (iRODS)”. Other collaborations are focusing on the replication of data into RZG's tape storage system for long-term archiving, like picture data from the Bibliotheca Hertziana in Rome or the “Deutsches Kunsthistorisches Institut” in Florence.
For plasma physics and fusion research the RZG acts as a central European data hosting site for the simulation data of the European fusion science community, which performs simulations on the IFERC supercomputer at Rokkasho, Japan, installed in the context of the “Broader Approach” agreed between Japan and the European Commission for the advancement of the ITER project.
Together with scientists from the MPI for Ornithology in Seewiesen the RZG has developed a metadata management tool called TACO (TAgs and COmponents). TACO allows to annotate arbitrary parts of a file system directory tree in a controlled and domain-specific way. A harvester then collects the metadata from the file system and writes them into

a web-accessible database that way allowing for remote searching and browsing of the metadata.
Apart from the already mentioned data management projects the RZG also participates in IT projects that require the acquisition and deployment of novel software techniques and advanced tools to become part of larger infrastructures extending over several cooperating sites. One such example is the ATLAS project where the RZG together with the MPI for Physics, the Leibniz Rechenzentrum (LRZ) and the LMU Munich operates a so-called Tier-2 centre within the "Worldwide LHC Computing Grid (WLCG)". In this project common computing power is provided for the particle physics experiments at CERN in addition to the infrastructure necessary for accessing the common data, which are used by many institutes and thousands of scientists all over the world.
In a European context the RZG participates in DARIAH, the Digital Research Infrastructure for the Arts and Humanities, which supports digitally-enabled research and teaching across the humanities and arts by developing, maintaining and operating an infrastructure in support of ICT-based research practices. In addition, the RZG is also a member of the CLARIN project (Common Language Resources and Technology Infrastructure), which aims at providing easy and sustainable access for scholars in the humanities and social sciences to digital language data (in written, spoken, video or multimodal form) and advanced tools to discover, explore, exploit, annotate, analyse or combine them, independent of where they are located. To this end CLARIN is building a networked federation of European data repositories, service centres and centres of expertise – one of which being RZG – with single sign-on access for all members of the academic community in all participating countries. Tools and data from different centres are made interoperable, so that data collections can be combined and tools from different sources can be chained to perform complex operations to support researchers in their work.
Complementary to this the RZG is also engaged in the EUDAT project, a pan-European data initiative that started in October 2011. EUDAT brings together a unique consortium of 25 partners – including research communities, national data and high performance computing (HPC) centres including RZG, technology providers, and funding agencies – from 13 countries. EUDAT is tasked to build a sustainable cross-disciplinary and cross-national data infrastructure that provides a set of shared services for accessing and preserving research data from all disciplines. RZG's main responsibility within EUDAT is the management of the operation of EUDAT's services such as B2SAFE, a safe replication service across participating data centers, or B2SHARE, a service supporting the sharing of research data across institutions.
Last but not least the RZG is also actively contributing to the recently formed Research Data Alliance (RDA) including its European branch RDA-Europe. RDA's mission is to build the social and technical bridges that enable open sharing of research data on a global scale and across all disciplines. It does so through focused working groups and interest groups, formed of experts from around the world – from academia, industry and government. Members of the RZG are actively involved in several working groups as well as in the RDA Technical Advisory Board and the RDA Secretariat.

Data Network

RZG's router facilitating the Internet connection had reached the end of its lifetime and was replaced by two Cisco Nexus 7000 switches. One of them is connected to a core node of the Deutsches Forschungsnetz at Erlangen, the other to a core at Frankfurt via independent lines, the total capacity being now 2 * 5 Gbps. The replacement of IPP's central network equipment was also completed. The routing protocol was switched to OSPF. Several buildings of the IPP and of the neighbouring Max Planck Institutes are now connected via redundant links to the two new core routers at the RZG. Some new "Demilitarized Zones" were set up to separate the servers of different projects by firewall rules. The Wireless LAN infrastructure on campus was extended.

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 supports the CODAC group of W7-X with the development of the data acquisition system of the experiment W7-X. In 2013 the in-house developed ArchiveDB data base software, which allows storing, migration, archiving and restoring of measured data, has been tested extensively and was made ready for production. For the magnetic diagnostics of W7-X a special version of the integrators with a very low drift has been developed to support continuous operation. The integrators can be operated correctly in any position in the stray magnetic field of W7-X. For the interferometer diagnostic an MTCA.4-(Micro Telecommunication Computing Architecture for physics)-based data acquisition system has been evaluated and installed afterwards.

Staff

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University Contributions to IPP Programme

Cooperation with Universities

Author: Gregor Neu

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

IPP is highly interested in fostering national and international students' interest in high-energy plasma physics and other fusion-relevant fields like plasma-material interaction. This interest is reflected in the long-term endeavour of teaching plasma physics at various universities in Germany and abroad. In 2013, 29 members of IPP taught at universities or universities of applied sciences: Many 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. The table 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 fusion research.

University	Members of IPP staff
University of Greifswald	Dr. Hans-Stephan Bosch Dr. Andreas Dinklage Prof. Per Helander Dr. Philipp Jan Kempkes Prof. Thomas Klinger Dr. Heinrich Laqua Prof. Thomas Sunn Pedersen
Technical University of Berlin	Prof. Robert Wolf
Technical University of Munich	Prof. Sibylle Günter Dr. Klaus Hallatschek Prof. Eric Sonnendrücker Dr. Philipp Lauber Prof. Ulrich Stroth
University of Munich	Dr. Thomas Pütterich Dr. Jörg Stober Prof. Hartmut Zohm
University of Augsburg	Prof. Ursel Fantz Dr. Marco Wischmeier
University of Ulm	Dr. Thomas Eich Prof. 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. Wolfgang Suttrop
University of Gent	Prof. Jean-Marie Noterdaeme
Università di Cagliari	Dr. Gabriela Pautasso
Technical University of Vienna	Univ. Doz. Dr. Josef Schweinzer Univ. Doz. Dr. Elisabeth Wolfrum

Table: IPP staff who taught courses at universities in 2013.

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 2013 for the 28th time in Greifswald (alternating with Garching). Most of the about 70 participants were from Europe but there is also a number of attendees from abroad. 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 five years ago and is presently supported by institutions in Germany, Italy (University of Padua), and Portugal (Instituto Superior Técnico). With the organisation of the yearly Advanced Courses in Fusion IPP provides a major contribution to this programme.

The international character of fusion research is also reflected in the countries of origin of graduate students at IPP: one-fifth of the postgraduates and approximately two-thirds of the postdocs are from abroad. In the year 2013 a total of 66 postgraduates were supervised, 20 of them successfully completing their theses.

Joint Appointments, Grown and Growing Cooperation

IPP closely cooperates with universities in joint appointment programmes: three W3 appointments at the University of Greifswald, a W3 and a W2 appointment at the Technical University of Berlin, and two W3 and a W2 appointment at the Technical University of Munich, the latter of which was finalized in 2013, mark the successful implementation of these programmes.

Another example of a close cooperation is the University of Augsburg devoted to the development of a negative-ion source for the neutral-beam injection (NNBI), which was selected as the reference source for ITER. The cooperation has led to the development and operation of the ELISE test-bed where a source half the size of that envisaged for ITER is currently being tested.

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.

Young investigators groups:

- A Helmholtz Young Investigator Group on the "Macroscopic Effects of Microturbulence Investigated in Fusion Plasmas" led by Dr. Rachael McDermott and doted with a financial support of 250 k€ until December 2017. The University partner is the University of Augsburg.
- The European Research Council (ERC) (Starting / Consolidator) Grant and on "Plasma Turbulence in Laboratory and Astrophysical Plasmas" headed by Professor Dr. Frank Jenko, which runs out in November 2016.
- The 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, until March 2014.

Research partnerships:

- DFG Research Training Group on "Intermolecular and Interatomic Coulombic Decay", together with the Goethe University Frankfurt, the University of Innsbruck, the University of Heidelberg, the University of Hamburg, and the Helmholtz-Zentrum Berlin. The research unit focusses on the investigation of amechanism for the transformation of electronic energy created by excitation or ionization with radiation in the UV and far beyond, or with energetic particles.

Virtual Institutes

- Helmholtz Virtual Institute "Plasma Dynamical Processes and Turbulence Studies using Advanced Microwave Diagnostics" where IPP cooperates in basic research of plasmadynamics and the development of novel microwawe diagnostics with the University of Stuttgart, the Technical University of Munich, the École Polytechnique, Palaiseau (F), and the Ecole Polytechnique Féderale de Lausanne (CH).

A few years after its formation, IPP joined the European Fusion Development Agreement (EFDA) 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 (2007–2013). FUSENET consists of 14 EURATOM associations – one of them IPP – and 19 universities from 18 European countries. IPP is also one of the eight partners of the Joint Doctoral College in Fusion Science and Engineering (FUSION-DC), which has been approved under the auspices of Erasmus Mundus, the European programme to promote training schemes. The doctoral college founded in October 2011 is being supported with about five million Euros and provides 40 doctoral scholarships for work in the field of fusion research.

Universität Augsburg
AG Experimentelle Plasmaphysik (EPP)

Head: Prof. Dr.-Ing. Ursel Fantz

The research at the University of Augsburg focusses 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. Fundamental studies for the development of negative hydrogen ion sources for ITER and DEMO are carried out in close collaboration with the ITER Technology & Diagnostics Division of IPP.

