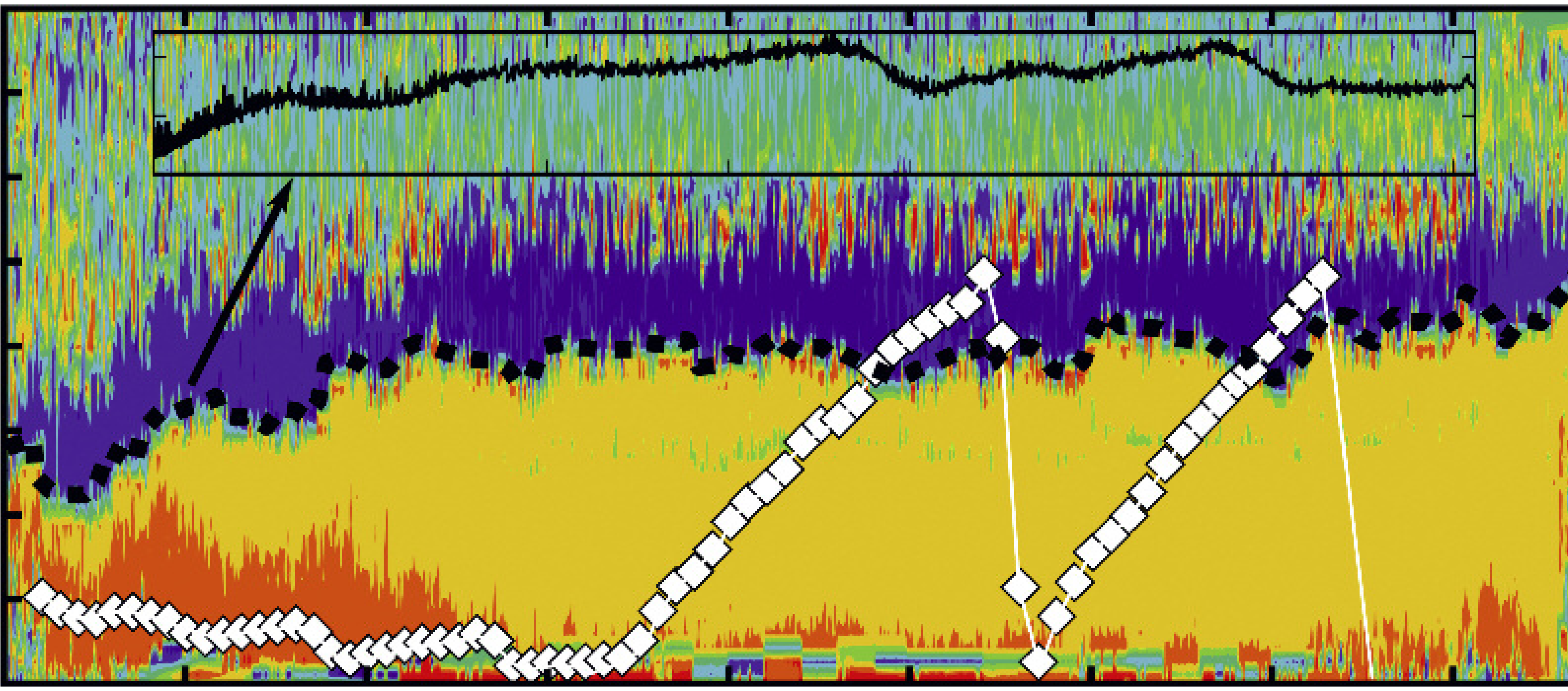
Max-Planck-Institut für Plasmaphysik

Annual Report 2012



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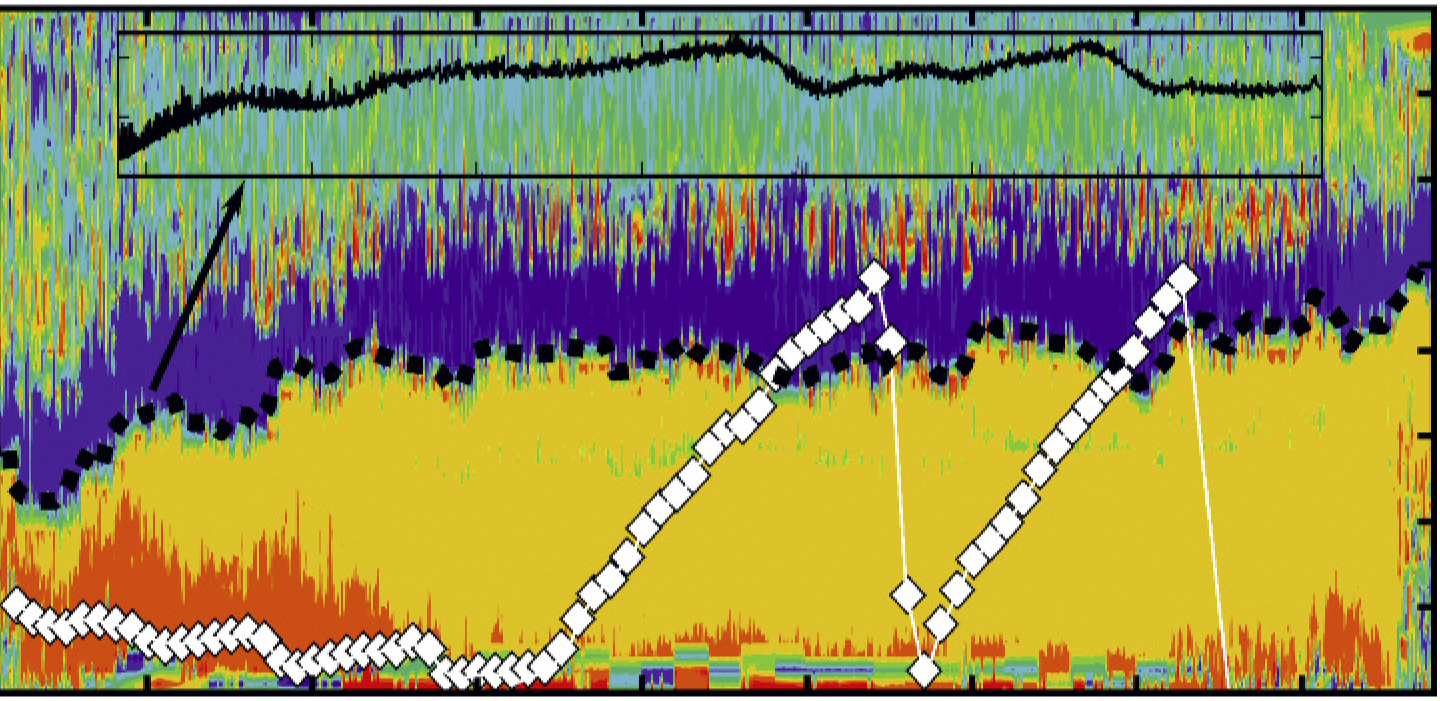

Phase differences of temperature fluctuations during an ASDEX Upgrade plasma discharge versus time. The y-axis ranges from the plasma centre (bottom line) to the plasma edge (top). The x-axis represents a time window of about 4.5 seconds. A magnetic island, which impairs the plasma energy confinement, is located here at about half-radius (dashed black line). An indicator of its size is shown in the black insert. The white diamonds represent the varying location of the absorbed power of an electron cyclotron current drive beam (microwave). If the beam hits the island, it is strongly suppressed, leading to a favourable recovery of plasma confinement.

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

Looking at IPP's Wendelstein 7-X stellarator, plasma vessel, coils and all other installations inside the cryostat are now completely covered up by the cryostat vessel. With its diameter of 11 metres Wendelstein 7-X now has the form of a big torus. In 2012 the assembly of the 254 ports, which protrude from the cryostat vessel, was completed. Once Wendelstein 7-X is in operation more than 20 diagnostics will view the plasma through these ports. The main work packages ahead are the installation of the cooling elements inside the plasma vessel, designed to take up the heat loads from the plasma, and of the current leads, developed and manufactured by Karlsruhe Institute of Technology, these connecting the superconducting coils to normally conducting power supplies. An increasing number of collaboration partners are contributing to the success of Wendelstein 7-X. Now that assembly of the superconducting joints by engineers and technicians from the Institute of Nuclear Physics of the Polish Academy of Sciences has come to an end, the first additional coils, provided by Princeton Plasma Physics Laboratory, for controlling the magnetic field configuration of the plasma boundary have been installed.

Exploitation of the flexible heating systems of the ASDEX Upgrade tokamak allowed physics studies of very high power scenarios. A novel double feedback system was introduced as independent control of the power flux into the divertor and onto the targets. This has been used for maximising the divertor radiating power and P_{sep}/R on the one hand and the main chamber radiation on the other. About half the ITER value of P_{sep}/R has hitherto been attained with very good plasma performance and a target power load acceptable under steady-state operation. ELM mitigation studies with resonant and non-resonant magnetic perturbations considerably broadened the range of magnetic spectra and plasma conditions. Disruption mitigation by massive injection of noble gases was investigated with injection valves located on both the plasma high-field and low-field sides. Very high electron densities corresponding to 20 per cent of ITER's critical density could be obtained during the energy and current quench phases. However, assimilation of gas by the plasma appeared to saturate at high total injection rates, and the improved fuelling efficiency from the high-field side diminished.

Electron cyclotron waves were used to study regimes with dominant electron heating and low plasma rotation velocities, which are particularly relevant to ITER. It is found that the ion pressure gradient at the plasma edge determines the radial electric field, in agreement with neoclassical theory. This background field value proves to be a key parameter for transition into the H-mode. Turbulent transport was studied in the core and edge plasma. A close link between core momentum and density transport was found, this being consistent with a gyro-kinetic turbulence model. With low collisionalities, this leads to centrally peaked density profiles which are favourable to burning plasma operation. A detailed comparison of probe data with a gyro-fluid code was made in the scrape-off layer. Excellent agreement in the fluctuation properties was found, which clearly points to the importance of drift-wave turbulence in the plasma edge. These measurements will allow quantifying the interaction of the plasma with the plasma-facing components. Fluctuation measurements will be intensified in the future within a newly founded "Virtual Institute" treating "Plasma Dynamical Processes and Turbulence Studies using Advanced Microwave Diagnostics".

Work in the "Plasma-facing Materials and Components" project ranges from investigations of microscopic processes on plasma-exposed surfaces to development and testing of new materials and components for current and future fusion devices. New experiments together with American collaborators at PISCES/USA have shown that erosion yields on plasma-exposed beryllium surfaces can greatly exceed laboratory results using ion beams. Hydrogen isotope exchange has been shown to be an efficient method for reducing the tritium inventory in ITER before major interventions or at the end of an operation period. Substantial progress was made in the development of a SiC-fibre-reinforced copper heat sink material for a DEMO divertor. The GLADIS high-heat-flux test facility was prominently involved in quality assessment of the first manufacturing series of the divertor components for Wendelstein 7-X. First steps were taken to assess the plasma compatibility of modern steels on large areas of the first walls of fusion devices.

To consolidate ITER design choices and prepare for operation, JET has implemented ITER's plasma-facing materials, viz. Be at the main wall and W in the divertor. During the 2012 JET campaigns, the experiments with this ITER-like wall achieved important results for operation of ITER, these confirming in many respects previous results achieved at Alcator C-Mod and ASDEX Upgrade. In addition, new ITER-relevant findings due to use of the exact ITER material mix were obtained. Although not all of the new JET results lead to positive scaling towards ITER, none of them need be considered as a showstopper. Some of the surprising results may even afford new insights in the confinement physics of H-modes.

The many efforts made within the ITER cooperation project at IPP during the past year were rewarded by some pleasant news towards the end of 2012: The ELISE test facility was commissioned and officially started operation in November. Also, IPP and its partners were awarded the Framework Partnership Agreement (FPA) on the development of the ITER diagnostic pressure gauges by F4E in December. Our response to the call for the FPA on the development of the ITER bolometer diagnostic is still under negotiation, but R&D efforts at IPP continue with national funding. The investigations relating to the ITER ICH antenna within the CYCLE consortium and those relating to the ECRH Upper Launcher within the ECHUL consortium continue. Furthermore, IPP is contributing to development of the ITER CODAC system, to simulations of ELM effects on ITER performance and to development of fusion materials, and did Paschen tests on cables for JT60-SA. Additionally, IPP is leading or contributing to many tasks within the EFDA Work Programme and the International Tokamak Physics Activity.

Our theory efforts focus on clarifying of the performance-limiting processes in tokamaks and stellarators, viz. losses caused by micro-turbulence, macroscopic instabilities of the plasma column and fluctuations driven by energetic particles, and on quantitative modelling of wave heating and of the energy and particle exhaust in the divertor. Most of these efforts require high-performance computing and got a significant boost from the petaflop Helios system now available to EU and Japanese researchers. It allows, in particular, turbulent transport simulations for larger-size devices. In stellarator theory it is now possible to make gyrokinetic simulations of an entire flux surface and do linear microstability calculations of the entire plasma volume. Gyrokinetic turbulence studies have also clarified the observed correlation between plasma rotation and impurity profiles in tokamaks. Macroscopic stability studies have identified the probable origin of low-mode-number contributions to the spectrum of Edge Localized Modes, and explained the larger-than-expected growth rate of axisymmetric instabilities for highly triangular plasmas. Combination of the LIGKA linear gyrokinetic stability code with the HAGIS code modelling the time development of the particle distribution function has afforded a qualitative advance in the modelling of energetic particle losses. Related work in stellarator geometry has made it possible to assess the stability of fast-ion-driven modes taking into account the full three-dimensional mode structure. Furthermore a new division devoted to computational plasma physics was created in September 2012. Its focus will be on developing efficient and robust numerical methods for fusion applications.

On behalf of the Directorate and the Scientific Board I would like to thank our staff for the excellent work performed in all divisions throughout the year 2012.

Scientific Director Sibylle Günter

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Tokamak Research

ASDEX Upgrade

Head: Prof. Dr. Arne Kallenbach

The ASDEX Upgrade experimental program is devoted to technical and physics input to remaining issues of the ITER design, the preparation of ITER operation and the design of a DEMO prototype fusion reactor. Key topics of the 2012 campaign were the development of high power exhaust scenarios, fast ion physics, the exploitation of improved turbulence diagnostics, ELM mitigation studies as well as ICRF coupling and tungsten sputtering investigations.

1 Overview

1.1 Experimental Programme and Operation

ASDEX Upgrade (AUG) operated from March till December 2012, with a two month summer interruption for power supply maintenance and repair of some damaged diagnostics and in-vessel components. Overall more than 1200 plasma discharges have been conducted in 2012, including two dedicated weeks with reversed I_p/B_t operation and special days with hydrogen and helium as major gas species.

Exploitation of its very flexible heating systems comprising 20 MW neutral beams (NBI), an ion cyclotron resonance system (ICRF) with up to 6 MW coupled power and 4 MW deposited power of electron cyclotron resonance heating (ECRH) allowed physics studies of very high power scenarios, variations of the electron-to-ion heating ratio and angular momentum transport studies with and without external torque. In addition to the standard scenarios at the toroidal field B_t=-2.5 T and plasma current I_p=1 MA (q_{95}=4.3) and I_p=1.2 MA (q_{95}=3.7), dedicated ITER studies were done with the safety factor q_{95}=3, using X3-mode ECRH at B_t=-1.8 T and I_p=1.1 MA. The latter conditions are challenging in AUG, since for achievement of the relatively low ITER-like $\beta_N \approx 1.8$ very limited heating is required and thus a low intrinsic ELM frequency is obtained which can give rise to tungsten accumulation in the central plasma. ICRF was operated predominantly using the antenna pair with boron coated limiters for reduction of the tungsten source. The tungsten coated antennas could be used in high power and high gas puffing scenarios. A special plasma configuration with the X-point very close to the roof baffle was set up and investigated in preparation of the WEST project at CEA-Cadarache. For preparation of the use of a tungsten divertor in ITER, the tungsten melt experiment with the divertor manipulator has been continued by further propagation of the melt damage by plasma impact. In addition, a close to double-null scenario was developed to obtain input for modeling of tungsten core penetration from the secondary upper divertor, where currently a change of the plasma facing material form beryllium to tungsten is considered by the ITER team.

1.2 Major Physics Results

Due to its versatile heating systems and power supplies, AUG is very well suited for studies of tokamak power exhaust. The ITER-like, closed divertor allows the compression of impurities in the divertor volume, which is a prerequisite for the achievement of high divertor radiation levels. A novel double feedback system was introduced for the independent control of the power flux into the divertor and onto the targets. This has been used for maximising of the divertor radiating power and P_{sep}/R on the one hand and the main chamber radiation on the other hand. About half the ITER value of P_{sep}/R could be achieved so far with decent plasma performance and exhaust conditions. An increase of this value can be expected in AUG with further optimization of power supplies and higher neutral fluxes in the divertor. This requires a reduction of pumping speed, which will become an option after the 2013 vent.

Plasma fluctuation studies benefited from new diagnostics such as the steerable Doppler reflectometer, lithium beam emission spectroscopy (LIBES) and electron cyclotron emission imaging (ECEI), which allowed to trace the propagation of fluctuations and filaments. Solitary magnetic perturbations (SMP), which are field aligned structures located at or closely inside the separatrix with 1-2 peaks per toroidal turn provide a handle to investigate the transition from the linear to the non-linear ELM phase. The observed small toroidal mode numbers are clearly lower than corresponding numbers obtained in linear stability calculations.