Developments for Negative Hydrogen Ion Sources

In negative hydrogen ion sources for the neutral beam injection system of ITER the surface conversion of hydrogen atoms and positive hydrogen ions at caesiated surfaces with low work function is utilized to meet the specified high current densities at the required low pressure (0.3 Pa). For that purpose caesium is evaporated into the source. The experiments at the IPP test facilities showed that the performance of the sources strongly depends on the caesium dynamics in the ion source, not only during plasma operation but also in vacuum phases. Therefore, basic investigations on the caesium dynamics are carried out in a laboratory experiment with comparable plasma parameters to the IPP prototype source. The used planar ICP is equipped with multiple diagnostics, which can be applied simultaneously. At background pressures of about 10^{-6} mbar relevant for ion sources the caesium dynamics is not influenced by nitrogen and argon whereas oxygen and water vapor decreases drastically the caesium density in the chamber due to the formation of caesium compounds at surfaces. In hydrogen plasmas the density of hydrogen atoms decreases by a factor of two with increasing caesium density showing a hysteresis. This effect is less pronounced in deuterium. The general decrease is attributed to the getter effect of hydrogen at the caesium coated vessel walls. Electron density and electron temperature of the hydrogen plasma remain unchanged with increasing caesium amount up to typical caesium densities of ion sources. However, several millimetres above a caesium coated stainless steel surface a decrease of the electron density by 25 % is measured, which correlates well with the observed reduction of co-extracted electrons in caesiated ion sources.

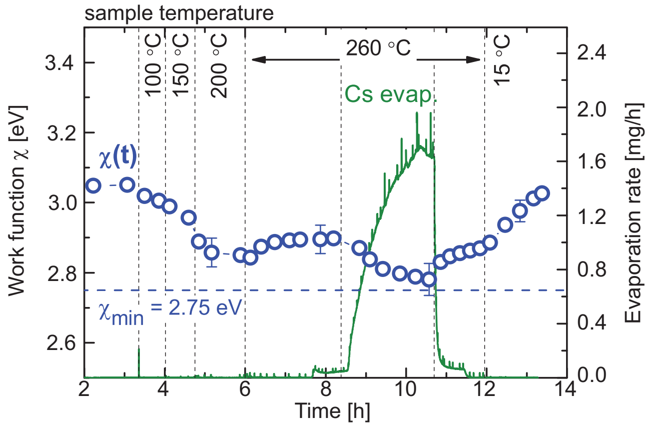

Figure 1: Work function of caesium on a stainless steel surface in vacuum (10^{-6} mbar background pressure) at different surface temperatures with and without caesium evaporation.

Measurements of the work function of caesiated surfaces in vacuum reveal degradation effects on a time scale of several minutes, which can be recovered by heating the surface to temperatures of about 150-200 °C (figure 1). This behaviour confirms the optimum temperature range empirically adjusted in ion sources so far. Additional evaporation of caesium results in a minimal achievable work function under these conditions, namely 2.75 eV, which is considerably higher than the one of bulk caesium and is attributed to caesium compounds. As it is expected that the plasma will purify the caesium surface, such measurements will be carried out in pulsed plasma operation.

In view of ion sources for DEMO where RAMI issues are a major concern, caesium-free operation is highly desirable. Therefore, principle investigations for alternatives are carried out using an ECR plasma experiment capable to operate at the relevant pressure of 0.3 Pa. The density ratio of negative ions to electrons is measured directly by laser photodetachment (H^-+hν → H+e). To obtain negative ion densities, the electron density has to be derived subsequently from the IV-characteristics of the associated Langmuir probe.

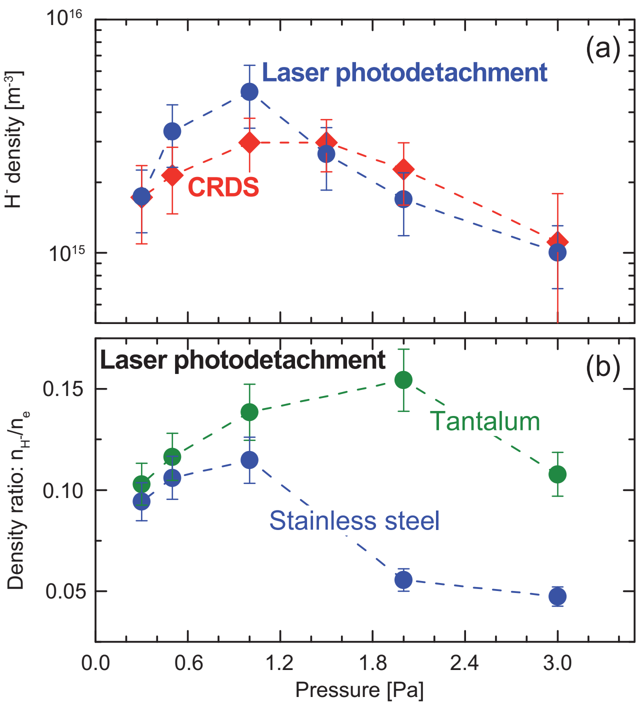

Figure 2: (a) Comparison of negative ion densities measured by laser photodetachment and by cavity ring-down spectroscopy (CRDS). (b) Density ratio of negative ions to electrons at a distance of 4 cm to the sample surface. Tantalum is compared to stainless steel.

As shown in figure 2 the method has been benchmarked with the highly sensitive, but line-of-sight averaged cavity ring-down spectroscopy (CRDS). For that purpose pure hydrogen plasmas with volume production of negative ions are used. Different materials can be mounted on a sample holder to explore their influence on negative ion production. Tantalum is known to enhance the ro-vibrational excitation of hydrogen molecules and thus negative ion densities. Compared to stainless steel an increased relative negative ion density for the whole pressure range is measured for the tantalum surface revealing a maximal gain of up to a factor of three at 2 Pa (figure 2). Further promising candidates are boron-doped graphite, diamond-like coatings, or materials with intrinsic low work functions. The influence of surface temperature and energy of the positive ions will be investigated as well.
The activities for neutral beam systems for DEMO are extended by exploring the laser neutralizer concept with proof-of-principle experiments in laboratory scale. For the required cavity system, the pulsed CRDS (see above) already allowed investigations on the stability of high reflective mirrors in plasma and hydrogen gas environment. A degradation of the mirrors on a time scale of minutes is detected during plasma operation, partly recovering in vacuum phases. By testing different configurations, the VUV emission of the hydrogen plasma is identified to cause the degradation of the sensitive dielectric coating of the mirrors. This however, will not be an issue for a laser neutralizer.
Alternative RF coupling mechanisms are explored to reduce the RF power level by simultaneously achieving similar ionization and dissociation degrees as in standard ICPs. Here the Helicon concept is pursued (Annual Report 2011 and 2012), which uses a Helicon type RF antenna and an axial magnetic field to excite Helicon waves. At RF powers of 600 W (13.56 MHz frequency) atomic to molecular density ratios of about 0.1 are measured in hydrogen plasmas at 0.3 Pa. Stable operation at this pressure was possible only above field strengths of 4 mT. For deuterium, the density ratio changes strongly with the field strength: from 2 mT up to 12 mT remarkably high density ratios between 0.1 and 0.4 are obtained. At 2.5 mT a sharp maximum evolves (low field peak of Helicon coupling), which shifts slightly with pressure. At 1 Pa the density ratio increases up to 0.6. In a next step the RF frequency will be reduced to an ion source relevant frequency of 2 MHz (2 kW power at maximum). Additional investigations concern an improved RF coupling by using ferrites in a planar ICP setup at 2 MHz.

Low Temperature Plasmas

Langmuir probe systems are commonly used to determine the plasma density. However, the analysis of the IV-characteristics and in particular the ion saturation branch is always a point of discussion. In a planar ICP at 27.12 MHz measurements with an RF compensated Langmuir probe system are benchmarked with microwave interferometry (MWI), which depends on the line-of-sight averaged measurement of the phase shift only. For the comparison the electron density profile from the probe measurement is taken into account. As shown in figure 3, in all cases the electron density obtained from the current at the plasma potential agrees well with MWI. The routinely used OML theory reveals remarkably higher values whereas the ABR theory underestimates the density as commonly expected.

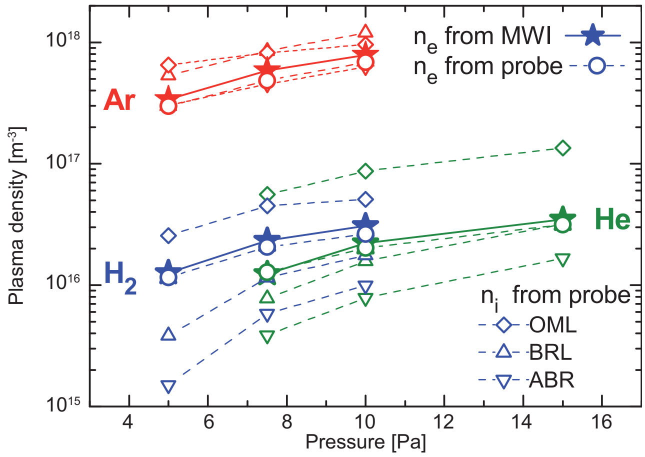

Figure 3: Comparison of plasma densities obtained from the Langmuir probe system using different analysis methods: electron density from the electron saturation current at the plasma potential, positive ion density from the ion saturation current using the common probe theories: OML, BRL and ABR theory. The measurements of different gases as a function of the pressure in the planar ICP are benchmarked with microwave interferometry (MWI).