Measurements of the radial electric field E_r in the H-mode transport barrier were accomplished with Doppler reflectometry and spectroscopy using different species (He, B, C, N) and compared to neoclassical predictions. Very good agreement has been obtained throughout the database, confirming the main ion pressure gradient as the major constituent to E_r and thus negligible poloidal rotation of the fuel ions in the steep gradient region. Good agreement between neoclassical theory and experimental values was also found for the current density at the pedestal, which is dominated by its bootstrap component. Equilibrium reconstruction with the CLISTE code allows the current density to be calculated based on magnetic measurements alone. Surface-averaged current densities were also calculated using kinetic data and good agreement for the height and width of the current peak between the two methods was demonstrated.

Intrinsic plasma rotation measurements by charge exchange recombination spectroscopy (CXRS) with short neutral beam blips gave new insight about turbulent plasma transport. In particular on the transition region between dominant ITG and TEM core turbulence, strong changes in the internal redistribution of toroidal angular momentum have been observed, which can be also correlated to changes in the density profile. These measurements enabled direct experimental tests of first principle transport calculations using ad-hoc assumptions for turbulent eddy tilting. First measurements of poloidal asymmetries of impurity densities open new possibilities for testing the gyrokinetic modelling of impurity transport.

Fast ion D_α (FIDA) measurements of the velocity distribution of energetic ions were significantly improved by an update of the collisional-radiative atomic data. With no free parameter left in the data evaluation, anomalous transport effects on the radial distribution of NBI injected fast could be ruled out down to low values of corresponding diffusivities for MHD-quiescent conditions. This result revived the question about the origin of reduced NBI current drive efficiency at high heating powers, since the previously assumed anomalous fast ion transport has been ruled out.

ELM mitigation studies with resonant and non-resonant magnetic perturbations (MP) considerably broadened the range of magnetic spectra and plasma conditions. ELM mitigation was obtained for n=1, 2 and 4 configurations of the 16 B-coils. Still, no significant effect of the magnetic spectrum on ELM mitigation has been observed in the high density regime. As minor effect a reduced density window appeared for ELM mitigation with n=4. More subtle effects have been observed for low collisionality conditions. Here, density pump-out and magnetic braking are sometimes observed, albeit full ELM suppression has not been observed so far. Significant changes of fast ion loss behaviour during ELM mitigation have been detected by the fast ion loss detector (FILD). High amplitude, steady fast ion losses with a broad frequency spectrum exchange the burst like losses observed during type-I ELMs. First ELM mitigation experiments in helium plasmas showed the surprising result that mitigation is obtained in resonant configuration close to the empirical deuterium density threshold, while no effect has been observed in the non-resonant case.

The real time control system for MHD control has been continuously upgraded and matured. It is now able to operate in the presence of more than one mode, e.g. (3,2) and (2,1) neoclassical tearing modes. Mode localization obtained by correlation of ECE with magnetic measurements and subsequent analysis of intensities and phases of the ECE fluctuations at the mode frequency. However, the required accuracy of mapping of the mode location using real-time equilibria on to the poloidal ECRH mirror launching angle appeared challenging. As a result, real-time NTM stabilization or pre-emptive stabilisation requires either a known scenario (known radial offset for mode position) or additional input for the equilibrium reconstruction.

Disruption mitigation by massive injection of noble gases was investigated with injection valves located on both the plasma high field and low field sides. Very high plasma densities up to corresponding to 20 % of the ITER critical density could obtained during the energy and current quench phases. However, the assimilation of gas by the plasma appeared to saturate at high total injection rates, and the improved fuelling efficiency from the high field side diminished.

1.3 Preparation of near Future Enhancements

A major vent is foreseen from May-November 2013, which induced a lot of preparation work in 2012. Planned are the installation of a solid tungsten divertor-III, two 3-strap ICRF antennas for reduced tungsten production and two rings of P92 steel on the high field side. P92 steel is very similar to EUROFER, which has been developed to withstand the high neutron fluxes in a reactor. Its test as plasma facing material is part of the DEMO studies in AUG, where the impact of the ferromagnetic properties and sputtering behaviour will be tested under real tokamak conditions. Finite element calculations of the resulting magnetic forces show radially inward directed values up to 1.4 kN per tile, which is acceptable for the support structure, which experiences a maximum displacement of 0.5 mm at the free ends of the P92 tile supporting wings. The new divertor-III will also be equipped with a new, large manipulator, which will allow the test of components and materials up to the size of two divertor tiles. A special liquid helium valve has been developed to allow partial operation of the cryopump and thus tailor its pumping speed. This will enable studies with even higher neutral gas pressure in the divertor after its installation in 2013.

2 Power Exhaust

A multi machine study of thermographic measurements of the power decay length λ_q for attached divertor conditions was set up including AUG data. Figure 1 shows an example for a re-evaluation of divertor I infra-red data using a dedicated fit function, which takes into account diffusive heat flux broadening. The multi-machine dataset revealed the independence of λ_q from the size of the device.

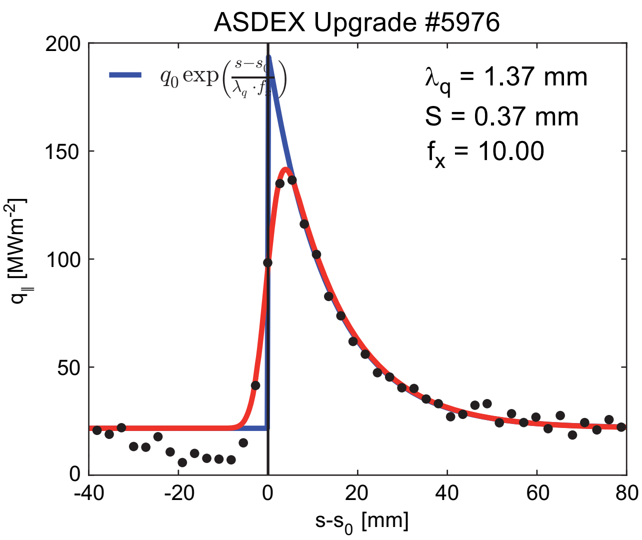

Figure 1: Fit to the measured parallel heat flux at the target using the dedicated functional dependence.

This finding challenges the power exhaust scenarios foreseen in future high current, high power devices. As shown in figure 2, λ_q depends in very good approximation inversely on the poloidal magnetic field B_{pol} in the outer mid-plane.

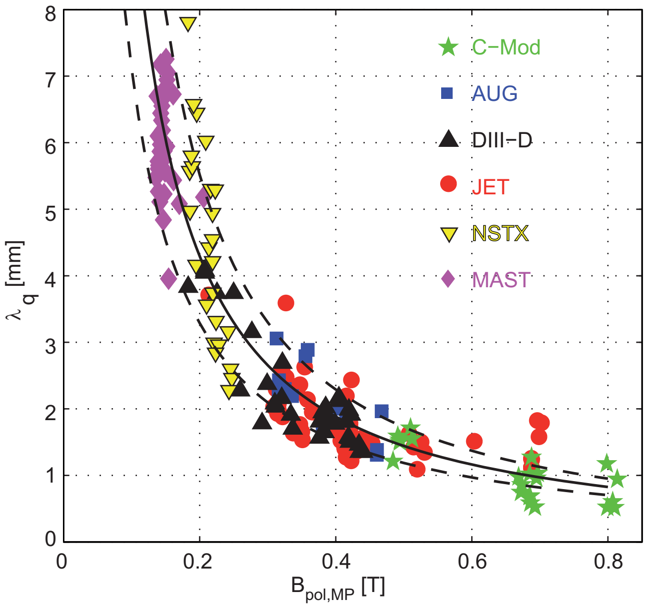

Figure 2: Power decay length λ_q derived from divertor infra-red thermography on various devices. The values shown have been mapped to the outer mid-plane, where just an inverse dependence on the poloidal magnetic field describes the whole multi-machine dataset with good accuracy.

The scaling shown above predicts a power e-folding length of about 1 mm in the outer mid-plane of ITER. The corresponding divertor values for fully attached conditions will be larger due to the magnetic flux expansion and by diffusive broadening of the power flux along the field lines. Nevertheless, the power flow channel remains narrow, which is problematic for the necessary radiative power dissipation and the achievement of partial detachment around the outer strike point.

To improve the power dissipation capabilities by radiative cooling, a double feedback system has been developed, which allows the coupling of core radiative cooling by a medium-Z impurity like argon with divertor cooling by nitrogen. Figure 3 shows time traces of a discharge where different combinations of feedback modes have been used sequentially. Core radiation control is used either separately or in combination with two options for divertor heat flux control. The power flux into the divertor, P_{div}, is controlled by a simple real-time estimate of the core radiation power using a linear combination of three foil bolometer lines of sight and the heating power. For the divertor heat flux control, either T_{div} feedback using a thermoelectric sensor is used or the power flux to the target, P_{tar}, is derived from the balance of P_{div} and the divertor radiation. The latter is estimated from a single real-time bolometer signal in the upper outer divertor.

As shown in figure 3, the different feedback modes co-operate smoothly and also the mode switching does not produce instabilities.

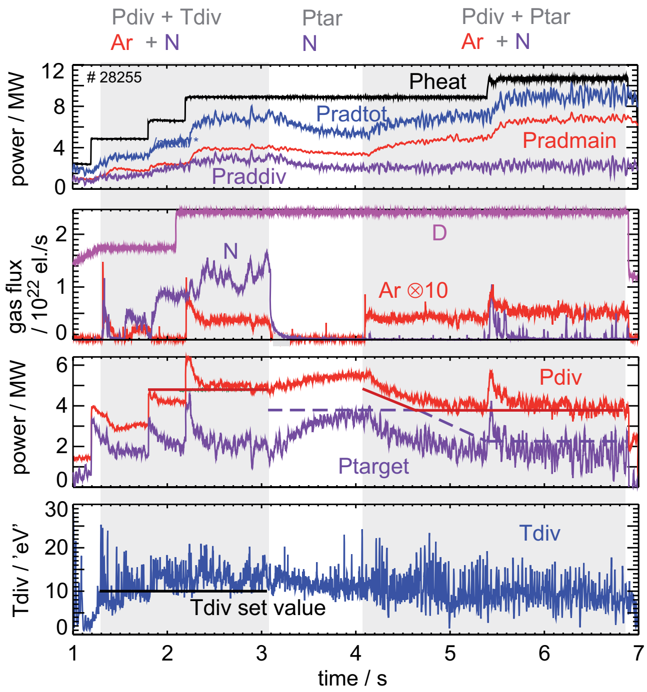

Figure 3: Time traces of a pulse with different combinations of radiative feedback modes using simple bolometric evaluations of main chamber and divertor radiation as well as the thermoelectric T_{div}-sensor.

The fact that the power width in the radiating divertor region is about similar in AUG, ITER and even DEMO allows divertor identity experiments with P_{div}/R as a scaling parameter, where R is the major radius of the device. A necessary condition is density identity, which can be fulfilled in AUG at an I_p of about 1.2 MA. ITER/DEMO has very high values of the parameter P_{div}/R, which cannot be achieved in present day devices so far. For DEMO, high main chamber radiation will be required in addition to high divertor radiation values for dissipation of the high α-heating power.

The high power heating systems in AUG allow the study of the heat exhaust as close as presently possible to ITER/DEMO parameters. The radiative double feedback has been used to maximise either main chamber radiation or divertor radiation for conditions of maximum heating power (23 MW) while keeping the peak heat flux at the target below 5 MW/m^2, which is currently regarded as conservative maximum acceptable value for DEMO. Figure 4 shows time traces of a discharge where the maximum heating power was mitigated accordingly by simultaneous control of power flux into the divertor by argon seeding and target heat flux by nitrogen injection. Despite the onset of a (3,2) neoclassical tearing mode, good H-mode confinement with H_{98}=1 was retained.

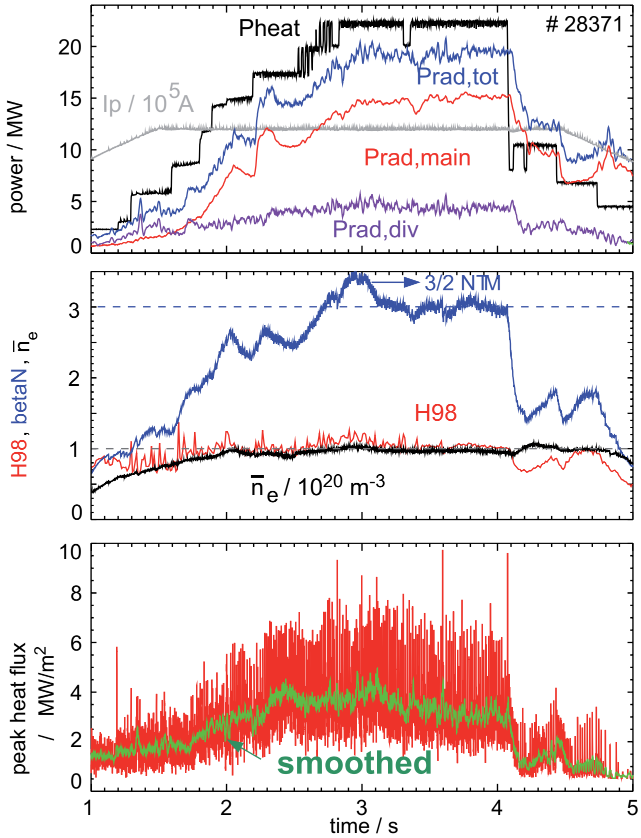

Figure 4: Time traces of a high power discharge at I_p = 1.2 MA, where the peak heat flux in the divertor was kept below 5 MW/m² by combined feedback control of main chamber radiation (Ar) and target power load (N_2).

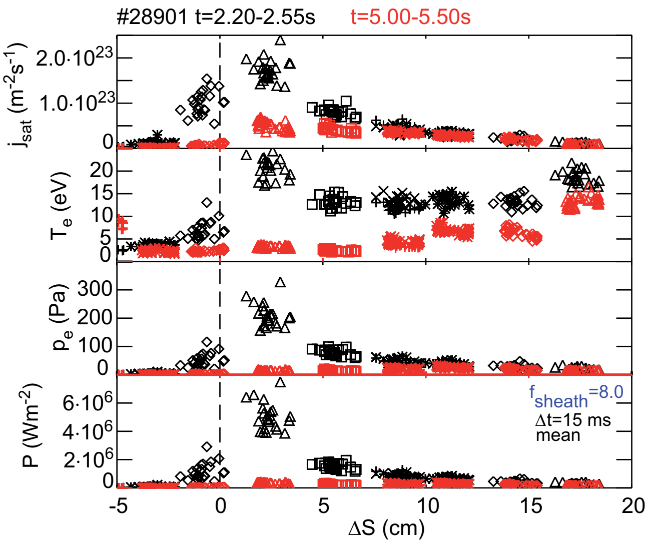

Figure 6: Profiles of ion saturation current, T_e, electron pressure and heat flux measured with Langmuir probes along the outer target before (black) and during (red) strong N_2 seeding.

In addition to the target heat flux, erosion of the plasma facing material sets a boundary condition for acceptable divertor plasma parameters in front of the surface in DEMO. Tungsten or tungsten composites are currently the favourite candidates for the divertor high heat flux region.

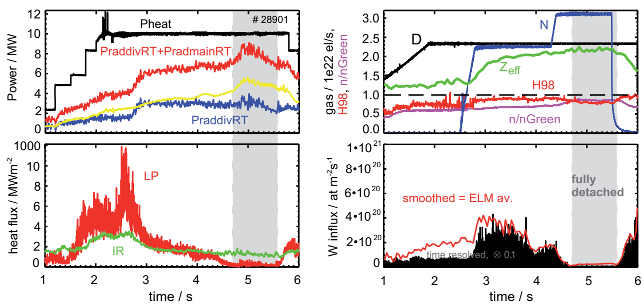

Figure 5: Time traces of a discharge where full detachment of the outer divertor has been obtained by strong N_2 seeding.

Nitrogen seeding was used in AUG to investigate the possibility of full divertor detachment, albeit still not at maximum possible heating powers. As shown in figure 5, the heat flux in the outer divertor as well as the W erosion is almost extinguished.

Target profiles from Langmuir probes are compared in figure 6 for conditions before and during the strong nitrogen injection. Both heat flux and electron pressure are substantially reduced by N_2 injection over at least the first 10 cm in the scrape-off layer above the strike point, corresponding to several power decay lengths. Good divertor neutral particle compression is maintained during the detached phase, but a rise in the core density indicates a change in plasma fuelling. The pronounced reduction of T_e in front of the target is required to keep the W erosion acceptable in a steady state device. Assuming, for example, a maximum allowed net erosion of 5 mm over 2 burn years lifetime of a divertor, and 80 % prompt re-deposition of eroded W atoms, the maximum permitted sputtering rate is 0.4 nm/s or $2.5 \cdot 10^{19}$ W/m²s. The criterion is fulfilled during the strongly detached state of the discharge in figure 5, but not during the intermediate partially detached phase around t=4 s, although the peak heat flux is just around 3 MW/m². This simple example shows that the sputtering limit may be more critical than the heat flux limit in a future DEMO.

3. Fast-particle Physics

Fast ion confinement is of special interest for future fusion devices because they significantly contribute to plasma heating and current drive. Fast ions produced by fusion reactions and external heating systems such as NBI and ICRF can be redistributed or ejected from the plasma by processes such as MHD instabilities or micro-turbulence. In this case damage of the first wall can occur. The so called anomalous transport of fast ions, related to these processes, must consequently be investigated and understood.

3.1 FIDA Spectroscopy

Fast ion D_α (FIDA) spectroscopy permits the distribution of confined fast ions to be studied. The Doppler shifted Balmer α-radiation (λ_0=656.1 nm) emitted by fast ions after charge exchange reactions along a neutral beam can be analyzed. The measured intensity yields information on the fast ion density and observed wavelength shifts contain information about the fast ion velocity distribution. Profile information is obtained by using multiple lines of sight (LOS) that are radially distributed along NBI.

The powerful and flexible NBI heating system allows the study of the confinement of fast ions injected with different energies, pitch angles, and vertical positions. Of special interest is the confinement of fast ions produced by off-axis sources because previous experiments indicated weaker off-axis current drive efficiency than expected. The FIDA diagnostic now allows the discrepancy caused by a strong anomalous diffusion of fast ions to be clarified.

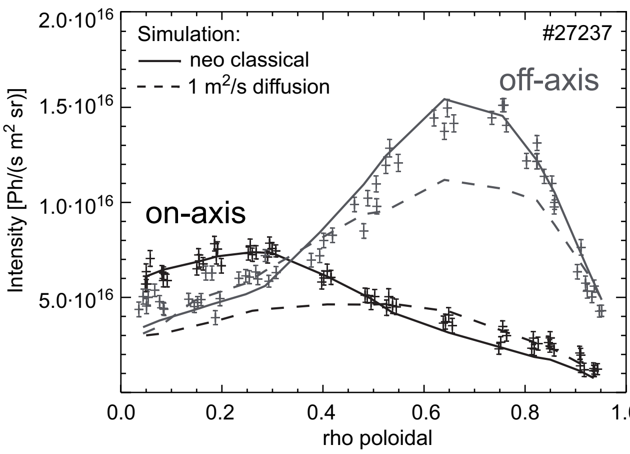

Figure 7: Measured and simulated radial FIDA intensity profiles during 5 MW of on- and off-axis NBI.

Figure 7 shows radial FIDA intensity profiles that were measured in a MHD quiescent discharge with 5 MW of on-axis NBI (black) and 5 MW of off-axis NBI (grey). The profiles correspond to co-rotating fast ions above 25 keV and have been calculated by integrating the FIDA radiation per LOS between 659.5 nm and 661.0 nm. As can be seen, the shape of the profiles clearly illustrates the on- and off-axis character of NBI. In addition, simulated profiles are plotted with lines that represent TRANSP predicted fast ion distribution functions assuming a neo-classical (solid) and an anomalous fast-behavior (dashed). The good agreement between the measurement and the neo-classical simulation indicates that, in the presence of only weak MHD activity, the anomalous fast ion transport is well below 1 m^2/s. This now opens new questions regarding the current drive efficiency of NBI.

In contrast, a significant redistribution of fast ions is observed in the presence of sawtooth crashes. Figure 8 shows the evolution of approximated fast ion density profiles during several sawtooth crashes that were observed with a temporal resolution of 2 ms. After each crash, the central fast ion density is reduced by up to 50 % while, at ~1.9 m, an additional off-axis contribution becomes visible. The decay of this off-axis contribution after the crashes represents the fast ion slowing down time, which has been found to be in good agreement to neo-classical predictions. This again indicates that in the MHD quiescent phases between sawtooth crashes, the fast ion confinement is not affected by a strong anomalous diffusion.

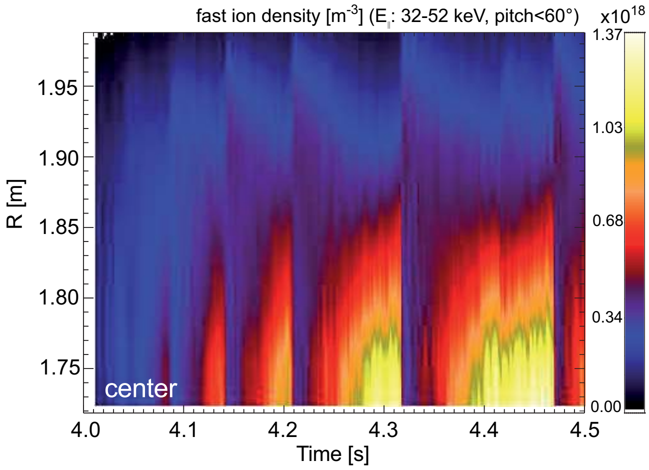

Figure 8: Temporal evolution of approximated radial fast ion density profiles in the presence of sawteeth.

3.2 Fast Ion Response to MP

The fast ion response to externally applied resonant and non-resonant magnetic perturbations (MP) has been investigated in a wide range of plasma parameters for n=2 perturbations. ELM mitigation by 3D externally applied MP is achieved above a certain density, ~0.6 n_{Gw} and a rather high collisionality with a little to no-effect on plasma profiles. In low collisionality and q_{95} discharges, however, a strong impact on kinetic profiles is observed, i.e. density pump-out and plasma braking. Although in both cases (low/high densities) MP induced fast ion losses are typically measured, in low q_{95} and density/collisionality plasmas, MP have a dramatic effect on fast ion dynamics. The density pump out has a significant impact on the beam profile, leading to a deeper beam deposition and to an apparent (large change in n_e but not in T_e) displacement of the separatrix of ~2-3 cm. During the mitigation/suppression of type-I ELMs by externally applied MP, the large fast ion bursts observed during ELMs are replaced by a steady loss of fast ions with a broad-band frequency and an amplitude of up to an order of magnitude higher than the NBI prompt loss signal without MP. In figure 9, the energy and pitch-angle of the escaping ions measured by FILD1 with and without MP during different NBI phases are shown.

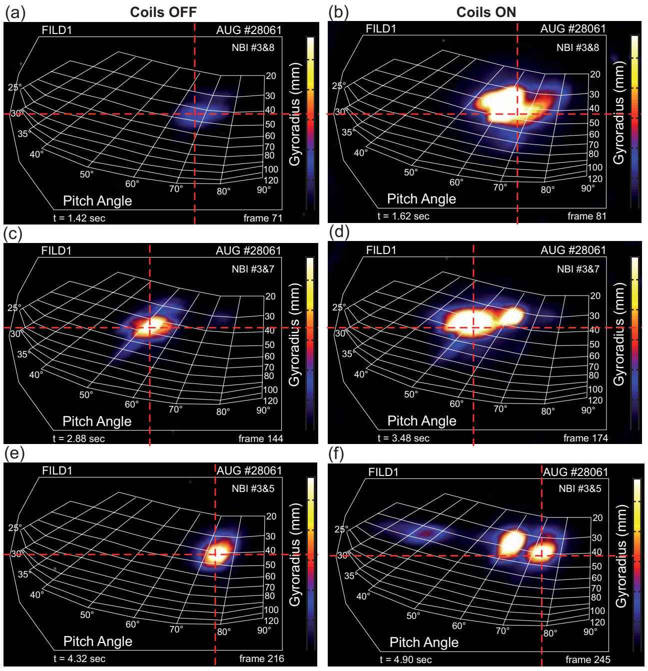

Figure 9: Velocity space of escaping ions measured by FILD1 with MP coils OFF, (a), (c) and (e) and with MP coils ON, (b), (d) and (f).

The plasma response has been simulated using the two fluid M3D-C1 code. Resonant field amplification at rational surfaces with negligible electron rotation causes a stochastic layer in the pedestal due to island overlap. An efficient shielding in the plasma core is predicted by M3D-C1 simulations. The perturbed background fields, including plasma response, are used to simulate the fast ion response to externally applied MP with orbit following codes. Accurate measurements of the escaping and confined fast ion response to MP help to better understand the MP field penetration and overall plasma response.

4 Improved Operation of ICRF Antennas with W-wall

A significant part of the ICRF-specific plasma wall interactions in AUG can be attributed to the existence of $E_{||}$, the parallel component of RF electrical field near the antenna. This field contributes to elevated sheath potentials, which can directly influence the W sputtering. It can affect, as well as depend on, the plasma convection in the scrape-off-layer.

In AUG, two strategies for establishing the compatibility of ICRF antennas with the W wall are being pursued. The first strategy, long-term, is based on overall reduction of $|E_{||}|$ by following the guidelines on antenna design elaborated with the help of finite-elements EM calculations. The second, short term strategy on making the ICRF operation compatible with the W wall at the low gas injection rate conditions in AUG makes use of boron on the antenna limiters.

Figure 10: The broad-limiter antenna A4 with spots of spectroscopic observation.

The first, low-cost step of the antenna design strategy was the modification of one two-strap antenna by installing narrower straps and broader limiters, ("broad-limiter" antenna, figure 10). To compare the original antenna (*A3*) and the broad-limiter antenna (*A4*), an H-mode scenario with P_{NBI}=5 MW at a magnetic field B_t=-2 T and plasma current I_p=0.8 MA and a ramp-down of D_2 gas injection rate Γ_{D2} was used with ICRF power of 0.5 MW at 30 MHz for central heating. The data from a series of such discharges are summarized in figure 11, where the change of W concentration ΔC_W due to ICRF is shown with respect to Γ_{D2}.

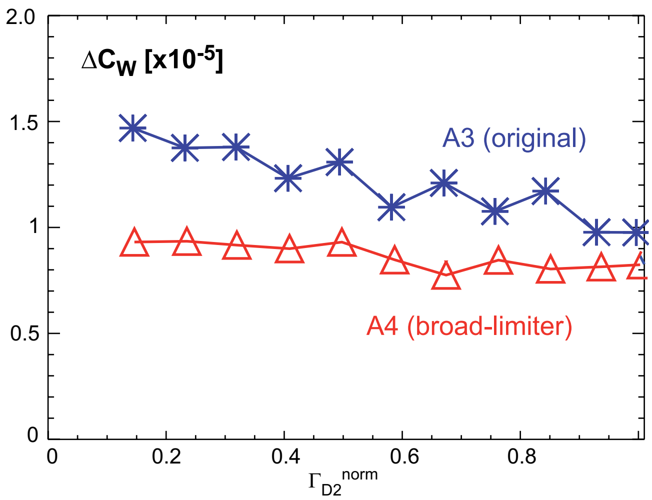

Figure 11: ΔC_W due to ICRF power from original (blue stars) and the broad-limiter antennas (red triangles).

The latter is normalized to allow the use of data taken at different machine conditions during the 2011 campaign. A value of Γ_{D2}^{norm}=0 corresponds to the W accumulation threshold, whereas Γ_{D2}^{norm}=1 corresponds to the maximum value of Γ_{D2} at the beginning of ramp-down of the gas injection rate.

The data plotted is limited to $\Gamma_{D2}^{norm}>0.1$ to show stationary conditions only. It can be seen that the broad-limiter antenna is better for plasma operation. It is characterized by lower ΔC_W than the original antenna, being about 40 % lower than that for the original antenna at the low gas injection rates.
To shed more light on a connection of the effect of RF power on ΔC_W to the W sputtering, W sputtering patterns at *A3* and *A4* are plotteded in figure 12. These were measured by the local limiter spectroscopy looking at WI and D emission the antenna limiter at several spots (see figure 10 for those at *A4*). Figure 12 shows a comparison of the change of effective sputtering yield ΔY_W at *A3* and *A4* averaged over the time of operation of either *A3* or *A4*, and over the same range of the vertical positions of the measurements, depending on the plasma outermost position R_{out}. It can be seen that the broad-limiter *A4* is characterized by lower ΔY_W, both for the inside and the outside rows of the lines of sight, and especially so at higher R_{out} when the plasma is closest to the antenna. Thus at $R_{out} \approx 2.165$ m, ΔY_W measured at *A4* is about 40 % lower than at A*3*. It is therefore likely that the improved operation of the broad-limiter antenna is related to the reduced W sputtering.

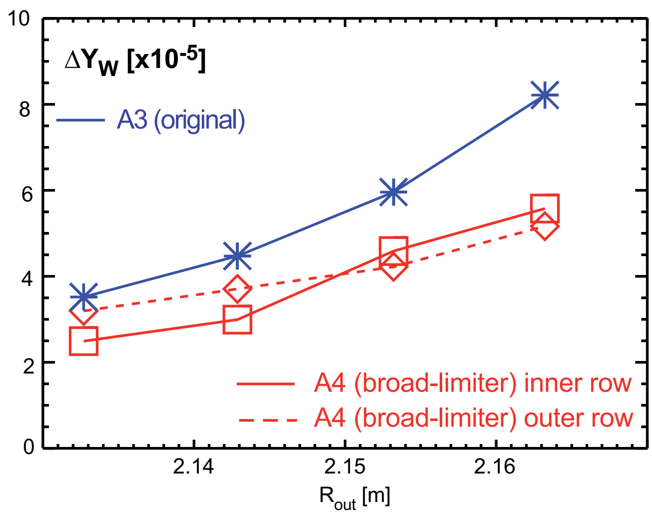

Figure 12: ΔY_W comparison for A3 and A4 depending on the plasma outermost position R_{out}.

Previous studies have shown that the antenna limiters play a dominant role as a W source during ICRF. To increase the ICRF operational window in the short term, the side limiters of antennas *A1* and *A2* were coated by a 50 µm thick layer of B prior to the installation in the vessel. Boron is used during boronisations, therefore no new material was introduced into the machine.
For the 2012 experimental campaign, both antennas *A1* and *A2* with the boron-coated limiters were connected as a pair within the 3 dB hybrid connection scheme, whereas *A3* and *A4* were connected as the other pair. This allowed a discrete operation of the antennas with the boron-coated limiters and of the antennas with the W-coated limiters.
The difference in production of W between the two antenna pairs was clearly visible in the experiment. Figure 13 shows the comparison of the two antenna pairs in terms of W concentration for the case of the scenario with I_p=1 MA, B_t=-2.5 T, P_{NBI}=7.5 MW, P_{ECRH}=2.5 MW, P_{ICRF}=1.5 MW per antenna pair at the frequency of 36.5 MHz. A very similar picture is observed with B_t=-2.0 T at 30 MHz. The side W limiters account for more than half of the increase of W concentration. Based on the local spectroscopic observations on the upper row of the limiters at *A3*, the contribution of the upper and the lower rows of the limiters, not replaced by the B-coated limiters at *A1* and *A2*, can be roughly estimated to be 1/4 to 1/3 of that from the side limiters. The total effect of the antenna limiters on the W source is thus even stronger, even more so considering the fact that the *A4* broad-limiter antenna, one of the two antennas with the W limiters, has previously shown the reduced W release. Therefore the observations confirm the dominant role of the antenna limiters in the W source associated with the ICRF power.

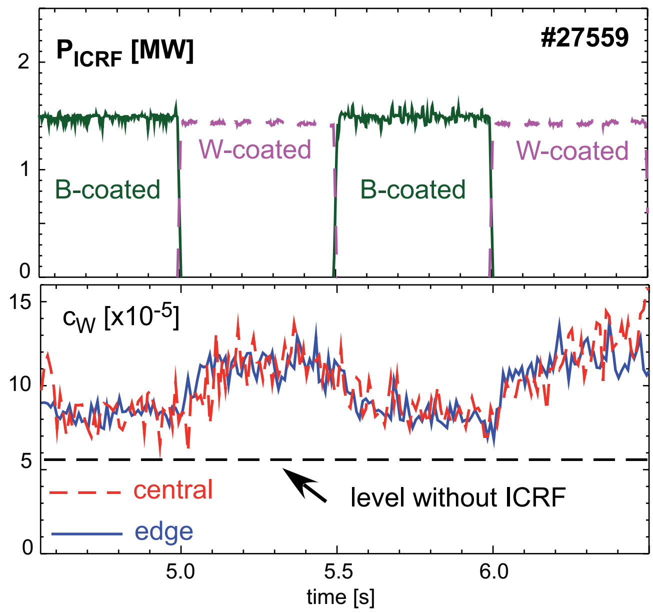

Figure 13: Comparison of operation of the antennas with B-coated side limiters and with full W-coated limiters.

5 Technical Systems

In 2012, the focus of the experimental programme was on ELM mitigation by exploring the complete set of MP-coils consisting of 8 upper and 8 lower so-called B-coils. AUG was in operation for about 9 month performing 1887 pulses in total with 1335 pulses useful for the physics programme. 168 discharges were heated with more than 10 MW, 9 of them with about 17.5 MW.

5.1 Machine Core

Before the start of operation during the vessel baking a leakage in the water cooling of the roof baffle and the inner divertor was detected that requires an unscheduled opening of the vessel and results in a delay of the start of operation of three weeks. The leakage was identified in the water flanges of 3 out of 16 transition modules (BG5). These components were installed in 2008. Further investigation reveals that the copper sealing was corroded. A more detailed inspection has shown that the prestress of the fixing screws was not applied to the flanges/copper sealing because the length of a few screws was 0.1 mm to long. Because of this systematic error, all copper sealings and bolts of BG5 were changed.