The diagnostic setup for the atmospheric plasmas generated by a water discharge – an IPP experiment – has been extended by a photo diode system based on interference filters. This allows for measurement of the temporal behaviour of the emission of hydrogen, sodium, and calcium atoms, as well as the OH radical with a time resolution of milliseconds. First promising measurements are carried out revealing the dynamics of chemical processes in the formation of the plasma phase as well as in the fast ascending plasma during the autonomous phase.

Theses

R. Friedl: Experimental Investigations on the Cesium Dynamics in H_2/D_2 Low Temperature Plasmas (PhD Thesis).
M. Küß: Realisierung einer Sonde zur Messung von Magnetfeldfluktuationen in einem Heliconexperiment (Bachelor Thesis).
S. Reschke: Charakterisierung einer Glimmentladung mit Sondendiagnostik (Bachelor Thesis).

Scientific Staff

U. Fantz, S. Briefi, J. Doerfler, D. Ertle, R. Friedl, P. Gutmann, M. Küß, U. Kurutz, I. Pilottek, D. Rauner, S. Reschke.

Universität Bayreuth
Lehrstuhl für Theoretische Physik V

Head: Prof. Dr. Arthur G. Peeters

Through the Chair for theoretical plasma physics, University of Bayreuth and IPP continue and strengthen their collaboration. The focus of the joint activities is the (gyro)kinetic description of small-scale instabilities in tokamaks, the related transport processes and their interaction with long-wavelength instabilities. First results documenting the self-consistent growth of a tearing mode in the presence of gyrokinetic turbulence are presented.

In June 2010 the University of Bayreuth opened a new Chair researching the physics of high temperature plasmas. The Chair is financially supported by the University, the 'Volkswagen-Stiftung', through a Lichtenberg Professorship for Prof. A. G. Peeters, and the IPP. Through this Chair the University and the IPP continue and strengthen their long term collaboration, in particular in the areas of nonlinear dynamics and computational physics.

The dedication to the collaboration is clearly expressed through the involvement of an IPP employee, PD Dr. W. Suttrop, in the teaching at the University. It is also evident from the multiple collaborative projects between the University and the IPP. The projects deal with a number of subjects: toroidal momentum transport, mirco-instabilities and the interaction of small scale turbulence with large scale MHD modes. Below we discuss briefly the progress in 2013 on only one of these topics: the study of the interaction of turbulence with the tearing mode.

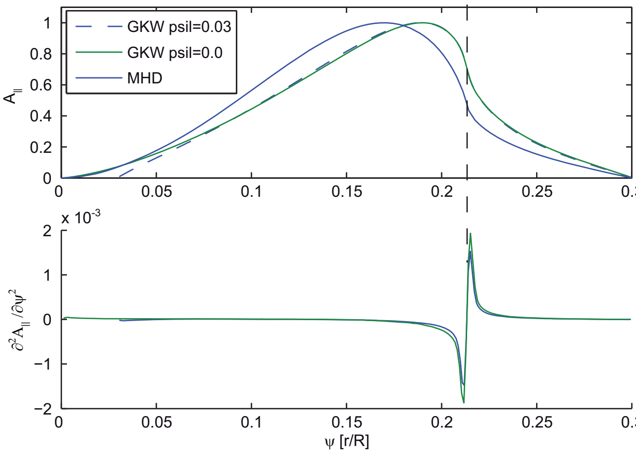

Figure 1: Radial profiles of the parallel magnetic potential (top) and of the second derivative of $A_{||}$ (bottom) showing the discontinuity in the derivative, which signifies the position of the resonant layer of the tearing instability. Profiles calculated using the global gyrokinetic turbulence code, GKW.

The magnetic islands in a tokamak that are generated by the tearing mode can lead to loss of confinement or even major disruptions of the plasma. In particular it is expected that the neoclassical tearing mode (NTM) sets the beta limit in a reactor. Plasma turbulence and tearing modes occupy disparate time and length scales. Nevertheless, there is growing evidence of an interaction between the two. In previous work the influence of a (stationary) tearing mode on micro-turbulence has been investigated. The change in magnetic field line topology was found to lead to new phenomena like the electro-static vortex mode.

Recent development of the nonlinear gyro-kinetic GKW code has enabled the study of the self-consistent tearing mode evolution (see figure 1) in toroidal geometry for realistic parameters (i.e mass ratio, collisionality). It has been found that electromagnetic turbulence has a profound effect on the nonlinear evolution of the magnetic island. Electromagnetic turbulence provides, through nonlinear mode coupling, seed island structures of the order of the ion Larmor radius, larger than the singular layer width. At this island size, linear tearing stability is no longer applicable. When the turbulence saturates the seed island continue to grow provided it is driven by a gradient in the background current. Turbulence, therefore, does not disrupt the development of a coherent tearing mode structure. The presence of small scale turbulent fluctuations, however, does lead to a stochastisation of the seperatrix and X-point (as seen in figure 2) even at electron betas as low as 0.1 %. This stochastisation is expected to significantly affect the boundary layer around the island structure, and possibly on the polarization current as well. Indeed no evidence of a threshold behaviour due to the polarization current is observed in these simulations. The turbulence, furthermore, forces the island to rotate in the ion diamagnetic direction as opposed to the electron diamagnetic direction observed without turbulence.

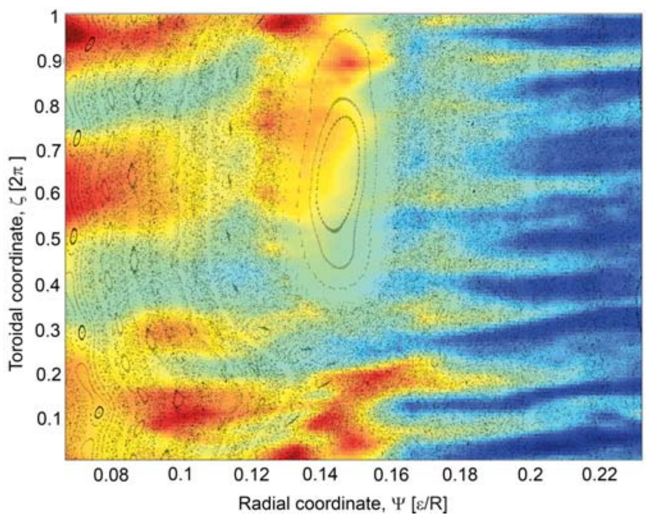

Figure 2: A snapshot of the (in colour) electrostatic potential in the psi-zeta plane, and the (black) field line intersections of from an electromagnetic turbulence simulation where the tearing mode is self consistently evolved with the turbulence.

Scientific Staff

C. Angioni, A. Bottino, R. Buchholtz, F. J. Casson, W. A. Hornsby, S. Grosshauser, P. Migliano, E. Poli, B. D. Scott, D. Strintzi, W. Suttrop, G. Tardini.

Technische Universität Berlin
Plasmaphysik, Plasma-Astrophysik

Heads: Prof. Dr. Robert Wolf, Prof. Dr. Wolf-Christian Müller

The collaboration between the Technical University of Berlin (TUB) and IPP has led to the establishment of the research groups Plasma Physics (2011) and Plasma-Astrophysics (2013) within the Centre for Astronomy and Astrophysics (ZAA). This fosters interdisciplinary research and university teaching incorporating the physics of high-energy and laboratory plasmas as well as of fundamental, and thus also astrophysically relevant, nonlinear plasma dynamics.

Convectively-driven Turbulent Dynamo

Magnetic fields are prevalent throughout the universe. Finding and understanding plasma-physical mechanisms, which are able to amplify such fields and to sustain them at dynamically relevant levels is therefore an important challenge. The nonlinear turbulent fluctuation dynamo in a convectively driven plasma flow, a viable candidate in this context, had been studied beforehand by direct numerical simulations (DNS) of magnetohydrodynamic (MHD) Boussinesq turbulence in the framework of an inter-institutional collaborative effort of IPP and the Max-Planck institute for Solar System Research. Tying in with these investigations, an apparently new nonlinear effect has been identified, which can serve as an additional building block in the theory of convectively driven dynamos. It is based on the spontaneous and intermittent formation of coherent large-scale flows giving rise to intense local shearing of magnetic fluctuations, the 'shear burst'. As visible in figure 1, the associated amplification of magnetic energy lasts significantly longer than the actual burst which caused it. The bursts can thus successively increase and sustain the mean magnetic energy of the system.

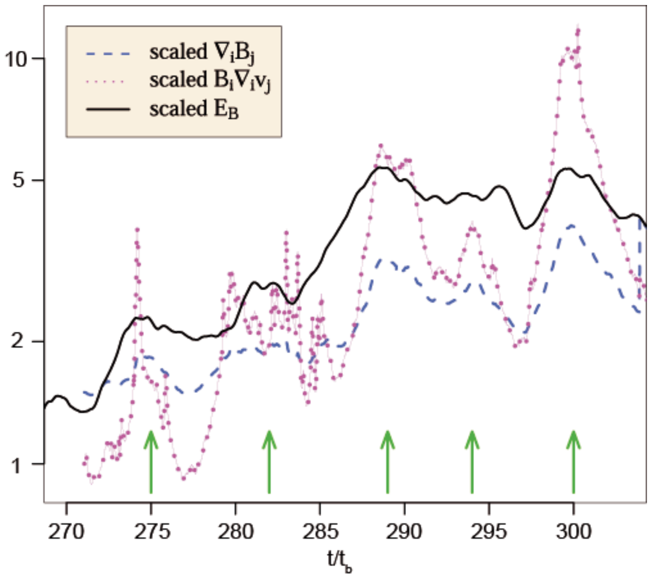

Figure 1: Magnetic energy, E_B, is significantly amplified over long times due to repeated shear bursts in DNS of MHD-Boussinesq turbulence. The signature of the shear bursts, identified here with arrows, is clearly visible in the simultaneous peaks of the magnitude of the magnetic shear tensor, and the magnetic stretching tensor (normalized to their initial values for easy comparison).

MHD Turbulence in Strong Magnetic Fields

The nonlinear transport of cascading energy in three-dimensional MHD-turbulence in a mean magnetic field which is significantly stronger than the root-mean-square value of the turbulent fluctuations is currently a controversally debated issue. Specific physical relevance of the cascade mechanism follows for example from its direct impact on the characteristics of dissipation, i.e. heating, which are believed to strongly influence many astrophysical systems such as, e.g., the hot solar corona or regions of the interstellar medium. Aided by direct numerical simulations a consistent and new theory of quasi-resonant interactions in MHD turbulence has been developed and numerically confirmed. This theoretical model closes the conceptual gap between the Iroshnikov-Kraichnan theory valid in strictly two-dimensional MHD-turbulence and the Goldreich-Sridhar picture believed to describe three-dimensional MHD-turbulence in a dynamically weak or moderately strong magnetic field.

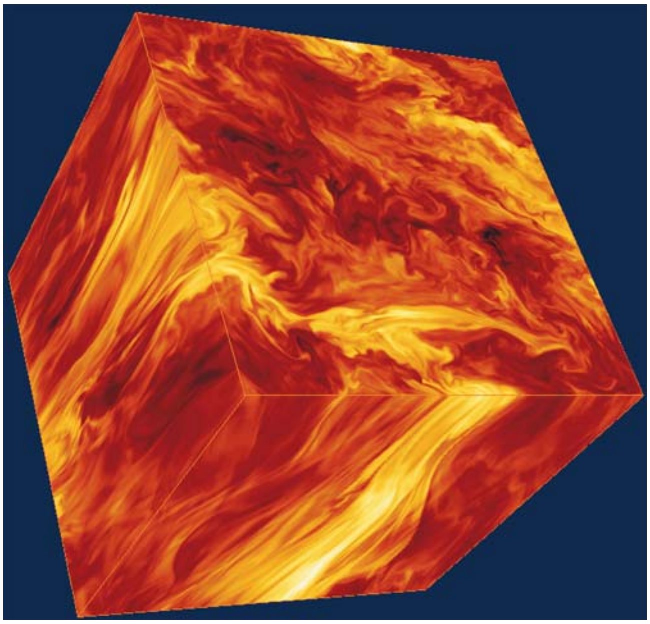

Figure 2: Magnetic field fluctuations in DNS of MHD-turbulence with strong mean magnetic field (modulus, color coded in brightness), the mean field direction is normal to the top face of the volume.

Modeling of Solar Active Regions

Active regions (ARs) of the Sun and their evolution have an impact on weather, communications, and sometimes health here on Earth. Sunspots, flaring regions of the photosphere, and coronal mass ejections (CMEs) are some of the ARs, which consist of turbulent magnetized plasma. These are monitored by space- and Earth-based solar observations. Magnetograms obtained from these instruments provide valuable knowledge of the physics and evolution of these regions. Their statistical properties such as structure function scaling, statistical flatness, and correlation lengths had been studied using these magnetograms. The experimental data has been compared to DNS of incompressible 3D-MHD turbulent flow (initially forced, subsequently freely decaying), which exhibits two-point statistics similar to those of observed ARs. The detected multifractality of the flow is well modeled in a log-Poisson framework. The pre-flaring and flaring phases in the AR development can be distinguished by different co-dimensions of the most singular dissipative structures in the flow. This suggests that the preflaring and flaring states of AR can be treated to some extent in a simple incompressible forced 3D-MHD framework where the influence of complex phenomena like solar convection and differential rotation are roughly approximated by the small-scale stochastic forcing.

Ernst-Moritz-Arndt Universität Greifswald

Electron Beam Ion Trap

Head: Prof. Dr. Lutz Schweikhard

The former Berlin EBIT has been rebuilt at the atomic and molecular physics group of the Ernst-Moritz-Arndt University for the study of the interaction of atomic clusters with highly charged ions. Charge transfer and dissociation are expected to be the prominent reaction channels, which result in multiply-charged clusters and cluster fragments, respectively. New knowledge about the fragmentation pathways of clusters is expected by comparing the interaction between atomic clusters with highly charged ions and with fs lasers.

Highly-charged ions up to Ar^{18+} have already been produced in the EBIT by electron impact ionization at the new location at Greifswald. They have been extracted and guided by a beam line to a Wien filter for charge-state selection. Currently, a deceleration unit to vary the projectile velocity is built and the original reaction chamber is modified to allow the investigation of the reactions of interest. The modifications concern, in particular, the region of intersection of the ion beam with a beam of atomic clusters. The charged reaction products will be extracted and analyzed by a reflectron-type time-of-flight mass spectrometer.

The experiments will require a well-defined ion beam. Therefore, the electrostatic lenses and deflectors of the ion optics were optimized to improve the ion-beam properties. At the same time, a high-density cluster beam has to be provided by the cluster source. In first experiments neutral fullerenes will be used as target systems. To this end, a fullerene oven has been constructed and installed. Experiments are planned with charged metal cluster as target systems, which can be accumulated and size selected in a radio-frequency trap. However, progress has been hampered by the occurrence of “cold leaks”, i.e. vacuum leaks that open under cryogenic conditions only and are not easily found and fixed, at the heart of the EBIT.

Scientific Staff

C. Biedermann, J. Clementson, S. König, G. Marx, B. Schabinger.

International Helmholtz Graduate School for Plasma Physics

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

Started in October 2011 as a successor program to the International Max Planck Research School “Bounded Plasmas”, the “International Helmholtz Graduate School for Plasma Physics (HEPP)” is a well established part of the education of Ph. D. Students. Together, the partner institutions IPP (Greifswald and Garching), the Ernst-Moritz-Arndt University Greifswald, the Technical University Munich, including the Leibniz Computational Center Munich and the Institute for Low-temperature Plasma Physics Greifswald provide a structured Ph. D. Education in the framework of the HEPP. It is embedded in an interdisciplinary research environment and offers a broad range of structured training. A key aspect of the program is the exchange of lecturers to provide a homogeneous research portfolio across the institutions supplemented by external guest lecturers and courses.

These include research-related as well as general topics like soft skills training, frequently in cooperation with other (local) institutions, like the EMAU graduate academy (Greifswald). Essential part of the structured training programme is the bi-weekly HEPP seminar. Besides its main purpose, serving as a means for regular exchange on the progress of the individual Ph. D. Projects, it is also well accepted as a platform for practicing and discussing presentation skills and techniques (regular feedback sessions are established along with the seminar) and as a means for social interaction, not only among the students but also including the supervisors. Additional part of the programme is a yearly HEPP colloquium, which is organized in form of a 3-day workshop and in 2013 took place in Strausberg in September with roughly 50 participants. The colloquium provides a platform for the students close to finishing their Ph. D. work to present their latest results. This is complemented by poster presentations of the first and second year students and invited general and topical lectures. As a novum, the colloquium 2013 has been fully organized by Ph. D. Representatives, with minimal administrative support. This organization scheme made it possible for the students to set up the scientific and social program according to their preferences, which further enhanced the acceptance of the HEPP among the students and provided them with an excellent possibility for networking. In addition the Ph. D. Organizers had the opportunity to gain experience with the self-responsible organization of a mid-size workshop. After the successful colloquium the students voted for keeping the organization scheme for the next year with newly elected Ph. D. Organizers. Additionally, it is planned to combine the colloquium 2014 with the annual spring meeting of the German Physical Society as a Symposium.

By the end of 2013 51 students were members of the HEPP.

The “International Helmholtz Graduate School for Plasma Physics“ is further established as key element of the cooperation with the Ernst-Moritz-Arndt University Greifswald. Two distinct scientific collaborations are performed, through PhD students partially in the framework of the graduate school: Investigation of ensembles of highly charged ions and their interaction with atomic clusters and 3D gyrokinetic simulation of magnetic reconnection.

Modelling of Magnetic Reconnection

Head: Prof. Dr. Ralf Schneider

Magnetic reconnection is a process in plasmas where magnetic field lines break and rejoin. Thus, the magnetic field configuration changes its topology. In this process magnetic energy is converted into kinetic energy. Therefore, magnetic reconnection plays a key role in the generation and evolution of many astrophysical phenomena, e.g. interstellar fields, solar flares or planetary magnetospheres. It also occurs in fusion devices and laboratory experiments.

In ideal MHD magnetic reconnection is forbidden according to the frozen-in flux theorem. There exist several theories for magnetic reconnection, but especially for collisionless plasmas the trigger and the underlying processes, which cause the field lines to break are not fully understood. To investigate this will be of future interest.