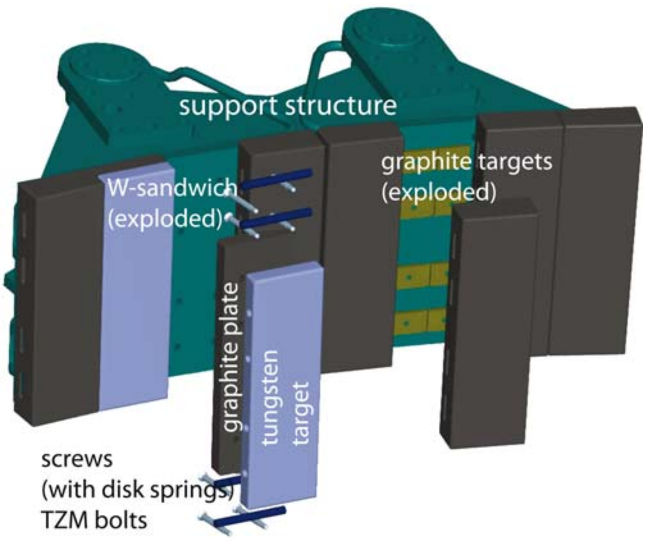

Figure 14: Lower outer divertor. Comparison of a standard graphite tile and the W-sandwich test tiles.

The summer shut down was used to repair a few broken magnetic coils, to replace a broken vacuum window and to harden parts of the vessel against ECRH-stray radiation. The magnetic coils at the high field side were damaged by ECRH radiation due to wrong polarization (missing absorption) in combination with a wrong angle of the 1st ECRH mirror. Signal cables and the peek isolation of the B-coil 3 in section 6 were molten by ECRH stray radiation during high density plasma operation near to the cut-off limit. The magnetic coils and the cables were repaired. In addition a hardening against ECRH stray radiation was applied. The main concern is a melting of the thin bellows (1.2 mm Inconel) at the isolation gap of the vacuum vessel, which are unprotected behind the heat shield. Here 1.5 mm stainless steel stripes coated with TiO_3 were fixed behind the vertical gap of the inner protection tiles between sector 4/5, 6/7 and 14/15. The gaps between the upper B-coil protection tiles were closed by stainless steel stripes. The area accessible for ECRH above the upper PSL was reduced by installing additional protection tiles.

In preparation of the installation of the massive tungsten divertor-III, first prototype tiles were installed in the outer lower divertor during the 2010 opening. These tiles are replacing standard graphite tiles as shown in figure 14. To be compatible with the present divertor design, they are designed as a sandwich tile consisting of a 15 mm thick W plate and a 15 mm graphite interface. One tile was removed in 2011 for investigation. The averaged and the maximum energy deposition onto this outer target during the 2011 campaign is shown in figure 15. The second tile is still in operation.

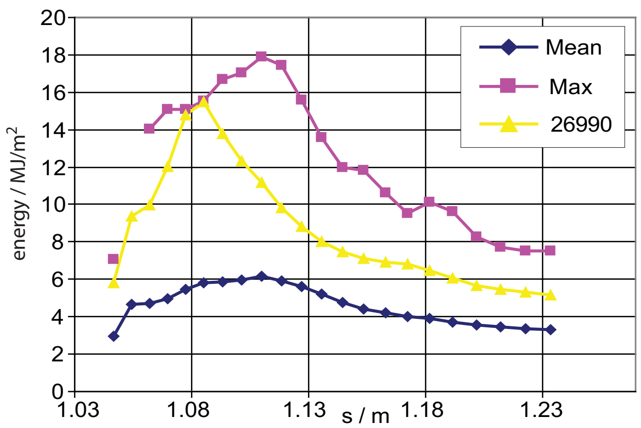

Figure 15: Energy distribution at the lower outer divertor target for the 2011 campaign. MAX – max. value taken from all pulses. # 26990: energy load profile for a single pulse with high divertor load. Mean: The pulse averaged divertor load.

Torus Pumping and Gas Inlet System

The gas matrix of the gas inlet system now supplies 14 piezo valves (PV) in total. For special applications as ICRF power coupling experiments one PV is feeding in the limiter of ICRF antenna 3. Another PV in section 13 equipped with a slim tube blowing in the mid-plane close to the plasma boundary is installed for plasma fluctuation studies via fast cameras. The first of 3 planned PVs puffing into the inner upper divertor region came recently in section 7 into operation. Caused by diagnostics constraints the PV in section 9 used for injection of expensive gases is shifted to section 1.

A refurbishment of the gas inlet system has been started with re-wiring of the PVs. To improve the flow signal quality a specially designed cable was installed comprising both the current supply of the piezo crystal and signal of the pressure sensor. Tests are envisaged in early 2013.

After some leakages during the start of this campaign the torus vacuum as well as the torus pumping system performed without major problems over the year.

The installation of the inter-vacuum system of the 16 electrical feed-throughs of the B-coils has been completed. Using a turbo molecular pump for evacuating the conduit in routine operation a vacuum pressure of clearly lower than 10^{-4} Pa in all 4 half-ring tubes is routinely achieved.

To optimize leak search during maintenance phases a new type of dry vacuum pump has been installed on the inter-vacuum system for the water cooling pipes and taken into routine operation now allowing a base pressure of about 10^{-2} Pa.
Caused by the extension of the ECR heating system into the north of building L6 a massive upgrade of the vacuum and baking service laboratory was necessary. In this context a completely new ventilation system operating independently from the existing L6 building air-conditioning has been installed to accelerate the He removal from the laboratory.

5.2 Experimental Power Supply

Due to the short summer outage there was no time for major enhancements or maintenance. The focus was to keep the technical systems running for experimental operation.
With "Stadtwerke München" a contract was signed to bring in the IPP mains backup systems into a "virtual" power plant. The necessary modifications at the control of the diesel generators were implemented.
A contract to replace the 35 years old, fault-prone direct converter of generator EZ3 by a new drive converter with integrated digital control was signed with company Siemens. The new system is based on a commercially available converter used in wind turbines. The implementation is scheduled for the 2013 outage. An improved control to accelerate generators EZ3 and EZ4 in parallel with EZ2 was introduced. This reduces the start-up time before every plasma pulse by about three minutes.
The most serious incident was the flash-over at an insulator of the 80 kA diode rectifier of EZ2, followed by a burst fuse and an electric arc across one of several paralleled diodes. The faulty fuse and diode could be removed and one day later AUG could continue operation. To understand the sequence of the event, detailed simulations were performed.
Shortly before the summer break, the damping coil for the torsional vibrations of EZ3 was seriously damaged by arcing. The reason was a regression of clamping at the terminals of the coil. To sustain AUG operation, the faulty coil was temporarily substituted by coils with lower inductivity. This resulted in reduced damping power and thus required a more sophisticated power distribution between generators EZ3 and EZ4. The re-installation of a new coil with full power is scheduled for January 2013.
Since IPP does not get additional funding for the procurement of the desired power supplies for the independent operation of the internal B-coils with arbitrary waveforms, an in-house development was launched. The intention is to build-up multi-level inverters using commercially available power modules (Semicube) to limit the EMC impact on the AUG diagnostics to a minimum. A test facility with matching transformer, DC link and control and measurement equipment was built-up. Four power modules are delivered and an experimental setup was prepared to demonstrate the feasibility of the proposed concept. First experimental results are expected before the end of the 2012/13 campaign.

To allow for a more flexible power distribution between EZ3 and EZ4, the 10 kV lines for the high voltage power supply were reinforced. The "FiSi" high voltage power supply for ECRH-2 received a new digital control and was integrated into the HV supply network. IPP received two 7 MW HV power supplies from DESY at Hamburg. The systems are aimed for the supply of ECRH-3. Until 2016 they will be successively maintained and adapted for the AUG pulsed operation. As a result of the OH-coils safety studies additional safety limits were implemented into the pulse control and safety system.

5.3 Neutral Beam Heating

In 2012 neutral beam injection was provided with up to 17.5 MW of injected power for about 1000 discharges, despite an unfortunate series of vacuum leaks. In March a fatigue crack caused a cooling water leak in a 20 year old copper liner inside the bending magnet of box-1. The liner receives only moderate heat fluxes by negatively charged ions. Repair was immediately begun and first beams were attempted two weeks after the incident. Unfortunately, these first conditioning shots caused another cooling water leak at the D_2^+ ion dumps resulting from a wrong bending magnet current that in turn was due to the incomplete recovery from a serious malfunction of the SIMATIC controller in the time between the two leaks. Repair was begun after one week and plasma heating was resumed in early May, four weeks after the incident. Next, in early June, an air leak developed in bellows of the torus gate valve. However, evacuating the volume around the high-pressure side of the bellows with a roughing pump allowed continuing operation until the summer break when the gate valve received a complete overhaul and repair. Finally, in late October within less than a week the almost identical leak occurred independently on both injectors as a result of fatigue; on each system one of the bellows of the lifting gear that allows for moving the calorimeter in and out of the beam line developed an air leak that rendered further operation impossible. Spare bellows were in stock and repair was carried out simultaneously on both systems during the week of the AUG programme seminar. NBI heating could be provided again about four weeks after the first of the two leaks had occurred.
In support of the construction of the neutral beam injection system for W7-X various configurations of the radio-frequency transformers for the rf ion sources were tested on the AUG rf ion sources. Furthermore, a candidate data acquisition system for the W7-X NBI was tested for compatibility with a fusion experiment environment.

5.4 Ion Cyclotron Heating

One of the ASDEX/W7-AS generators, which was used to test the modification to accept a still commercially available EIMAC 4CK2.500KG tetrode, in cooperation with IPR, India, has reached 1.8 MW. To push the generator to 2 MW, the existing modified power supply has to be reconnected in a way to be able to increase the voltage on the final stage tetrode while maintaining it within the limits for the driver tetrode. In the present configuration, voltage on both tetrode is the same. The 3-D CAD design of the 3 strap antenna, which was optimised to reduce the impurity production of the antennas, has been finalised. Two new antennas are being built in international cooperation with ASIPP, Hefei, China and ENEA, Frascati, Italy. ASIPP took the responsibility to make the manufacturing drawings and to manufacture all the stainless steel parts of the antenna (return conductor, central conductor, septa, side place and other components), while ENEA will make the TZM Faraday screen, the CuCrZr cooling frame and the springs connecting both. ENEA will complement the existing limiters with the extra pieces needed due to the antenna modification. In addition, an extensive reflectometer system will be built into the antenna, allowing measurements of the density and its modification at several toroidal and poloidal locations. Work is progressing and the antennas are expected to be installed in the 2013 opening.

5.5 Electron Cyclotron Resonance Heating

In 2012, the installation of the ECRH-2 system has been completed taking into operation also the forth gyrotron at its nominal parameters of 1 MW for 140 GHz and 0.8 MW at 105 GHz (pulse length 10 s) in October. In July one of the other gyrotrons was sent back for a guarantee repair to GYCOM due to excessive body current. Consequently, only 3 new units were in operation in 2012, as in the previous year. A major issue limiting the reliability of ECRH-2 operation is occasional arcing at the last mirror before the torus above 0.8 MW, combined with poor accessibility of these mirror boxes, which makes a cleaning intervention after a major arc difficult. Conditioning is still observed but slow, a redesign of these mirror boxes has been started together with IPF Stuttgart.

High power gyrotron operation is very reproducible and it is hardly disturbed by internal arcing. HV-insulators between gyrotron body and magnet turned out to be a weak point in the design and had to be replaced several times. A first insulator has now been manufactured from POM-C bulk material. This bulky high precision component was produced in November at the central IPP workshops.

The ECRH-2 system has been used in the majority of the discharges in the 2012 campaign, the old ECRH-1 system was operated only on specific request. Three melting events in vessel were found during the summer opening. They could be clearly ascribed to ECRH operation. As a consequence, ECRH settings for launchers and polarizers shall be cross-checked automatically by the discharge control system when loading the shotfile making use of the set values for B_t and I_p. Additional sniffer probes were installed to survey the volume above the upper PSL.

The ring-resonator based multi-frequency window for the last gyrotron of ECRH-2 has been tested successfully up to 100 ms at GYCOM. Experiments with longer pulses at four frequencies are planed at IPP after the end of the ongoing campaign.

Construction of ECRH-3 as a replacement of the old ECRH-1 system has started. IPP receives additional funding from HGF for this project. The new system will be similar to ECRH-2 (4×1 MW, 10 s, 2f), using the ECRH-1 ports. Major changes are the use of cryogen-free magnets and semiconductor-based water-cooled body-modulators. The optics of the ECRH-1 launchers is adapted by IPF Stuttgart: The change from large boron-nitride windows to smaller synthetic diamond windows requires a smaller beam diameter leading to larger divergence at the wave guide exit. The larger wave length at 105 GHz enhances the divergence further. This can be compensated by using a mode converter, which converts the wave guide mode HE_{11} to a pure Gaussian free space mode, which has a higher directivity, such that the spill-over losses at the mirrors can be kept at the 1 % level. In 2012 the NW-corner of the L6-hall has been emptied (formerly used as storage area) and reconstructed to house the HV-cabinets, gyrotrons and subsystems. Gyrotrons and diamond disks are ordered. The first gyrotron is expected to start operation at IPP end of 2014.

5.6 CODAC

The discharge control system has been migrated from the VxWorks operation system to the Concurrent Computer Corporation's real-time RedHawk Linux. With exception of one VxWorks client interfacing to legacy hardware for real-time data acquisition all functionality has now been concentrated on a single multicore computer. The previous computation nodes have been mapped to multi-threaded real-time processes communicating via internal memory. This has boosted processing performance such that control cycle times of one millisecond and better are possible. Thanks to the operation system and network abstraction layers of the DCS infrastructure, the migration only required enhancements in these areas, while the control applications were not affected. A replacement of the legacy hardware with a tailored SIO frontend, which can be directly connected to the Linux computer, is in preparation. It will allow to finalise the migration to Linux and to shut down the DCS internal Bit3 reflective memory real-time network, which has reached the end of its lifetime. On this basis, MHD feedback control has been further developed featuring an evaluator process, which collects, filters and processes data from real-time diagnostics separately for (2,1) and (3,2) mode numbers and feeds them to the MHD controller commanding ECRH mirror positions and gyrotron power. Using the in-house standard serial I/O (SIO) computer interface a series of new and existing diagnostics have been set up and/or refurbished: X-Point reciprocating probe (XPR), Doppler reflectometry (PRD), Pulse Height Analysis (PHB, PHD), ICRF monitoring (ICF). Other activities were dedicated to the real-time tuning of critical DAQ systems like the real-time ECE system used in the NTM stabilisation project. Because an increasing number of diagnostics coming to end of life in the near future and will be modernised using SIO technology, further development of the SIO system has been launched.

6 Core Plasma Physics

6.1 ECR versus Combined NBI and ICR Heating in H-mode

The investigations about the influence of pure electron heating versus combined electron and ion heating on H-mode plasmas were continued at lower collisionalities (NBI increased to 8.5 MW and gas puffing reduced). The mixed electron and ion heating by NBI was partly and stepwise replaced by ECRH. Similar to the high collisionality cases discussed in last years annual report, also in this parameter regime the global plasma parameter like stored energy, plasma β or confinement factor do not change significantly when changing the heating mix. The electron temperature increases only slightly with increasing ECRH fraction, while the ion temperature decreases by roughly 30 %. The peaking of the electron density is not changed, which is in line with linear gyrokinetic calculation of GS2. They show an approach to the transition from the ITG to the TEM micro-instability dominated regime. The pedestal values of T_e, T_i and n_e do not change within the uncertainties of the measurements, only v_{tor} is influenced by the changing torque input. It's contribution to the radial electrical field at the edge is small so that the E_r profile is not affected. The exchange term by Coulomb collisions increases with increasing ECRH so that the heat flux in the ion channel stays constant with heating mix. However due to the increased heating power approximately 1/3 of the heat stays in the electron channel towards the edge. Transport modeling of electron and ion temperature with TGLF shows a good agreement with the experimental profiles and reproduces the trend of increased T_e/T_i with increased ECRH when applying a sawtooth model.

6.2 Impurity Emission by CX from Beam Halo Neutrals

Charge exchange recombination spectroscopy on NBI measures the active impurity radiation, which is invoked by CX reactions from beam neutrals onto impurity ions. One systematic effect, that so far has been thought to be only important at high T_i values of 20-30 keV, is the CX excited impurity radiation from beam halo neutrals. Halo neutrals are produced from beam neutrals by CX onto deuterium ions. Even at low values of T_i the effect is considerable due to CX from excited deuterium. This has been found by simultaneous measurements of the D_α emission of beam and halo neutrals and the CX emission from B on the n=7-6 transition of B^{4+} at 494.5 nm for beams 2 and 3 of NBI-1 operating at 60 keV. Beam 3 is centrally intersected by the sightlines and the halo neutrals contribute between 25 and 30 % to the total impurity emission for ion temperatures ranging from 1 to 4 keV. For beam 2 the contribution of the halo neutrals even rises up to 50 % in the plasma centre. Here, the lines-of-sight observe only the periphery of beam 2, where the density of the halo is not as reduced as the beam density due to the wider extent of the halo cloud. For other popular CX-lines of He, C and Ne a similar halo contribution has been calculated. The halo production is decreasing with rising beam energy and the effect starts to become negligible above 100 keV. The density ratio of halo to beam neutrals peaks around 3-4 keV and the effect is strongest in this temperature range.