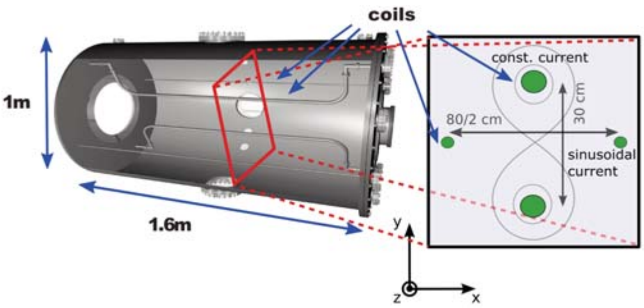

Figure 1: Schematic of the VINETA device (left side) and its corresponding representation in the simulation (right side). The reconnection event is driven by applying a sinusoidal current to axial drive coils and thereby generating an antiparallel field configuration.

One dedicated experiment for the investigation of driven magnetic reconnection is the VINETA experiment at IPP, Greifswald. In a joint effort reconnection will be examined experimentally and via simulations.

A three-dimensional gyrokinetic Particle-in-cell (PIC) code from Richard Sydora is specifically adapted to mimic VINETA experiment and its field configuration.

The setup of the device is seen in figure 1. It contains two axial coils with steady current in order to produce an x-point configuration. Two coils have a time-varying current to perturb the magnetic field configuration and to drive the reconnection process. The domain is bounded by conducting walls whereas particles are reflected.

Technische Universität München
Lehrstuhl für Messsystem- und Sensortechnik

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

There has been a continuous cooperation of IPP and the TUM Institute for Measurement Systems and Sensor Technology in the past. Thermography and speckle interferometry have been a field of broad research. For three years now, the focus is on the collaboration with the ITER Bolometry Group. A robotic based measurement tool has been developed and performed last year the geometrical in situ calibration of the ASDEX Upgrade bolometer lines of sight.

Collimator Prototype Design for ITER

The ITER bolometer cameras will be realized as a collimator construction type. The viewing cones of the lines of sight (LOS) in ITER will have to pass through very narrow gaps between the plasma facing components which provide neutron shielding; thereby they cannot be easily modified. This means that the aperture parameters determining the toroidal width of each LOS are restricted. Only the poloidal width can be freely optimized with regard to criteria like signal to noise ratio, tomographic spatial resolution and hence a more accurate calculation of the radiated power. The current collimator in the "LOS lab" version is shown in figure 1. A maximum number of 12 apertures can be fitted on the cylindrical steel rod. In the figure, one aperture in the middle is removed. The components of the final version of the collimator will be soldered together to assure an optimal heat flow from the top to the heat sink at the bottom.

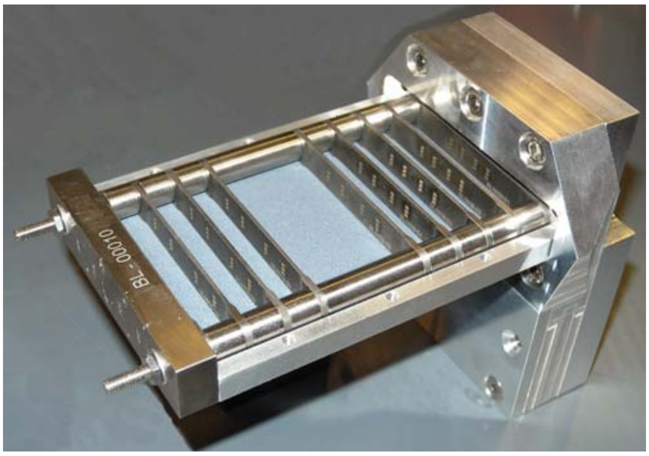

Figure 1: Isometric view of the collimator prototype with 12 apertures mounted on a cylindrical steel rod. One aperture in the middle is removed to investigate the effect on stray light reduction.

ITER Bolometer Robot Test Rig: IBOROB

The ITER Bolometer Robot Test Facility (IBOROB) was developed in order to measure and analyze the LOS characteristics of the different collimator versions necessary for the ITER bolometer diagnostic and to serve as a proof of concept for a future device envisaged for ITER. As a laboratory tool, it has been used since last year as a regular measurement device to quantify the design changes of the collimator prototypes manufactured as part of the development for the ITER bolometer diagnostic (see chapter 5). The device helped to assess the impact of stray light, evaluated the geometrical parameters of multiple bolometer collimator channels and could identify design imperfections of the camera concerning the LOS alignment. Thus, IBOROB significantly influenced the collimator design development for the ITER bolometer cameras.

Measurements in ASDEX Upgrade

During a regular maintenance shutdown of ASDEX Upgrade, which was used to install new components and allowed hardware upgrades, IBOROB was installed in the vessel to measure the transmission function of ASDEX Upgrade bolometers for the first time. The robot was attached manually on a specially manufactured mounting device on the inner heat shield of the relevant sector.

Figure 2: The LOS measurement tool IBOROB operating in ASDEX Upgrade.

This device can be rotated in 90° steps, which allowed to position the robot foot in an optimal alignment w.r.t. its operational space (divertor or main chamber). To prepare these measurements, the system was mounted in the test-octant for optimizing the robot trajectory planning. The narrow working area of a tokamak required significant efforts to avoid collisions with other components. Although exclusion zones for the end effector can be specified, the arrangement of the joints has to be controlled individually by implementing intermediate positions during the motion. Thereby, the whole procedure could be prepared in the test-octant beforehand; for the measurement in the vessel, the motions and positions of the robot only had to be slightly adapted. To determine these exact parameters and to provide a global alignment of all involved systems, a mobile coordinated measurement machine (FaroArm) was used. The alignment of each involved bolometer camera and the final robot position were measured. This procedure is absolutely necessary for determining the alignment of a LOS towards the vacuum vessel coordinate system. Three bolometer foil cameras have been measured exemplarily: A divertor camera, a camera in the area of the A-port, and a camera positioned at the top of the vessel close to the upper PSL. Figure 2 shows a picture of IBOROB operating in the vessel.

Results of the LOS Measurements

A contour plot of the calibration measurement of a camera in the top of the vessel (FHC) is shown in figure 3. The bolometer bridge voltage of each channel is normalized to its corresponding maximum. Channels 16 to 24 are plotted versus the poloidal and toroidal coordinate system of the vacuum vessel, which then represents the normalized transmission function of each channel. A rounded trapezoidal signal is expected and can be identified for the channels 24, 23, 22, 21, 17 and 16. The remaining channels had problems with the data acquisition (19, 20) or were damaged (18) during the last experimental campaign. However, all channel cores do not match the maximum of the measurement. This can be explained and was shown in the laboratory by an inaccurate vertical or horizontal positioning of the laser center on the bolometer aperture. Finally, the most interesting feature is the measurement of the alignment: The dotted lines in the plot indicate the theoretical orientation of the bolometer LOS which has been assumed so far for the past experimental campaigns. The toroidal orientation of this camera is expected at a toroidal angle of 108°, which agrees very well with channels 22, 23 and 24. For the other channels it is likely that some of the internal detectors are slightly inclined within the range of a few degrees relative to its vertical axis. This is just one example that can be derived from these measurements. The challenge in the data analysis lies in the fact that only the sum of all misalignments, manufacturing and integration errors can be determined.

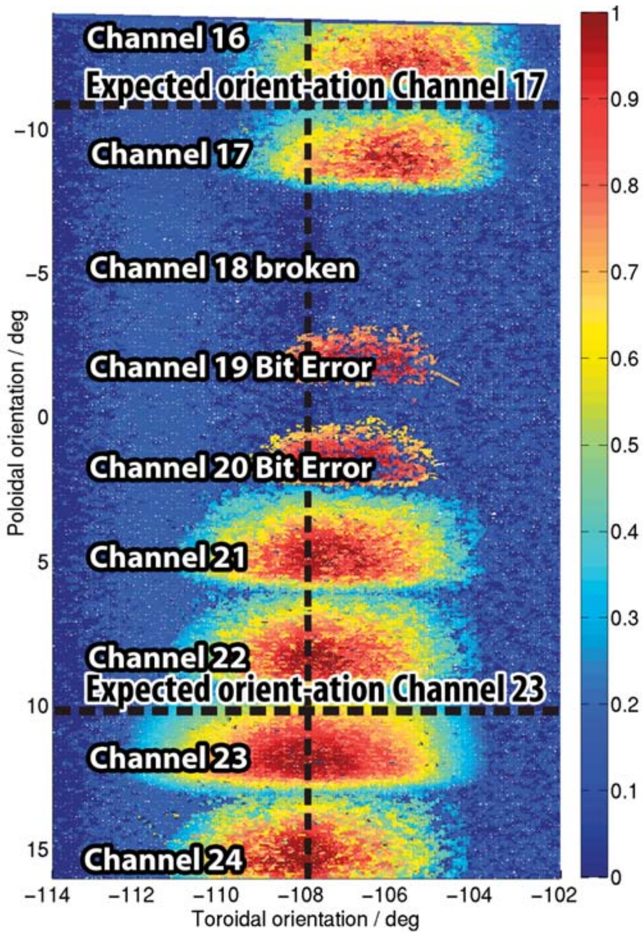

Figure 3: Contour plot of the measurement results for FHC camera channels 16 to 24 in the ASDEX Upgrade coordinate system. The expected alignments of channels 17 and 23 are indicated with the dotted lines. Channel 18 was broken, 19 and 20 were corrupted by a DAQ problem.

Future Collimator Development

For the future, the emphasis of the research to be performed will be on the optimisation of the ITER collimator. In parallel, analysis based on Monte-Carlo ray-tracing methods has been started. Its objective is to gain a better theoretical understanding of the complex behavior of reflections. Some of the results obtained helped to optimize the ASDEX Upgrade bolometer cameras, but the challenges for ITER will be more demanding, in particular the question, if the required extremely narrow viewing cones can be achieved while sufficiently reducing the impacts of stray light.

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The joint program between IGVP 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 IGVP: 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 otherwise inaccessible to electromagnetic waves. The EBWs are of electro-static nature and need to be coupled to injected electromagnetic waves. At the stellarator TJ-K, heating with EBWs at high harmonics has been successfully established. For very low magnetic fields corresponding to harmonic numbers as high as 8, a quasi-coherent mode appears. This mode of approximately 4 kHz is evident throughout the whole plasma cross section. The general broadband turbulent background was found to be decreased in this regime.
The first stage of the build-up of the new 14 GHz microwave heating system has been finished. It consists of two klystrons with a combined power output of 4 kW and a transmission line with over-sized circular waveguides. The magnetic field system allows steady state operation (up to 20 seconds) at 500 mT. A series of parameter scans were performed to characterize the plasma in the new operational regime. The energy stored in the plasma was found to increase with the magnetic field strength, which is mainly due to an increase of the plasma density. The increase of the electron temperature is less pronounced. The degree of ionization reaches 100 % in argon for magnetic fields higher than 400 mT, indicating the possibility of increasing temperature and, hence, decreasing collisionality with further increasing heating power. Additional 2 kW of heating power will be installed within the second stage of the build-up. Indications for reduced collisionality were already seen in low-pressure hydrogen discharges.

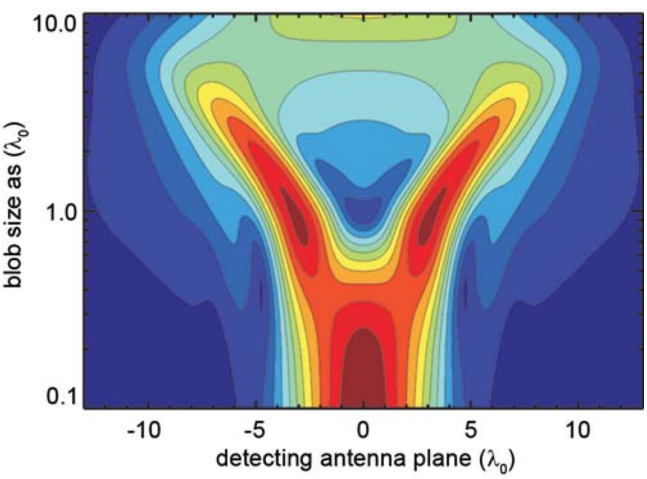

Figure 1: Contour plot of the spatial distribution of E_{rms} at the receiving antenna located behind the blob-microwave interaction region as a function of the width of the blob.

The mode conversion into EBWs usually takes place at the plasma boundary. In this region, perturbations of the plasma pressure like so-called blobs or filaments are known to occur. Depending on the size and amplitude of the blob, they can significantly distort microwaves traversing them. The full-wave code IPF-FDMC is used to study the influence of such blobs on propagating microwaves in a 2D geometry. The perturbation of a single blob was studied first, where the blob was modelled as a Gaussian shaped density perturbation added to a homogeneous background plasma. To analyze the distortion of the microwave beam, a receiving antenna is located behind the blob recording the spatial distribution of the perturbed beam. The signal of this antenna is shown in figure 1 as a function of the width of the blob, with the peak density of the blob being below cut-off density. As can be clearly seen, the distortion is largest for blobs having a width on the order of the vacuum wavelength λ_0. For very thin and very wide blobs, the distortion is decreasing.

Global Turbulence and Confinement Studies

A new experimental setup is dedicated to the quantitative investigation of driving and damping mechanisms of zonal flows (ZFs). Poloidal limiter plates were constructed specifically to shape the radial profile of Reynolds-stress (RS) drive. This way, the RS drive could be optimized in the radial range of the 128 pin RS probe array (see figure 2).

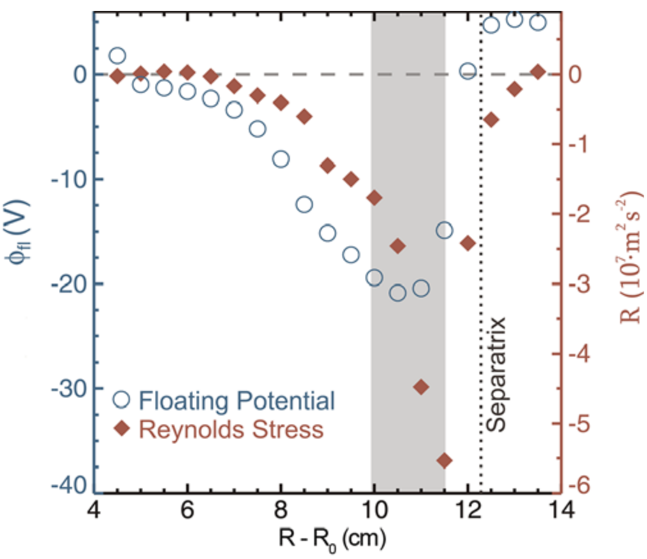

Figure 2: Radial profile of floating potential (circles) and Reynolds stress (diamonds). The radial position of the probe array coincides with maximum zonal flow drive (shaded).

In this range, background shear flows are observed and the radial correlation in potential fluctuations turned out to be decreased. Further analyses address the radial structure and dynamics of long-range correlations associated with ZFs. In the future, the ZF drive will be opposed quantitatively to damping in dependence of, e.g., the collisionality. Plasma biasing can serve as a complementary drive.

Intermittent density structures were traced by a fast camera and Langmuir-probe measurements. These so-called blobs are observed mainly in the region of negative normal curvature of the magnetic field lines, which emphasizes the role of curvature as driving mechanism of blobs. Radial blob velocities were found to be close to theoretical predictions, provided that the cross-phase between density and potential fluctuations is taken into account. While normal curvature is made responsible for the radial E×B blob motion as a consequence of polarization, the effect of geodesic curvature is usually disregarded. Analyses of blob trajectories indicate a contribution of geodesic curvature to the poloidal blob propagation.

Further analyses of the edge turbulence data base showed that characteristic length scales in the injection region of turbulent power spectra scale linearly with the drift scale length ρ_s. The scaling of correlation lengths of dominant turbulent structures, however, turns out to be weaker with a square root dependence only. The linear dependence relies on most unstable scales of drift-wave turbulence, which does not need to be the same for the remaining dominant structures. This could resolve the contradiction between the different results. As consistent with results from camera measurements in TJ-K, the scaling of dominant structure sizes is found to be the same for both edge regions, inside and outside the separatrix.

Doppler Reflectometry Simulations with IPF-FD3D

In collaboration with G. Conway and T. Görler (IPP), the fullwave code IPF-FD3D is used to simulate Doppler reflectometry on ASDEX Upgrade, in close coupling with experimental investigations and with incorporation of simulated plasma turbulence using the turbulence code GENE. Figure 3 shows the resulting spectrum from IPF-FD3D simulations.

The GENE simulations are tweaked so that the turbulent transport matches the measured transport from experiment. Even then, the spectral indices from experiment and simulation do not match up. It can be seen that a non-linear saturation effect takes place at the higher fluctuation strengths ("GENE*2"), which changes the slope of the spectrum. The inherent spectral shape is "squished" against a maximum level, beyond which an increase in density fluctuation amplitude will not result in the backscattering of more power. This needs to be investigated further.

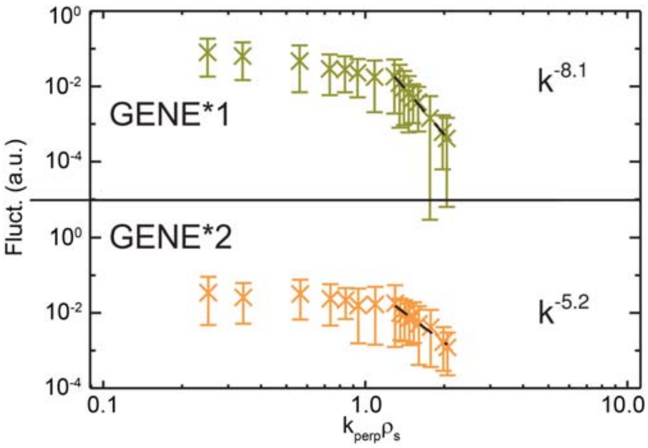

Figure 3: Doppler spectra from IPF-FD3D for GENE turbulence in an L mode scenario. The absolute fluctuation amplitudes have been scaled by 2 changing the spectral index from -8.1 to -5.2.

Ion cyclotron resonance heating (ICRH) can induce coherent density fluctuations, which oscillate at the ICR frequency. Being able to detect these very minute fluctuations would give useful information on ICRH power deposition.

Figure 4 shows the simulated density fluctuations of the ICR wave (provided by N. Tsujii, IPP). Conventional reflectometry at the two positions shown was simulated to gauge whether such fluctuations are detectable. The result shows a coherent signal at the heating frequency, at a level of about 1 % of the fundamental reflection. It is present over a wide range of normalised radial positions an should be detectable by a suitably modified receiver.