6.3 Intrinsic Plasma Rotation

Analysis of the AUG intrinsic rotation database has shown that the core rotation is determined by the rotation gradient around mid-radius, which is in turn set by the local electron density gradient. This result was confirmed separately for the newly created Ohmic L-mode database by a multiple variable regression, which indicated that the density gradient followed by the effective collisionality and ion temperature gradient are the most important parameters in determining the core rotation behaviour. These dependencies help to identify theoretical explanations of the observations and to explain the heretofore-mysterious reversals of the core intrinsic rotation from co-current to counter and back again with increasing plasma density.

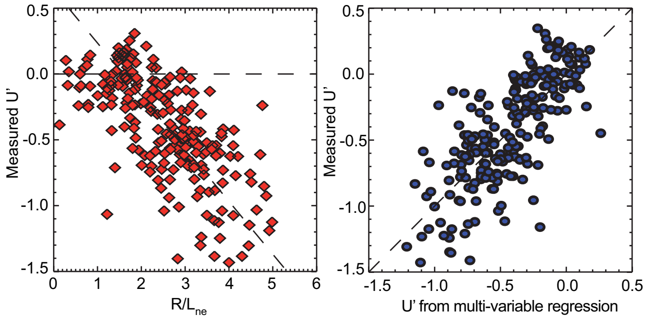

Figure 16: Normalised rotation gradient U' versus R/L_{ne} and the regression at ρ_φ=0.35.

6.4 ECE-imaging of T_e Fluctuations during ELMs

The ECE-imaging diagnostic (installed at AUG by FOM-Institute DIFFER) provides a local, 2D measurement of the electron temperature and its dynamics. An important research topic in 2012 was the characterization of the various T_e fluctuations associated with ELMs. In the type-I ELM cycle, distinct phases of mode activity have been identified. At the onset of the ELM crash, a short lived mode is observed in the pedestal region. During the actual crash phase, multiple filamentary structures are observed just outside the separatrix. In between type-I crashes, the occurrence of a third type of mode prolongs the length of an ELM cycle. In type-II ELMs, T_e crashes are absent. Instead, a continuous broadband fluctuation is observed with similar characteristics to the mode that lengthens the type-I ELM cycle: in type-I ELMs it delays the next crash, in type-II ELMs it might cause the complete absence of crashes. During type-I ELM suppression with magnetic perturbation coils, smaller crash events become more frequent. Although some of the features of the small ELMs are shared with type-I and/or type-II ELMs, these small ELMs are clearly distinguishable from either type. With increasing edge n_e, e.g., the frequency of the small ELMs increases and that of the type-I ELM decreases.

The main difference between the small ELMs and the type-II ELMs is that the latter display continuous T_e fluctuations, whereas the T_e fluctuations during the small ELMs are only seen for very short times.

6.5 2D T_e-profiles in MHD and Impurity Transport

A new method for the reconstruction of mode-resolved 2D T_e-profiles on the full poloidal plane from the 1D ECE has been developed. Magnetic perturbations of any (m,n) can be characterized and, for (1,1) modes, the mode displacement can be evaluated through geometrical analysis of the resulting temperature contours. Based on harmonic decomposition of the ECE data using short time Fourier transform, the 2D T_e-profiles can be reconstructed in any mode phase through the amplitude and phase information of each ECE channel. The method can be used for mode characterization and mode-resolved electron heat transport studies as well as for disentangling impurity density and electron temperature contributions to SXR tomographic reconstructions, giving the chance, for the first time, to study impurity transport in 2D in the presence of MHD instabilities.

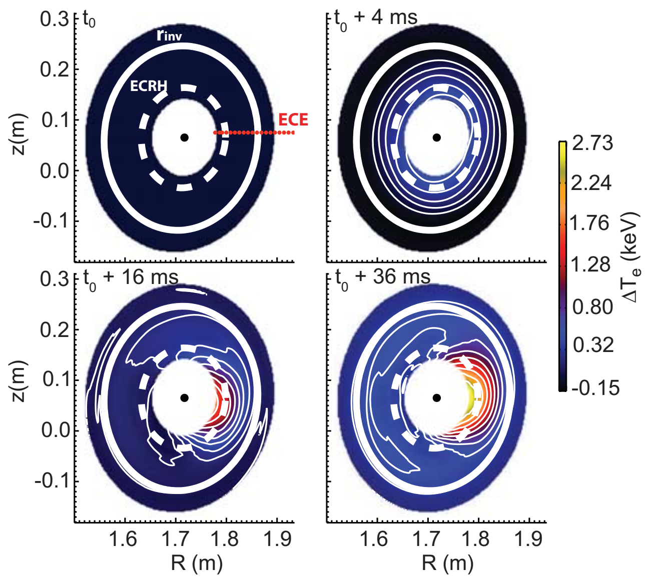

Figure 17: Evolution of 2D T_e-profiles during a sawtooth cycle with respect to the crash time t_0 (mode phase fixed to Θ=0).

6.6 Minimal Model for Interaction of MHD Instability with Plasma

Larger scale plasma instabilities not leading to an immediate termination of a discharge often result in periodic nonlinear perturbations of the plasma. Examples of such behavior are ELMs, sawtooth crashes and other events. A minimal possible physical model is formulated for description of these systems with drive and relaxation processes, which have strongly different time scales. This zero-dimension model contains only three parameters: power input, relaxation of the instability and influence of the instability on the heat diffusion coefficient. The model is based on two equations. The first equation being responsible for the relaxation dynamics and can be derived either from linearization of the energy principle or from linear MHD force balance equation. The second equation represents the energy balance. In spite of its simplicity, the model has a rich variety of possible solutions depending on the model parameters (periodic oscillations, stochastic regime, periodic crashes, etc.). Pellet pacing is also integrated into the model, which allows making basic predictions for pellet triggering. It was shown, for example, that pellets are able to increase the ELM frequency but is not able to reduce it (which is in agreement with experimental results). The proposed zero dimension model does not qualify for a complete description of the plasma phenomena, which require full scale nonlinear simulations. However, it provides a useful tool for understanding the basic physics and allows the estimation of some relative quantities.

6.7 Enhanced Particle Confinement with HFS Pellet Injection

The revised and upgraded system for the inboard launch of deuterium pellets has been applied for plasma fuelling and ELM trigger investigations. A maximum line averaged density of twice the Greenwald density n_{Gw} was obtained with pellet fuelling into phases where ELM mitigation was established by B-coil actuated magnetic perturbations. Progressive density peaking is observed with increasing pellet flux while the edge density stays well below n_{Gw}. For low to modest pellet flux a gradual linear increase of the line averaged density is observed; however, once n_{Gw} is reached the plasma density response becomes much stronger. A further small flux increase subsequently causes a much stronger core density increase. This is correlated with a dramatic increase of the sustainment times of the particles deposited by the pellet. The critical parameters responsible for this change in behaviour and the underlying mechanism for the increasing particle confinement time are currently under investigation.

In an all metal wall environment it appears that there is no longer an inevitable ELM triggering by pellet injection into an ELMing plasma. In an 1 MA H-mode plasma developing a spontaneous ELM frequency of about 40 Hz, no pellet ELM triggering is possible within 6 ms after the onset of a spontaneous ELM. A sharp rise in trigger probability is observed with increasing elapsed time reaching certain triggering beyond 10 ms. Changing the local pellet perturbation by varying pellet speed or mass did not show significant impact on this behaviour.

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

Real-time magnetic equilibria are calculated by a Grad-Shafranov solver constrained to fit 40 magnetic probes and 18 flux loop differences. Another solver, that includes 10 further constraints from the Motional Stark Effect (MSE) diagnostic, runs simultaneously with a cycle time of 0.6 ms for 6 fitting coefficients. The 33×65 poloidal flux matrix is available on the reflective memory network with a ~2 ms cycle time. Using the real-time equilibria with magnetic constraints only, pre-emptive NTM stabilization could be demonstrated. In a preliminary discharge, the mirror was scanned across the rational surface. The location of the normalized temperature fluctuations measured by ECE, that predicted by the solver and that inferred from TORBEAM microwave ray tracing calculations could be compared and small systematic differences identified. A (3,2) NTM was then stabilized by feedback control of the launching mirror to deposit ECCD at the normalized radius of the rational surface predicted by the solver with compensation for the systematic offset. In a subsequent discharge, pre-emptive stabilization was only partially successful as the NTM reappeared for a short time. When the angle of the mirror launcher was moved away from the predicted stabilizing position-, the NTM reappeared. Routine MSE measurements are needed to improve the accuracy of the predicted location of the rational flux surface.

6.9 Active Control of NTM via ECCD

Advanced tokamak scenarios are candidate plasmas for achieving efficient fusion power. However, these scenarios are prone to the occurrence of NTM, which form magnetic islands that deteriorate the plasma confinement substantially. These instabilities need to be controlled in order to achieve high performance and minimise the risk of disruptive behaviour. An MHD controller able to steer up to 4 ECCD beams to arbitrary targets in the plasma has been successfully commissioned and can operate all 4 mirrors independently such that the corresponding beams are depositing at arbitrary radial positions. Since NTM localisation is available in real-time using a correlation of T_e measurements and magnetic pick-up coil signals, controlled interaction of ECCD beams and NTM is now possible.

It could be shown, that precise alignment of ECCD deposition and island position is crucial for effective stabilisation of NTM, when using continuous wave heating. Deviations of less than 2 cm already have a measurable influence on the achievable size reduction of a fully developed (3,2) island. With this sensitivity, errors in the equilibrium reconstruction without internal measurements are relevant. Having closed loop operation now routinely available, full active NTM control is one of the major goals in 2013.

6.10 Disruption Forces Mitigation via MGI

Massive gas injection (MGI) experiments were conducted in 2012 with two fast valves located within the vessel on the high and low field side (HFS and LFS) of the torus in order to study the fuelling efficiency and the ratio of the critical density attained with these valves, and to characterize the power radiated during MGI induced shut downs.

The HFS valve exhibits a larger (compared to the LFS valve) fuelling and assimilation efficiency only at low amounts of injected neon. As the amount of gas is raised to ITER-relevant values, the assimilation drops to the level observed with the LFS fast valve. The impressive effective (for collisional REs suppression) density of $9 \cdot 10^{21}$ m^{-3}, which corresponds to 20 % of the ITER critical density, has been reached. Nevertheless the injection of more gas with multiple valves could not raise the density further. It is tempting to talk about an MGI free electron density limit, which is of the order of $1.5\text{-}2 \cdot 10^{21}$ m^{-3} for the specific experimental conditions (1 MA, q_{95}~4.5, H-mode). In the light of these latest experiments, the attainment of the critical density on AUG with the existing MGI system does not seem possible. Measurements of the radiated power in the sector closest to the valve and in the sector on the other side of the torus, show large toroidal asymmetry factors during the pre-TQ phase of injection, which can reduce to unity during and after the TQ. The presence of MHD mode activity tends to decrease and increase the degree of asymmetry of the radiated energy during the pre-TQ and TQ respectively. Multiple valve injection is expected to redistribute the localized energy deposition on a larger surface but this has not been confirmed experimentally yet. Simulation of the whole process of gas-plasma interaction is ultimately required to evaluate the spatial and temporal distribution of the thermal load on the ITER wall.

7. Edge and Divertor Physics

7.1 ELM Mitigation with Non-axisymmetric Magnetic Perturbations

Previous studies with magnetic perturbations produced by the newly installed set of active saddle coils have been continued to explore the accessible parameter range of ELM mitigation.

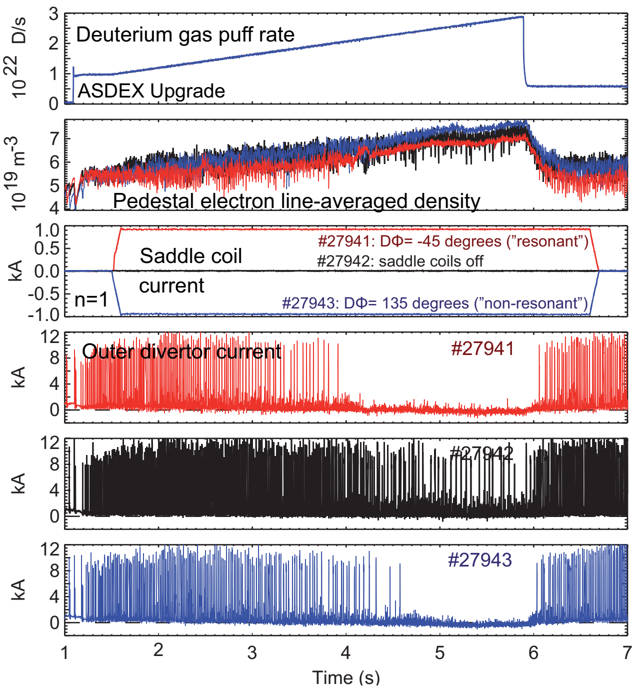

Figure 18: Time traces of ELM mitigation.

Figure 18 shows time traces of a pulse with n=1 perturbation, which shows suppression of type-I ELMs with both resonant and non-resonant phasing between upper and lower coil rings. The main effect of a resonant field is to lower slightly the plasma density for a given gas puff (density "pump-out"). ELM mitigation is marked by the occurrence of small ELMs, which also appear without magnetic perturbation in between type-I ELMs at high density. ELM mitigation is observed as well with n=4 perturbations, however only with non-resonant phasing and in a narrow density range. The search for ELM suppression at low pedestal collisionality has been continued with varying mix of neutral beam co-current injection, however so far only a modest reduction of ELM energy loss has been observed along with a reduction of plasma density. These studies are being continued.

7.2 Equilibrium Reconstruction during 3D External MP

Due to their limitations in number and position magnetic probes are insufficient to reconstruct full 3D equilibria with an adequate accuracy. Therefore other methods must be used to get the toroidal variation of equilibria: An easy way is to start from a toroidal symmetric equilibrium and to add the vacuum field of the MP-coils. Using a 3D field line tracing code it is shown that the separatrix is perturbed sinusoidally around the torus in accordance with the configuration of the coils. Also the shift of plasma profiles around the separatrix is consistent with this perturbation of the separatrix. However, this approach neglects any shielding currents by the plasma on the perturbation field, such that field lines can penetrate arbitrarily into the plasma. This leads to a formation of a stochastic region with islands, but up to now no experimental evidence for such a region could be found. The opposite approach is done using the NEMEC code, originally developed for stellerators, which calculates free boundary ideal MHD equilibria by minimizing the total plasma energy. It assumes nested flux surfaces inside the plasma, so it does not permit the formation of a stochastic layer. The form of the separatrix calculated by NEMEC is consistent with the deformation of the separatrix calculated with the vacuum field approach. In addition, equilibria from NEMEC can also show the toroidal variation of the interior flux surfaces, which helps to map measurements from different toroidal positions.

7.3 SOL Transport Modification by Non-axisymmetric MP

It is not sufficient to achieve good confinement and small ELMs. Particle and heat transport in the SOL has to be compatible to operational limits of the PFCs. Therefore, the influence of the non-axisymmetric magnetic perturbations on the transport in the SOL is important. Strike-line splitting in the divertor is a footprint of non-axisymmetric MP. It was observed in L-mode for densities $n_{e,int} < 3{\cdot}10^{19}$ m^{-2} while it was smeared out at higher densities due to radial transport, the plasma no longer 'realizes' the MP. This is also visible in the outer mid plane. At low $n_{e,int}$ the MP flattened the density profile +/-2 cm around the separatrix causing a higher SOL density. This vanished at increased $n_{e,int}$ as the strike-line splitting did. In H-mode strike-line splitting occurs with MP independent of ELMs mitigation. The splitting becomes more pronounced when $n_{e,int}$ increases (closer to ELM mitigation). With MP the mid plane heat flux in the far SOL increased and the profile became flatter. Also the density in the far SOL went up.

7.4 Edge T_e via ECE forward Modelling and Effect of MP on Edge Kinetics

A new method for the analysis of Electron Cyclotron Emission (ECE) data has been developed. In contrast to common straightforward ECE analysis, it delivers accurate and reliable electron temperature profiles also at the plasma edge by considering the broadened emission and absorption profiles and solving the radiation transport via forward modeling in the framework of integrated data analysis. Steeper H-mode gradients compared to common ECE analysis are resolved and the 'shine-through' peak of increased radiation temperatures with cold resonance in the SOL is reproduced. Thanks to the high accuracy of this method, it is now possible to investigate small changes in the edge T_e and pressure caused by magnetic perturbations that are used for ELM mitigation. Mitigated ELMs tend to occur at higher density and reduced temperature at the pedestal top and flatter edge pressure gradients compared to type-I ELMs. The L→H transition in the presence of MP happens at the same pressure gradient and diamagnetic radial electric field shearing but requires higher power flux.

7.5 Investigations on the Edge E_r

Active CXRS is a well established method to measure the impurity ion temperature, density and rotation in a plasma. A combination of poloidal and toroidal views enables the measurement of E_r using the radial force balance equation. The edge diagnostic suite combined with an established alignment procedure allows for a high-precision comparison between E_r and the edge kinetic profiles. In H-mode the maximum E_r shear and the steepest gradients in the ion profiles lie inside the position of the E_r minimum indicating that the negative E_r shear region is the important region for turbulence reduction. The E_r profile has been compared to the main ion pressure gradient term, which is found to be the dominant contribution at the plasma edge, supporting the idea that the E_r well is created by the main ion species. From these measurements the perpendicular main ion flow velocity is evaluated and is found to be close to 0 in the ETB, consistent with neoclassical theory for small toroidal rotation. This result is evidenced by direct measurements of the main ions in He plasmas. Further measurements on the dominant impurity species demonstrate that their poloidal rotation is also well described by neoclassical theory (see figure 19). Thus, the poloidal main ion flow is driven by the T_i gradient, while the poloidal impurity flow is determined by both the ion temperature and pressure gradient.

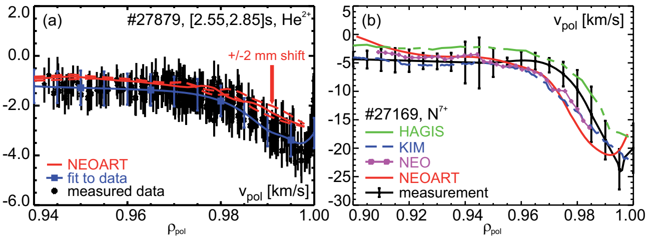

Figure 19: Comparison between neoclassical predictions (evaluated using different neoclassical codes) and experimental measurements: poloidal rotation of (a) main ions (measured in a He plasma), (b) N^{7+} (D plasma).

7.6 Spectral Dependence of Turbulence using Doppler Reflectometry

A new optimized Doppler reflectometer front-end was brought into operation in 2012. Bistatic antennas with a steerable ellipsoidal mirror (via piezoelectric drive) are used to probe different turbulence wavenumbers ($k_\perp$= 5-25 cm^{-1}) to provide edge/core radial profiles of E_r and δn^2.

Figure 20 (a) shows an example δn^2 profile obtained during ECRH power and radial deposition scans. δn^2 increases from core to edge, dropping at the pedestal due to strong E_r shear. Fluctuation amplitudes fall from small to large $k_\perp$. The wavenumber spectra in figure 20 (b) show two inertial ranges, rather flat at low $k_\perp$ and cascading at smaller scales ($k_\perp$> 8 cm^{-1}). First comparisons to both ASTRA and GENE (non-linear) numerical simulations show reasonable agreement. Although radial trends in Q_i and δn^2 are consistent with the experiments, inertial ranges in $k_\perp$-spectra differ. Further scenarios are under investigation, both for improved experimental understanding and benchmarking of the GENE code.

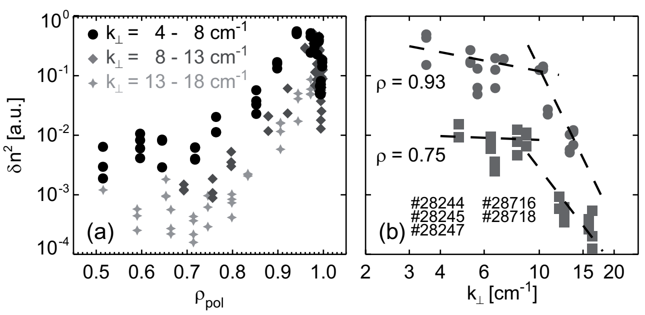

Figure 20: (a) Radial δn^2 profiles for different turbulence structure scales and (b) $k_\perp$ spectra at different radii.

7.7 Effect of Experimental Uncertainties on the Calculations of Peeling-ballooning Stability Boundaries

The ideal MHD stability code MISHKA in the ILSA framework was tested against uncertainties in the experimental profiles. In order to investigate the differences in the predicted pedestal stability boundary with and without systematic errors in the T_e profile, discharge # 23417 was first analyzed using T_e from the conventional integrated data analysis method (IDA) and then with the results of the more accurate, newly developed, electron cyclotron forward modelling method (ECFM). It can be seen in figure 21 that the position of the stability boundary does not depend on the input profile. However, accurate pressure and current density profiles are still needed to identify the position of the operational point, which determines whether the plasma is unstable or not. Furthermore, it was shown that the relative alignment of the profiles and the shift relative to the magnetic measurements strongly influence the outcome of the stability analysis. As expected, an outward shift of the pressure profile and current density results in a higher growth rate of the peeling-ballooning modes, while an increase of the toroidal mode numbers is also observed.

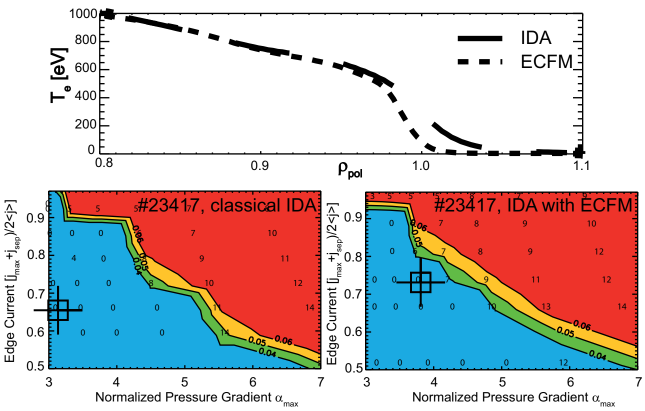

Figure 21: T_e profiles and corresponding stability diagrams using conventional IDA (left) and ECFM (right) as input.

7.8 Non-linear Evolution of ELMs

Advance analysis of data from the experiments AUG and TCV in combination with non-linear MHD simulations enable advanced characterisation and understanding of the processes during ELMs. Especially dominant magnetic perturbations (DMP) observed in close temporal vicinity to the onset of pedestal erosion help to reveal the 3D perturbation structure of ELMs. DMPs are caused by current perturbations at or inside the separatrix. At very low collisionality some DMPs display a similarity to solitons. Furthermore DMPs are often correlated to temperature perturbations. DMPs propagate in opposite poloidal direction as ELM filaments and display characteristics of a trigger of these. From TCV data it is concluded that DMPs are already in their non-linear phase, when they exceed the level of background fluctuations. A consistent picture of a transition from a high ($n \geq 10$) to a low ($n \approx 1$) dominant toroidal mode number from the linear to the non-linear phase has been established. This underlines the need for a non-linear description of ELMs.

7.9. Analysis of T- and n-pedestals in a Multi-machine Database

A comparison of type-I ELMy H-modes from a wide range of AUG and DIII-D scenarios showed significant differences between electron and ion pedestal temperature profiles. For high collision rates the ions are coupled to the electrons and show very similar pedestal top values and gradients. For lower collision rates both decouple and the ion pedestal becomes less steep. This indicates that the common assumption of $T_e=T_i$ is not valid generally. Theoretical descriptions of processes in fusion plasmas, which are based on the temperature equality might fail when considering a wider parameter range. The T_e-gradient in real space scales linearly with its pedestal top value. This holds also for different machine sizes, namely including data from JET. The trend $T_e \propto \nabla T_e$ is independent of collisionality and plasma shape. This behaviour is different from peeling-ballooning edge stability, which is influenced by the plasma shape due to additional information about the ions. This difference suggests a limit for the T_e-pedestal different from linear edge MHD stability.

7.10 L→H Transition, Pedestal Development and I-mode

Recent results evidenced the key role of the ion channel in the L→H transition physics through its diamagnetic contribution to the radial electric field. This, in particular, explains the well-known non-monotonic density dependence of the L→H transition power threshold, $P_{L\rightarrow H}$, which exhibits a minimum at $n_{e,min}$. New experiments indicate that both $n_{e,min}$ and the corresponding P_{thr} values decrease with plasma current, which can be explained by the requirement of a minimum edge ion heat flux to induce the L→H transition, confirming the previous results using a different approach.

The development of the density pedestal after the L→H transition until the first ELM has been investigated experimentally and modelled in time-dependent transport analyses. The density evolution after the L→H transition until the first ELM can only be explained by a strong reduction of the particle diffusion in the edge transport barrier, while a further contribution from an edge pinch cannot be excluded, but is not necessary. Moreover, assuming no change in diffusion, a pinch alone does not reproduce satisfactorily the experimental data.

The I-mode is a high confinement regime without ELMs, which exhibits a temperature pedestal while the density does not change. It occurs above a heating power, which is higher than the usual H-mode threshold and can therefore only be achieved for high P_{thr} conditions, e.g. unfavourable ion ∇B-drift. In AUG the I-mode could be obtained with all heating methods. The required power depends linearly on the density but weakly on the magnetic field. There also, the edge ion heat flux plays a key role in triggering the I-mode and in the development of the temperature pedestal.

7.11 Outer Target Heat Fluxes and Power Decay Length Scaling in AUG and JET L-modes

Previous work has identified a clear multi-machine experimental scaling of the outer divertor target power decay length, λ_q, leading to prediction for ITER of λ_q~1 mm for the case of H-mode with attached divertor plasma. To improve the physical understanding and prediction it is important to consider other confinement regimes than the H-mode. During 2012 we applied the same methodology to low density L-mode plasmas from AUG and JET. The basic dependencies of λ_q are identified through plasma parameters scans and for the case of fully attached divertor using numerical regressions (after mapping at the mid-plane, see figure 22). The resulting scaling shows qualitatively similar to H-mode trends with the safety factor, toroidal magnetic field and heating power though bulk data are about a factor of 2 larger in L-mode for both devices. Consistently a clear shrinking of the heat channel width is observed at the L→H transition linked with the formation of the pedestal temperature. Extrapolation of the empirical power scaling laws to ITER gives $\lambda_q \cong$3-5 mm with I_p=15 MA and P_{SOL}=50 MW.

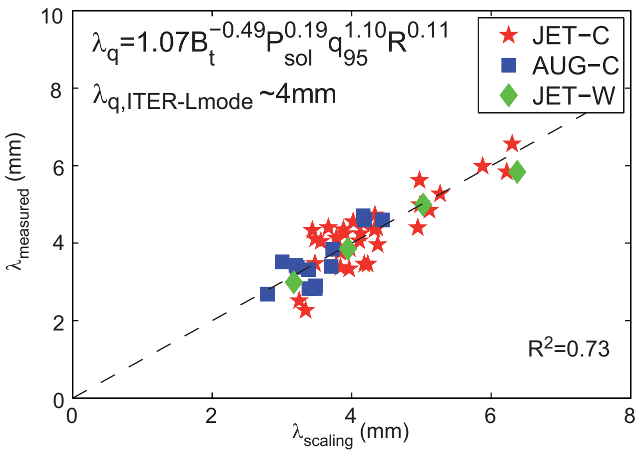

Figure 22: Scaling law for combined AUG and JET data. Red stars: JET with C-wall, green diamonds: JET ILW and blue squares: AUG with C-wall.

7.12 X-point Flow at the L→H Transition

The X-point probe was recommissioned in 2012 after a major upgrade of the drive system. A new SIO data-acquisition system was installed and the measurement electronics was streamlined and upgraded. The probe was routinely used to provide flow, n_e and T_e measurements for SOL and divertor experiments in L-mode. At the divertor legs, Mach 1 flows or higher are typically observed towards the strike points. T_e is higher on the LFS than on the HFS, while n_e shows the opposite trend. The resulting electron pressure was found to depart significantly from a flux function. During N_2 seeding experiments, no strong variations of the profiles were evident. Initial attempts to measure fluctuations at the L→H transition were carried out. Prior to the transition, coherent density oscillations in the 3 kHz range were observed, which were quenched within less than one period at or before the transition. They could be related with the fluctuations typically observed in I-modes.

7.13 Characterisation of the Fluctuating Detachment State

Divertor detachment has been studied in Ohmic and L-mode density ramp discharges. With increasing density it was observed that the detachment process can be divided into different distinct states and the behaviours of the inner and the outer divertor were found to be strongly coupled. Prior to the detachment of the outer divertor, strong fluctuations in the radiated power are measured with fast AXUV diodes. They suddenly appear in the SOL of the inner divertor close to the X-point. The frequency scales with the ion mass as $m^{-1/2}$ and, for deuterium, is about 5.5 kHz (figure 23 c). During this fluctuating state, a high-density region appears in the inner far SOL and around the X-point (figure 23, #1). The particle flux to the inner targets is already well below the prediction of the two-point model, which indicates that the plasma is at least partially detached from the inner target. After the disappearance of the fluctuations, complete detachment, defined by a strong reduction of the ion flux and the volumetric density in the vicinity of the target, occurs simultaneously along the entire inner and outer targets (figure 23, #2).

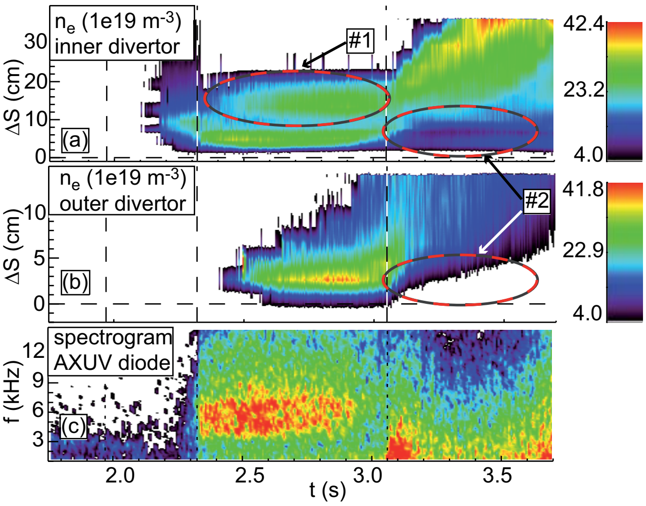

Figure 23: n_e profile in the (a) inner and (b) divertor vs. the distance to the strike point and (c) spectrogram of an AXUV signal for # 27100.

8 Stuttgart

8.1 SOL Dynamics and Transport

Correlation analyses of Langmuir-probe data from radial profiles measured in the SOL reveal a reversal in the poloidal propagation of turbulent structures. It could be shown that the propagation velocity roughly follows the background E×B drift. The step-like radial variations in the underlying electric field could be related to corresponding variations in the field-line connection lengths in the SOL, since here, the plasma potential is determined by parallel temperature gradients. This explains the appearance of strong shear layers in the SOL beyond the separatrix. Across the shear layer, however, the poloidal propagation does not turn gradually. The velocity rather switches discretely between two opposing values.

In AUG equivalent GEMR simulations, the discrete reversal could be observed, too. This behaviour can be attributed to an intermittent merging of structures from both sides of the shear layer. These structures were observed to approach each other poloidally, touch, and merge to one radially extended structure. During the merging process, before the structures are sheared apart again by the background flow, density is transferred radially outwards through the shear layer. Evidence for the radial overlap of structures propagating in opposite directions is found also in TJ-K, TJ-II, and Alcator C-Mod, which points to a universal transport mechanism across shear layers at the separatrix of magnetically confined plasmas.

8.2 High-Power Diplexer Experiments

A resonant high-power diplexer was commissioned and tested in the ECRH-2 system. This device had been developed for optimum control of neoclassical tearing modes (NTM) and for detection of ECE simultaneously with ECRH using a common antenna. It was equipped with an automatic tuner for the diplexer resonance contributed by colleagues from TNO Delft to cope with the gyrotron frequency drift during the experiments. The diplexer was connected to launchers L1 and L3, where L1 was aiming to an off-axis deposition region ($\rho \approx 0.35$) and L3 to the plasma centre ($\rho \approx 0.1$). In various experiments with power up to 0.6 MW, slow switching (by mechanical detuning of the diplexer resonator) and fast switching (by electronically controlled frequency-shift keying of the gyrotron) between the two launchers could be demonstrated. The minima of the cross-phase obtained from the analysis of the heat waves generated in the plasma confirm the switching between the two deposition regions.

In conjunction with a radiometer system operated by colleagues from DIFFER, Rijnhuizen, ECE could be measured via the same line of sight, and the modulation of the ECE signal due to NTMs could be detected. This is a clear prerequisite for a feedback control of the launcher via the in-line ECE signals. For 2013, after completion of the fast data acquisition, NTM stabilization experiments are scheduled.

9 European Co-operations

The call for participation in the 2012 AUG campaign was answered in total by 101 (48) scientists submitting 215 (62) experimental proposals and requesting 2081 (693) discharges. The numbers in brackets correspond to the contributions by non-IPP scientists. Particularly impressive is that the number of external authors (48) from 14 EU Associates who have submitted proposals, is almost as high as the one for IPP (53). In the following, short reports are given for the 2012 contributions of a selection of EU Associates. Due to limitation in space such reports were not possible for all EU Associates involved in the 2012 AUG Programme. Their contributions are documented in the staff list below and the section ‘Publications’.

CCFE

Sawtooth control on ITER is planned using electron cyclotron current drive (ECCD), although its effectiveness in the presence of a significant population of energetic particles had not been experimentally demonstrated. CCFE staff collaborated on experiments at AUG to control the period between sawteeth using steerable ECCD in the presence of ICRF and NBI, which generate fast ions within the plasma. In these conditions effective control was achieved with low ECCD power, in agreement with modelling predictions. Sawtooth control was then used to avoid sawtooth-triggered NTMs at normalised pressures above that anticipated in ITER.

CCFE staff also collaborated on AUG experiments to test the sensitivity of ELM suppression to the magnetic configuration of the plasma. In this investigation magnetic perturbations were applied to plasmas with a connected double-null configuration. Useful data were collected, including measurements of the divertor strike point ‘splitting’, which are being compared with modelling performed at CCFE.