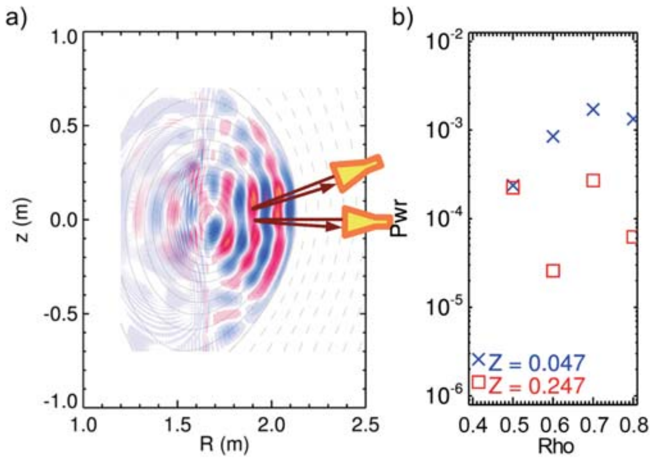

Figure 4: a) Simulation setup for reflectometry on ICR waves. b) Received power at ICR frequency.

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M. Köppen, P. Kornejev, M. Kostmann, R. Krampitz, W. Kraus, J. Krom*, M. Krychowiak, G. Kühner, F. Kunkel, B. Kursinski, A. Kus, H. Laqua, H.-P. Laqua, R. Laube, M. Laux, H. Lentz, M. Lewerentz, C. Li, S. Lindig, A. Lorenz, J. Maier, S. Marsen*, C. Martens, M. Marquardt, G. Matern, M. Mayer, P. McNeely, B. Mendelevitch, U. Meyer, G. Michel, B. Missal, H. Modrow, S. Mohr, St. Mohr, A. Möller, T. Mönnich, A. Müller, E. Müller, I. Müller, J. Müller, M. Müller, S. Nack, K. Näckel, M. Nagel, D. Naujoks, U. Neumann, U. Neuner, M. Nitz, R. Nocentini, F. Noke, J.-M. Noterdaeme, S. Obermayer, G. Orozco, N. Ose, M. Otte, E. Pasch, A. Peacock*, T. Sunn Pedersen, M. Pietsch, D. Pilopp, S. Pingel, H. Pirsch, F. Pompon, M. Preynas, B. Prieß, F. Purps, D. Rademann, T. Rajna*, O. Raths, L. Reinke, S. Renard*, T. Richert, R. Riedl, H. Riemann, K. Riße, A. Rodatos*, V. Rohde, P. Rong, K. Rummel, Th. Rummel, N. Rust, N. Rüter, H. Saitoh*, A. Scarabosio, J. Schacht, F. Schauer, D. Schinkel, R.-C. Schmidt, S. Schmuck*, M. Schneider, W. Schneider, P. Scholz, R. Schroeder, M. Schülke, H. Schürmann, A. Schütz, U. Schultz, T. Schulz, E. Schwarzkopf, C. von Sehren, K.-U. Seidler, O. Sellmeier, T. Sieber, G. Siegl, M. Smirnov, E. Speth, A. Spring, J. Springer, A. Stäbler, R. Stadler, B. Standley, T. Stange, F. Starke, M. Steffen, E. Stenson, U. Stridde, M. Stöcker, T. Suhrow, S. Thiel, H. Thomsen, H. Tittes, U. von Toussaint, J. Tretter, P. Uhren, I. Unmack, S. Valet, H. Viebke, R. Vilbrandt, O. Volzke, A. Vorköper, F. Wagner*, F. Warmer, L. Wegener, M. Weissgerber, J. Wendorf, U. Wenzel, A. Werner, K.-D. Wiegand, E. Winkler, M. Winkler, A. Wölk, R. Wolf, T. Xu*, G. Zangl, H. Zeplien, D. Zhang, M. Zilker.

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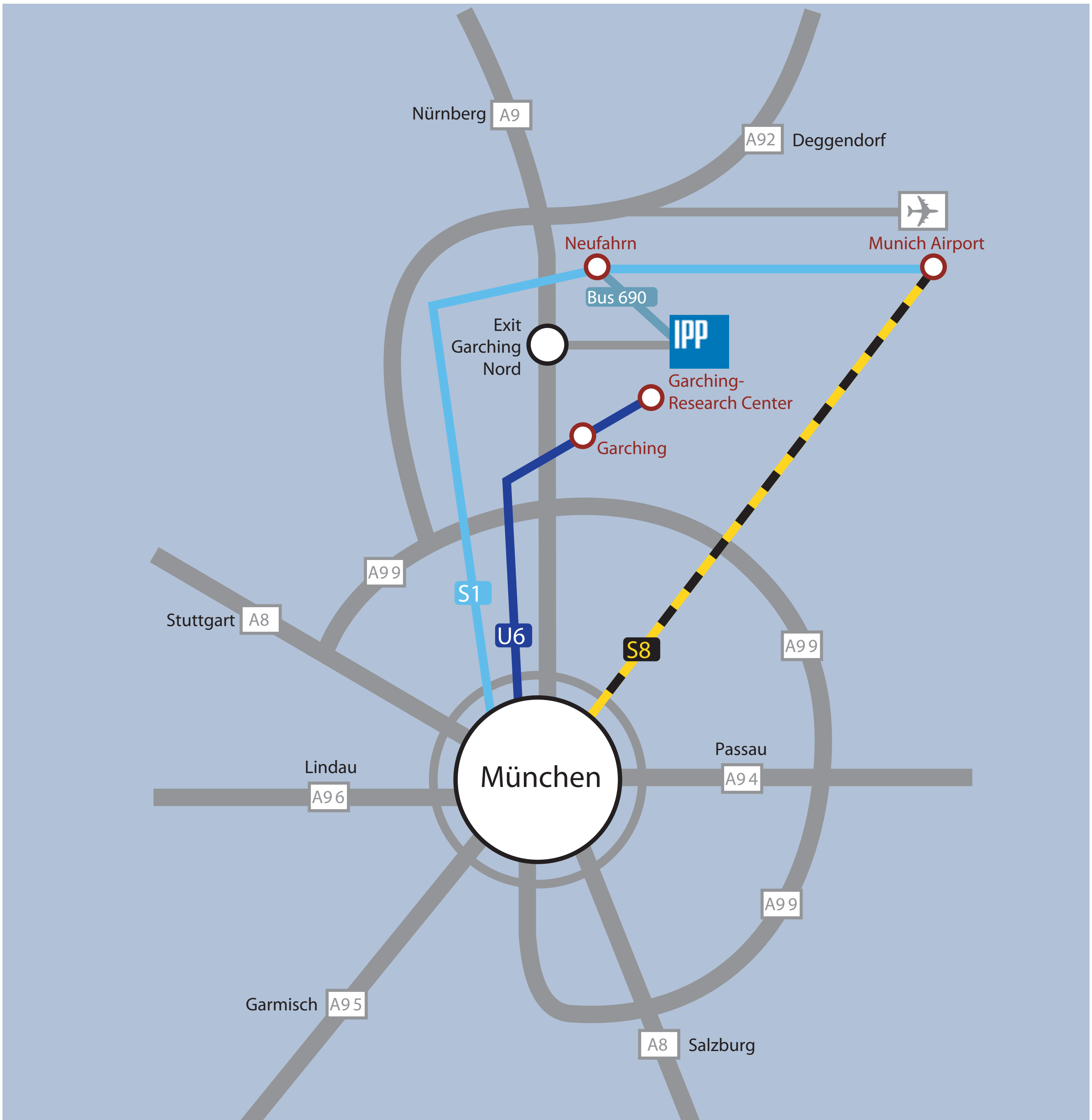
Appendix

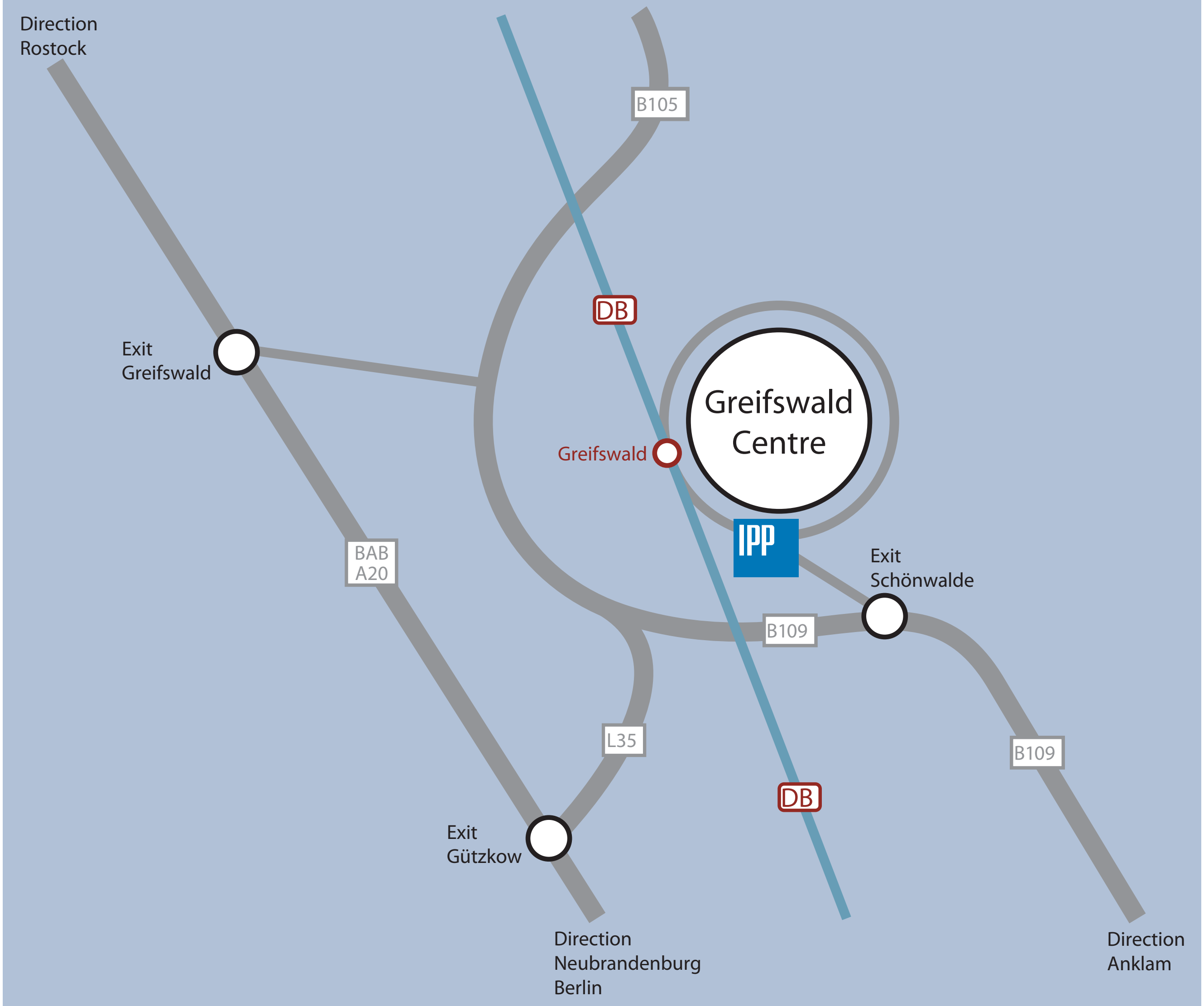
How to reach IPP in Garching



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

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

How to reach Greifswald Branch Institute of IPP



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

By bus:
From Greifswald-Railway Station (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

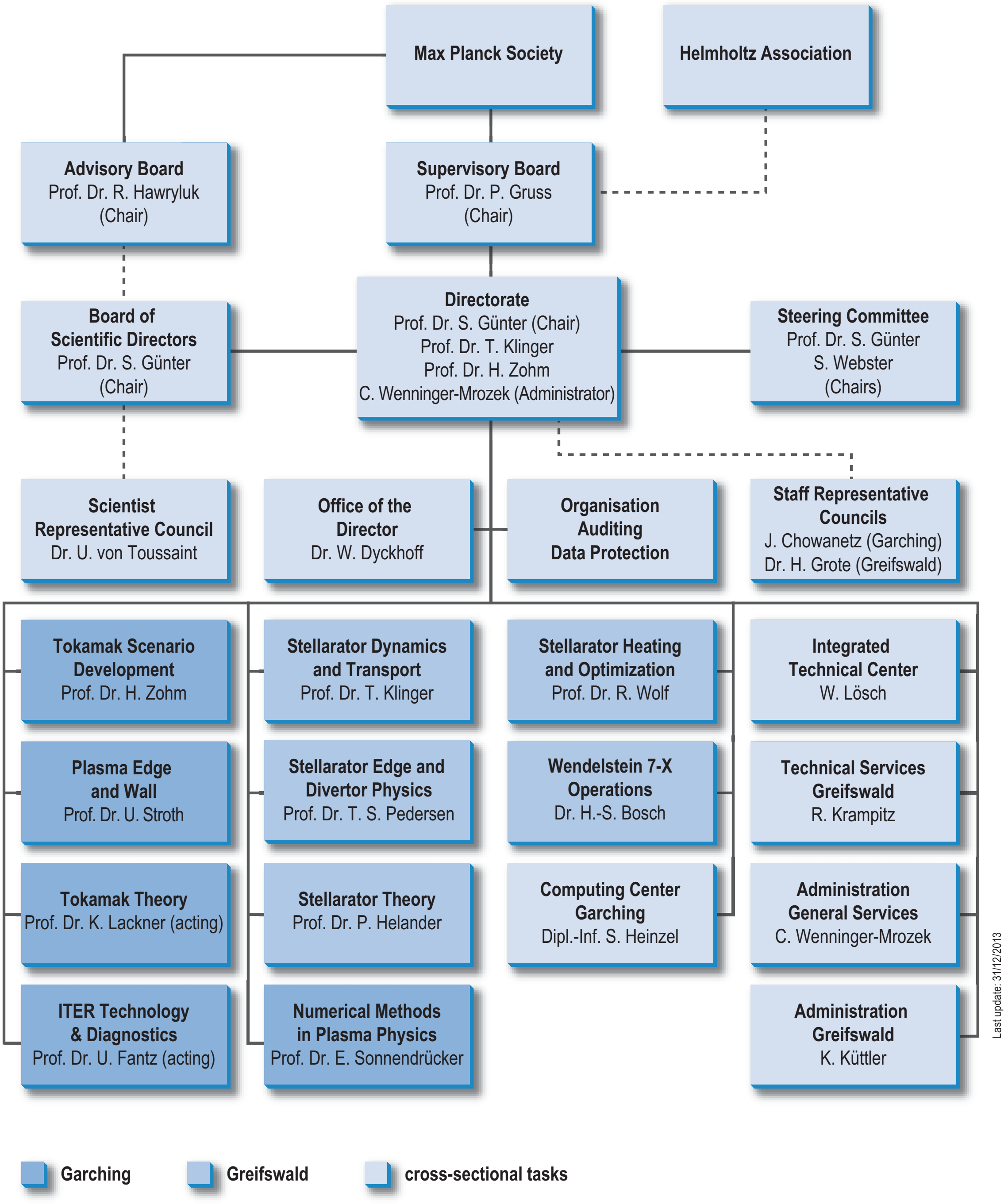
Funding

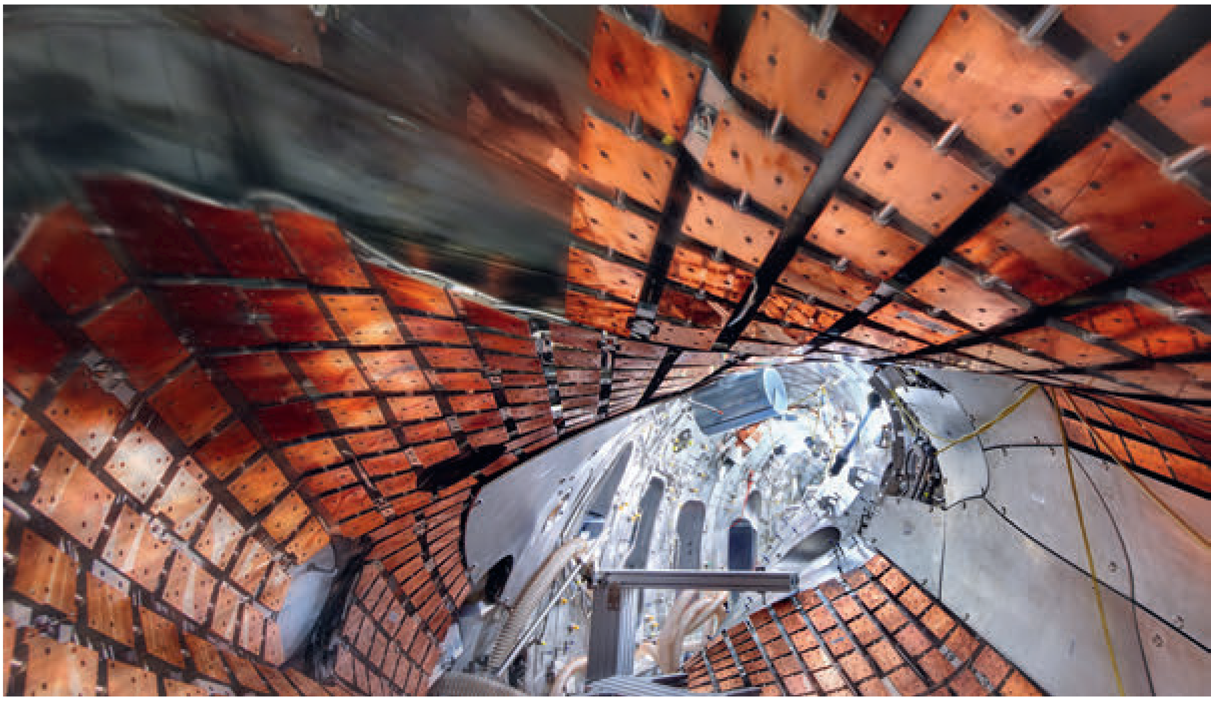
In 2013 IPP received approx. 13% of its total funding from EURATOM. Of the basic national funding 90% is met by the Federal Government and 10% by the states of Bavaria and Mecklenburg-West Pomerania. EURATOM baseline support and national funding amounted to approx. 121 million euros.

Scientific Staff

At the end of the year IPP had a total of 1.105 members of staff, 408 of them worked at IPP's Greifswald site. The workforce comprised 282 researchers and scientists, 42 postgraduates and 65 postdocs. In addition, 11 guest researchers used the research infrastructure.

Organisational Structure





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Further Information
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