The candidate plasma scenarios for ITER envisage the use of an H-mode transport barrier at the plasma edge, which is sensitive to the magnetic topology of the plasma. CCFE staff have collaborated with on-going experiments at AUG to investigate the dependence of H-mode access conditions on the height and radius of the magnetic X-point, which links the plasma core to the divertor region. Experiments were performed at various values of plasma density, but, in contrast to results from similar changes on other devices, the geometries tested on AUG did not result in a clear change in the power required to access H-mode for the different magnetic configurations.

DCU – University College Cork

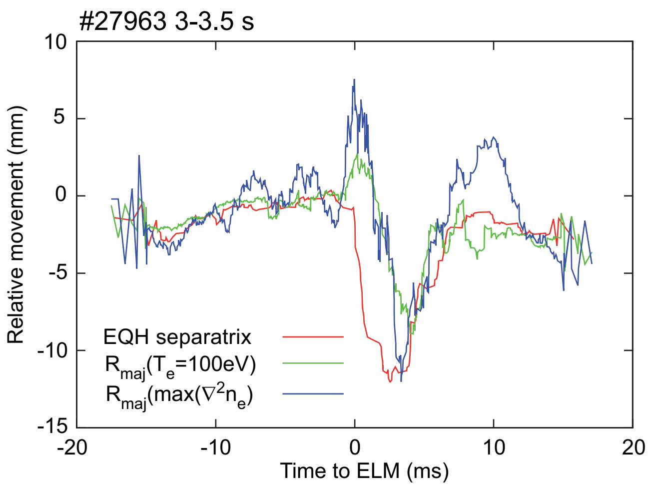

Figure 24: Movement of separatrix position during an ELM crash.

Following successful work in 2011 on edge current density analysis for a small number of type-I ELMs, a database of these reconstructions has been generated, which covers a wide range of plasma parameters including improved H-modes and N_2 seeded discharges. Its completion demonstrates the wide applicability and robustness of the technique. Detailed analysis of stability calculations using several of these discharges is in progress.

Comparison of CLISTE results with other diagnostics has also revealed supporting evidence for a rapid movement of the separatrix at the ELM crash, followed by a gradual recovery to its pre-ELM state. The location determined from the maximum curvature of the electron density as well as the position of T_e=100 eV agree well with the movement pattern (if not exactly with the location), as shown in figure 24. The differences also give rise to questions regarding the formation of the separatrix layer and under what conditions the assumptions of T_e^{sep}~100 eV and the curvature of n_e taking its maximum value on the separatrix hold.

With the aid of electron cyclotron forward modelling, the transition of the plasma, in particular the edge current, from type-I to type-II and MP-suppressed regimes is presently being analysed. Changes in the total edge current have been observed for several instances of MP-suppression, coinciding with the onset of the new ELM regime.

Further analysis of low-frequency Alfvén eigenmode activity has been carried out by solving numerically the low-frequency kinetic dispersion relation. In particular, the change in damping/drive of BAEs with variations in the ratio of electron and ion temperature profiles has been considered. A preliminary investigation has commenced into the frequency continuum structure and damping/drive of the electrostatic drift wave branch. This branch is likewise recovered by solving the kinetic dispersion relation.

Experiments have been carried out at AUG aimed at investigating low-frequency BAE-like modes that have been observed during the ELM-free H-mode phase of certain previous discharges. During the course of these experiments, modes that appear similar in nature to edge-localized TAEs have been observed. An investigation aimed at definitively determining the radial localization and structure of these modes is underway. This is being conducted using equilibrium reconstructions obtained using the CLISTE code and determinations of the frequency continuum and eigenmode structure calculated using the LIGKA code.

A new ECE resonant frequency constraint was added to the CLISTE equilibrium reconstruction code, and snowflake equilibrium generation was added to the predictive kernel of CLISTE. Further advances were made in the adaptation of CLISTE to ITM standards, with the objective of being externally data-driven using a standard Machine Description format. In late 2012, CLISTE was installed and executed for the first time on the ITM GATEWAY machine.

DIFFER

Researchers from the FOM Institute DIFFER (Dutch Institute for Fundamental Energy Research) contributed to the AUG

programme through the development of various diagnostic systems. After the completion of the conceptual design in 2011, the AUG multi-pass Thomson scattering (TS) project entered its implementation phase in 2012. Considerable progress was made in the finalization of the diagnostic design, the assessment of critical design issues and the construction and testing of a number of in-vessel components. For the assessment of critical design issues, vibration measurements were performed in order to establish their effect on the mechanical and optical stability of the diagnostic. It was found that the multi-pass cavity would remain stable for a majority of operating scenarios, and that the overall long-term stability of the system is good. With regards to component design and installation, several components where constructed and installed inside the AUG vessel. These include a mirror mount unit positioned on the bottom passive stabilization loop, the light collection optics unit near the tokamak mid-plane, and a number of peripheral components. In addition, reliability tests were performed on critical components, which will have to survive the harsh in-vessel environment, such as piezo-motors and mirrors. Finally, measurements of expected background light and assessment of the fibre transmission degradation due to neutron fluxes were performed.
The measurement requirements for the helium content (helium "ash" and slowing down helium), ion temperature and rotation on ITER, require a high optical throughput spectrometer, in order to deal with the low signal-to-noise ratio. To this end, such a spectrometer that can measure simultaneously carbon, helium and deuterium has been developed.
In 2012, this ITER prototype CX spectrometer has been installed and operated on AUG. The spectrometer has a high étendue and resolution, allowing for high quality CXRS measurements. The capabilities of the system, also in comparison with presently used diagnostics, have been examined and evaluated during the first phase of operation. In addition, the impact of ghost lines has been accessed and suggestions for further improvement of the design have been made. Recently the detectors have been replaced in order to allow measurements at a faster rate.
On the physics front, a model has been developed for the helium "plume" effect, which presents an additional challenge in the interpretation of the helium charge exchange spectra. The validation of the model with helium measurements obtained with the ITER prototype charge exchange spectrometer during the 2012 campaign of AUG is in progress.
The 2012 results from ECEI on ELMs can be found in section 6.4 .
The tuneable mm-wave cavity FADIS is used to enable ECE measurements along one of the AUG ECCD beams. Two diagnostic systems are used to collect the data. First a direct digitizing radiometer is build to observe back-scattered waves. Second a 6-channel radiometer is installed to determine the radial location and phase of tearing modes for control. These systems will be finalized in Q1 of 2013.

DTU

Two receivers for collective Thomson scattering (CTS) are now installed at AUG. The newly installed receiver was commissioned in 2012 and couples to the ECRH-2 transmission line in the NBI control room. A microwave periscope has been added to the receiver transmission line enabling the receiver to be coupled to different ECRH transmission lines. The choice of transmission line can thus be adjusted to the gyrotron availability and the physics objectives. When operating the two receivers in parallel, the signal, which does not originate from scattering in the measurement volume can be subtracted from the CTS signal, which was demonstrated in discharges during 2012. Using this technique, measurements of the fast-ion distribution function are expected to be performed during 2013.
A new 12 Gsample/s digitizer has been added to the IF section of the CTS receivers, which increases the frequency resolution to sub-MHz in a selected part of the frequency coverage. Ion cyclotron structures, which can be used to estimate the ion composition and the ion temperature, can thus be resolved in the CTS spectra for specific scattering geometries. Ion cyclotron structures have successfully been detected in the CTS spectra during 2012. The measurements agree with the theoretically expected spectra and the effect of ^{4}He injection is reproduced in the measurements. Measurements with increased signal-to-noise ratio are expected to provide ion composition measurements in 2013.

FZ-Jülich

The study of melt behaviour of castellated structures in a tokamak is crucial for the operation and design of full metal divertor concepts in future devices. Here castellated tungsten structures with a dedicated leading edge were exposed in the AUG divertor manipulator to study the influence of melt events on plasma exposed surfaces and the plasma discharge itself. Structures similar to the design of respective ITER PFCs were used to study material re-distribution as well as re-solidification and subsequent power handling. At a total heating power of 10.6 MW with 0.6 MW ECRH a plasma current of 0.8 MA and 2.4 T the strike point position was moved from an area next to the divertor manipulator on top of the castellated structure to induce melting.

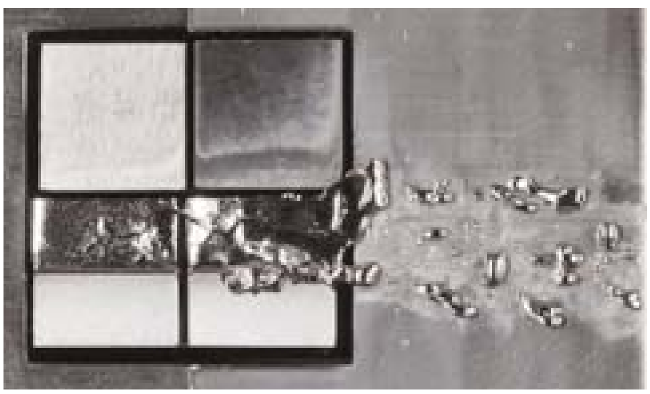

Figure 25: Deliberately melted tungsten in the AUG divertor.

Roughly 80 MW/m^2 impinged onto the leading edge. Moving the strike point onto the target lead to melting with a clear loss of W-droplets into the divertor (see figure 25) – the plasma ran though despite the obvious W-emission. Multiple repetitions (2×5) were performed in order to study the effect on the plasma and observe possible smoothing of the damaged area. A continuation of the experiment is envisioned for 2013 as no conclusive answer on the damage propagation was yet possible.

HAS – KFKI RMKI, Budapest

The NTI Wavelet Tool, which had been integrated into the AUG data analysis system MTR, has been upgraded to produce spectrograms in physical units with error bars to facilitate further processing. This tool was used to characterize core MHD modes to improve the understanding of core impurity transport. The interplay of fast ion transport and edge localized modes was also studied. First results showed that fast ions may have a significant effect on edge stability.
The exploitation of the newly installed Li-beam observation system was continued in 2012 together with the Austrian Association ÖAW (see below).
With a Photron SA5 camera, pellet clouds were observed with a frame rate exceeding 500,000 frame/s. The main emphasis was put on the analysis of the dynamics and drifts of such pellet clouds by applying image processing algorithms on the raw data. The applied optical flow method can clearly recognize drifting clouds (because their drift velocity – exceeding 2 km/s – is much higher than the pellet speed). The typical drift direction was a combination between horizontal (from HFS to LFS) and an upward direction. It was also observed, that the total cloud radiation has a local maximum if drifting cloudlets are also present and contribute to the radiation. This observation may imply that the fluctuation of the total radiation of the pellet cloud is not caused by the fluctuation of the ablation rate. This phenomenon will be further investigated by separating the radiation of the drifting cloudlets on the recorded camera frames.

Hellenic - National Technical University of Athens

A joint project was conducted by IPP and NTUA with the aim to explore new techniques for the suppression of tearing modes (TM) by localised ECCD. The basic idea has been to lock the (m,n)=(2,1) TM to the n=1 static resonant magnetic perturbation (RMP), to facilitate continuous-wave ECCD at the stationary “O” point for a very effective suppression of the magnetic island. At the dedicated discharges, the n=1 RMP was generated by the internal coils, generating and locking also the mode in a fixed position and causing a disruption. The toroidal location of the “O” point (of the mode induced by the RMP) was evaluated by a new locked mode detection system (which was also commissioned during the 2012 campaign). Subsequently, pre-emptive low-power ECCD (i.e. 0.25 MW, which on rotating island would have only a minor impact) was applied at the expected location of the “X” point and “O” point of the magnetic island. It was confirmed that the pre-emptive ECCD at the expected location of the “X” point accelerates the growth of the (2,1) TM and the disruption, while pre-emptive ECCD at the expected location of the “O” point prevents completely the growth of the (2,1) TM and the disruption, as we expected.

IPP.CR

The 2012 campaign has provided unique comparative measurements of the plasma potential by ball-pen probe (BPP) and self-emitting Langmuir probe (LP). The probe head consisting of four BPPs and four LPs was mounted on the horizontal reciprocating manipulator. The electrically floating LP has significantly changed its potential during the deep reciprocation. Previously, it has been observed that the LP becomes self-emitting due to the high heat flux. In the last campaign, this effect happened exactly in the moment when the probe head reached the maximum of the reciprocation. For the first time, good agreement between the plasma potential measurements by the self-emitting LP and neighbouring BPP was observed. With these two techniques similar values of the plasma potential and its fluctuations could be measured. In addition, good agreement between the radial electric field obtained with BPP and with Doppler reflectometry was achieved.

IST – Centro de Fusão Nuclear

Physics studies: (i) A study of NBI-driven Alfvén Cascade (ACs) for different heating scenarios revealed a bursting behaviour of ACs with the more tangential NBI source and pure ECR heating during the I_p ramp-up. ACs appear to be suppressed only when they are located closed to the ECRH deposition layer. The flat q profile in the core and the strong T_e gradient due to ECRH lead to the appearance of a (2,1) mode and then a sawtooth-like crash associated with q=2, which expels 50 % of the fast ion population from the core; (ii) Quasi-coherent modes and magnetic islands at the edge were studied with poloidal correlation measurements; (iii) signatures of edge/SOL filamentary structures were clearly identified in the reflectometer signals and their radial velocities were obtained. Modelling with a full wave code was initiated. (iv) the integration of GEMR simulations with reflectometry full-wave codes REFMUL(X) provided a powerful tool for turbulence characterization; (v) results at the L→H transition depict the formation of the edge barrier HFS/LFS.
Diagnostic developments: After the 2011 plasma position control demonstration using FM-CW reflectometry (outer plasma radius) further work aimed at inner/outer experiments. The HFS channels with modified front-ends were extensively tested and calibrated. K, Ka and Q-bands were also re-calibrated after a complete renovation of the in- and ex-vessel waveguides. The V-band channels were upgraded with new electronics, but they are not yet operational due to incomplete in-vessel waveguide connections. The W-band channel, for which a new dual driver was designed is under test. Sudden failure of the diagnostic workstation required a major reorganization of the diagnostic

control software. The standard density profile software had to be adapted to use the data generated by the real time (RT) data acquisition system. Both the RT and standard density profile software were modified to include the new HFS calibrations.
To study and optimize the ICRF wave coupling to the plasma the new 3-strap ICRF antenna (to be installed during the 2013 shutdown, see section 4) will be equipped with multiple microwave reflectometers to allow measurement of the density profile directly in front of the ICRF antenna. ENEA is responsible for the diagnostic project and IST will supply the microwave hardware for signal generation and detection.

ÖAW – IAP, TU Vienna

We performed predictive modelling to investigate the role of convective and diffusive particle transport at the edge during the density build-up after the L→H transition. Extensive parameter scans show that the density build-up can be reasonably reproduced by assuming only a diffusive edge transport barrier (ETB). Moreover, the replacement of the diffusive ETB by a strong inward directed convective velocity at the edge (edge pinch) did not deliver any satisfying results. This indicates that a diffusive ETB is required to explain the density build-up. Furthermore, the addition of an edge pinch to the diffusive ETB slightly enhances the agreement between modelling and experiment. Because of the large uncertainties in the source, it is not possible to pin down an additional edge pinch. But we could estimate an upper limit for a possible edge pinch of 5 m/s.
A new optical head for the lithium beam emission spectroscopy diagnostic (Li-BES) was installed and commissioned in collaboration with the Hungarian Association HAS. The shorter distance and larger aperture allows for a much better signal to noise ratio. As a result the new optical Li-BES observation system measures about two orders of magnitude more photons. The high number of collected photons is sufficient for a calculation of density profiles from the emission profile with the maximum time resolution of the new data acquisition system (5 μs) by means of a standard Bayesian algorithm developed at AUG. Therefore, the hardware improvements allow for the first time density fluctuation measurements with the Li-BES.

Tekes

Momentum transport studies were conducted in 2012. The first ever set of intrinsic torque experiments was performed on AUG by using the slow NBI modulation technique (2 Hz). Unlike the compensated modulation, the uncompensated modulation at 2 Hz creates a large enough perturbation to extract intrinsic torque. For momentum transport studies, ten good physics shots were performed, including a successful 3-point q-scan, a fair R/L_n scan, and an MP test pulse. The data from the R/L_n scan fits well with the ITPA database, showing a strong trend where the inward pinch increases with R/L_n, while in the q-scan, the inward pinch seems to decrease weakly with increasing q.
Related to momentum transport studies, a study on thermal ion orbit losses and their connection with the measured boundary rotation was initiated. A discharge with high quality toroidal and poloidal flow measurements was selected and a new synthetic diagnostic was prepared in ASCOT.
The fast ion studies concentrated on the effect of various MHD events on the confinement of NBI ions. In 2012, the emphasis was in validating the numerical tools against AUG data, preceded by code benchmarks and comparison of numerical models. In collaboration with IPP's TOK group, ASCOT has been refurbished with a model capable of simulating the effect of both slow NTMs and rapidly rotating TAEs on fast ions. A benchmark study between ASCOT and HAGIS was carried out for an AUG pulse with a TAE mode. The particle orbits were found to match well within the differences in the numerical models. Also a NTM benchmark study to model the redistribution of NBI ions was initiated. NBI ion confinement was also studied experimentally in the spring fast ion campaign with the FILD probe, followed by ASCOT simulations utilizing a synthetic FILD diagnostic.
In PWI studies, an extensive set of wall tiles was analysed for their ^{13}C contents from the 2011 global impurity injection experiment. The main chamber was found to be the largest deposition region for carbon, but also gaps between wall tiles account for surface densities comparable to those on the plasma-facing surfaces. ASCOT modelling reproduced the observed localized deposition at the outer midplane, but more work is needed to explain the measured heavy deposition at the inner heat-shield region and at the top of the vessel. The main suspects are the poorly known background flow and limitations in the collision model. The ASCOT collision model was enhanced and HFS flow profile was studied by injecting methane and following the emission plume by spectroscopy and video cameras. ERO simulations are used to connect the measured velocities to the actual background flow.
Erosion of different materials was studied using two graphite probes with C, Al, W, and Ni markers, exposed to a number of plasma discharges in 2010/11. The erosion of W and, to some degree, also C and Ni were nicely reproduced using the ERO code with rather low T_e and T_i and longish decay lengths.
Also the erosion behaviour of P92 steel was investigated at the inner heat-shield. Due to thick deposits of B, little erosion was observed, but the results indicate some preferential sputtering having taken place: the W content of the P92 tiles had been enriched from the values measured before their plasma exposure.

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During the 2012 JET campaigns with the ITER-like wall many strategies for tokamak operation with a metal wall developed at ASDEX Upgrade could be successfully applied at JET. Stable H-modes as well as the hybrid scenario could be re-established when using gas puff levels of a few 10^{21} electrons/s. On average confinement is lower with the new PFCs; nevertheless, H-factors up to 1 (H-Mode) and 1.3 (Hybrids) have been achieved with tolerable tungsten concentrations.

Introduction

In ASDEX Upgrade (AUG) and JET tungsten (W) is used as a plasma facing material. While at AUG a stepwise approach was pursued over 1999-2007, replacing the graphite wall tiles by W-coated ones, the ITER-like wall (ILW) at JET consisting of Be (main chamber) and W (divertor) plasma facing components was implemented during one single vent prior to C28 in 2011. Whereas the first experiments with the ILW were restricted to the operation at low heating power, from November 2011 onwards discharges with gradually increasing power were implemented with the main focus in 2012 being to prepare ITER relevant scenarios.

21 IPP scientists were seconded to the 2012 JET campaigns C29 – C30 from January to July 2012, leading in total to ~4 ppy of on-site participation. In many cases IPP personnel took a leading role in the preparation, execution and analysis of JET experiments. In particular, a senior IPP scientist led the JET Task Force E1. In addition, seven long-term secondments of IPP staff to the Close Support Unit (2) and to the JET Operator (JOC, 5) were active in 2012.

In August 2012 an intervention has started with the main aim to remove long-term samples out of the JET vessel. These samples will be used for the characterization of the ILW by applying a variety of surface analysis methods. In addition, preparation of the 2013 JET campaigns has started with a new generation of Task Force Leaders (TFL). Among them there are two IPP scientists working as deputy TFL for JET Task Forces E1 and E2, respectively. As part of the stepwise approach foreseen from the very beginning of the ILW, the next JET campaigns will concentrate on further expansion of the operational range by applying more than 30 MW of auxiliary heating power.

The following is a summary of selected results, which have been obtained with significant IPP involvement during the 2012 JET campaigns. Since both devices have metallic walls, IPP's contributions to JET are even more focused on the realisation of the so-called step-ladder approach AUG-JET-ITER. According to this approach, operational experience and insight gained from scientific results obtained at AUG are being transferred to JET. As will be shown in the following sections, many operational strategies developed at AUG could be successfully applied to JET.

Baseline H-mode Scenario

In order to allow the reliable and safe operation in high power H-modes special emphasis was dedicated to the H-mode scenario development. The main elements were the establishment of a stable current ramp up phase, the avoidance of large ELMs at the entry of the H-mode phase, the optimisation of confinement in the flattop phase and finally the safe exit from H-mode and discharge landing – always staying within the material limits given by the metallic wall. Stable Type-I ELM sawteething H-modes have been achieved for 4 to 5 s (duration of main heating phase) in low and high δ plasmas, initially at 2.0 MA / 2.1 T and then at 2.5 MA / 2.7 T with q_{95}=3.5 and above 20 MW of auxiliary power (see figure 1). It became clear that deuterium had to be puffed at a significant rate (above 10^{22} D s^{-1}) in the divertor during the main heating phase to achieve stable conditions with respect to central radiation peaking as already shown in AUG. By increasing the puff rate the ELM frequency increased whereby a minimum ELM frequency of typically 10 Hz or more was necessary to prevent excessive core plasma radiation arising from W and Ni, which could lead to a back transition to L-mode due to the associated decrease in power crossing the separatrix. In this situation, the sawtooth activity did not seem to prevent radiation peaking and even vanished as the temperature profile became hollow. In general, no disruption occurred if the auxiliary heating was maintained, whereas switching off the NBI power in such a case could lead to disruption by a radiation collapse event.

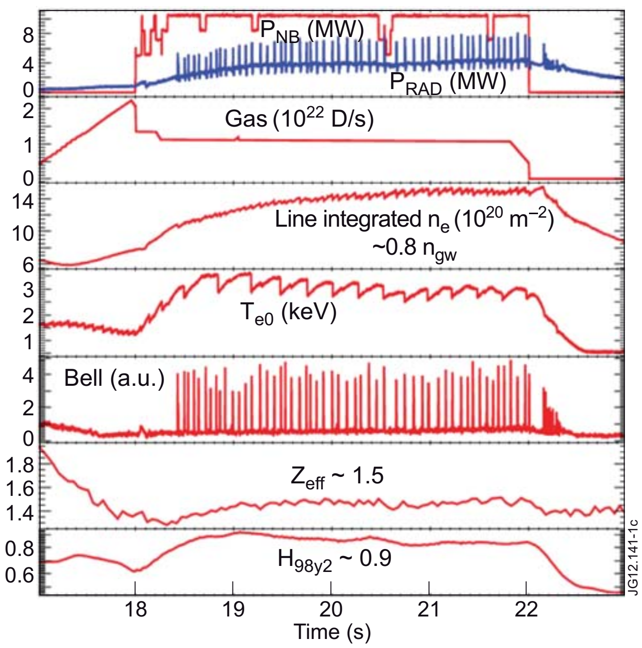

Figure 1: Stable H-mode discharge in JET-ILW with I_p=2.0 MA, B_t=2.1 T.

An increase of the NBI power combined with strong deuterium gas puffing rate led to an expansion of operational space by increasing central transport and the ELM frequency and therefore the flushing of tungsten from the bulk plasma as seen in AUG. Both the increase of the loss power (power crossing the separatrix) and the gas puff rate contribute to expel tungsten by increasing the ELM frequency. It was also found that the minimum gas puff rate for stable conditions decreased with increasing loss power. However, the required high gas puff rate deteriorated the confinement of the H-mode.

At high triangularity ($\delta \approx 0.4$) the H-mode scenario with gas puffing showed a confinement degradation by 10 to 30 %, which was previously not observed with the C-wall at a similar level of gas fuelling. For the cases with the lowest fuelling rate, the confinement factor H_{98} approached 1 on occasion indicating that the H=1 operation is possible at I_p=2.5 MA (without strong central heating). In an attempt to extend this space, vertical kicks have been applied to control the ELM frequency without introducing additional gas. Although the ELM frequency could indeed be controlled at about 30 Hz and the gas rate could be reduced to $5 \cdot 10^{21}$ D s^{-1} the H-factor could not be restored to values closer to 1, indicating that at least another ingredient is responsible for the reduced confinement.

On the basis of the initial low triangularity (δ=0.2) H-mode development at 2.5 MA / 2.7 T (q_{95}=3.5), the baseline operational domain was extended up to 3.5 MA / 3.2 T ($q_{95} \approx 3$). Large gas injection was intentionally used again to stabilise the discharge by maintaining the ELM frequency above ≈10-20 Hz. Strike point sweeping of about ±6 cm was successfully applied on the bulk tungsten tiles to keep their surface temperature below 1200 °C. Using this cautious approach, plasmas were successfully developed at $\beta_N \approx 1.4$ with 25 MW of NBI power for more than 5s duration and a Z_{eff} of 1.2-1.3. ICRH power was also coupled successfully up to a level of 3.5 MW during the flattop. An elevation of the core temperature and larger sawtooth activity were clearly observed in the ICRH phase but there was no clear evidence yet that it had a beneficial effect on the high Z impurity core concentration. In comparison to the C-wall high current scan with the same triangularity, confinement is consistently lower by 20 to 30 % at the same plasma current, q_{95} and shape. Attempts to recover the confinement by lowering the gas injection down to a rate of $2 \cdot 10^{22}$ D s^{-1} and increasing the heating power to provide $P_{loss}/P_{L\text{->}H}$ well above 2 while keeping the ELM frequency above 10 Hz, have not succeeded in recovering more than 10 % of the confinement. As a result, the ρ^* and ν^* values are still higher by typically 50 % and 30 % respectively than with the C-wall.

Hybrid H-mode Scenario

The hybrid scenario has also been developed using as references the work carried out in JET-C. This scenario is traditionally characterised by its access to high normalised pressure (β_N>2.5) and no or infrequent sawteeth activity due to its 'broad' q-profile shape with an edge $q_{95} \approx 4$. In JET the required q-profile is achieved by using the current overshoot technique, which helps to keep the central target q value (q_0) close to unity while maximising the amount of current density at mid-radius.

As already found with the baseline scenario, more gas had to be injected in the early discharge phase compared to the experiments in JET-C to achieve the same plasma density although the X-point is already formed after 1.4 s. Too little gas injection resulted in the creation of a run-away electron population and an augmented tungsten level. With increased gas injection, the early q-profile at the X-point formation was much lower in the plasma core (typically 3 or 4 instead of 6 or 7 as measured by the MSE diagnostic) than it was with the C-wall. Thus the current penetration into the plasma core during the current ramp-up phase is more rapid with the ILW and typically the main heating pulse had to be timed earlier to achieve the desired plasma conditions.

Using the I_p overshoot technique, the hybrid scenario has been developed at low $\delta \approx 0.2$-0.3 and high $\delta \approx 0.4$ at 1.4-1.7 MA / 2.0 T and 1.7-2.0 MA / 2.3 T. In all discharges, the outer strike point was located on the horizontal divertor bulk tungsten tile (with the C-wall the plasma configuration had a more outward strike point position closer to the pumping louvers). In these attempts the hybrid scenario could be reproduced, showing for about 2 to 3 s similar global performance (H_{98}=1.1-1.3 with $\beta_N \approx 3$) as achieved in the C-wall at both high and low triangularity, with the caveats that the density was higher and temperature lower for low triangularity. For both triangularities moderate gas fuelling ($5 \cdot 10^{21}$ D s^{-1}) was required to keep the discharge stable with regard to core radiation. There is evidence that the pedestal temperature was generally lower for the ILW hybrid plasmas compared with the equivalent C-wall plasmas, which may be partly due to the need for gas fuelling during the main heating phase to prevent impurity accumulation. However, the same analysis suggests that increased peaking of the pressure profile compensates for this deficit, at least to some extent, providing similar global performance.

The hybrid scenario with the ILW had in general similar m=1, n=1 fishbone activity as with the C-wall. However, unlike the experiments in JET-C, continuous m=1, n=1 modes sometimes appeared, effecting a significant reduction of confinement. Similarly, m=3 / n=2 and m=4 / n=3 MHD activities were also observed, leading to a slow decrease of central electron temperature and enhanced radiation from the plasma core. The impurity content at the plasma centre increased during such phases with MHD instabilities. This apparent linkage between MHD instabilities and impurity transport highlights the need for careful MHD control with the ILW. This is in contrast to observations with the C-wall where a recovery from such events was possible and did not terminate the discharge in a radiative collapse.

Preliminary experiments were performed to test the feasibility of replacing the current overshoot with a slow plasma volume compression followed by a rapid expansion. This was technically successful, but has not yet produced plasmas with a core region of low magnetic shear as broad as can be achieved with the current overshoot approach.

The observed difference in performance between the hybrid and the baseline H-modes is quite obvious, but the reasons for this are not yet understood, even though part of the improved performance can be attributed to better core confinement. A possible explanation could be that higher confinement in machines with metal walls is preferably achieved at higher β-values or at an operation clearly above the L-H threshold (2-3.5 instead of 1.5-2.0 used in the baseline scenario) as there are also hints for this from AUG. Additionally, the hybrid H-mode scenarios are run at lower I_p, and thus higher q_{95} as the baseline scenarios leading to differences in heating deposition and radiation profiles.

Tungsten Accumulation

In discharges where too much W enters the plasma core, W accumulation can develop, strongly impacting on the core plasma parameters and the confinement. Figure 2 shows an H-mode discharge with an ELM-frequency of 10-15 Hz, exhibiting the typical behaviour of slow W accumulation. From t=9.0 s on the deuterium gas puff is lowered to $5 \cdot 10^{21}$ D s^{-1}. Up to t=11.5 s the diamagnetic energy W_{dia} does not considerably change, while the radiated power in the main chamber P_{rad} continuously increases. Similarly, the core electron temperature T_e as measured by ECE decreases, while the edge values stay constant. During the same period the electron density n_e (see figure 2) as measured by Thomson scattering, keeps rising in the plasma core and the edge values stay constant, which implies that the density starts peaking. Only after t=11.5 s the core T_e collapses drastically and a steep increase of P_{rad} is observed affecting W_{dia} and correspondingly the H_{98}-factor (figure 2d)). As the line averaged $Z_{eff} \approx 1.2$ does not significantly change during the rise of the radiation, medium to high-Z elements must be causing it. However, the W-concentration c_W as measured by the spectrometer stays constant throughout. In order to estimate the radiated power due to W, the W-concentration, which is locally measured at a certain radial range, is assumed to apply for the full plasma volume – this estimate is depicted in figure 2 and labelled 'est. W-rad'. The W-radiation seems to be negligible during all phases of the discharge and thus seems to indicate that W may not be responsible for the rise of the main chamber radiation. However, the spectrometer line of sight is vertical and may be missing parts of the W emission, because of poloidal asymmetries that arise from centrifugal forces. Additionally, the measured W spectral lines in the VUV spectral range yield information from a limited radial region only. This interpretation is confirmed by SXR emission profiles revealing poloidal asymmetries, which can be described as a consequence of centrifugal forces acting strongly on rotating W ions.

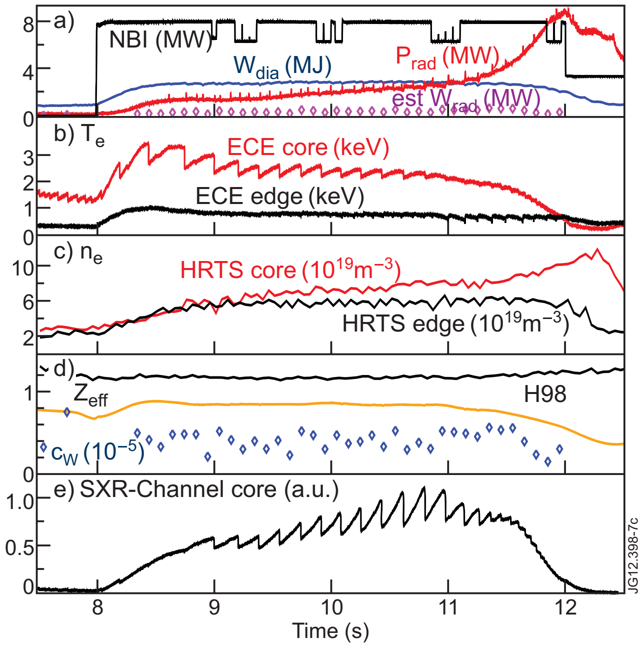

Figure 2: Evolution of W-accumulation in a JET-ILW H-mode discharge with I_p=2.0 MA, B_t=2.1 T.

A strong localized radiation peaking is very characteristic for so-called central impurity accumulation. At AUG it has been found that impurity accumulation occurs when turbulent transport in the plasma core is weak, and the neoclassical transport becomes important. The cleaning effect of large turbulent core transport is not only based on diffusive effects, but also supported by a turbulent outward pinch for the impurities requiring steep temperature gradients.

The radiation/heating balance in the core of the presented discharge #81913 (figure 2) reveals radiative cooling of similar size as the local heating power thereby decreasing the core T_e and flattening the T_e gradients leading to a positive feedback loop of decreasing transport and increasing radiation.

Radiative Cooling

With the change to the JET-ILW, a strong reduction of the C divertor radiation was expected (and actually also found). In order to prepare for this situation, specifically in the presence of the enhanced NBI heating power, an elaborate program on radiative cooling using either N_2 or Ne was conducted in JET-C. Typical for these discharges was a moderate degradation of the confinement with increasing impurity injection. The transition from the type-I to the type-III ELM regime turned out to be the limitation in achieving a large ratio of divertor/X-point radiation over main plasma radiation with an H-factor close to 1.

Similar discharges were repeated in the JET-ILW with practically identical shape (2.5 MA / 2.7 T) with the aim to characterize the differences between JET-C and JET-ILW. As described above, the W contamination in the main plasma restricted operation to fuelling levels higher than a certain threshold. Generally, the unseeded discharges in the ILW show a lower radiation fraction and a lower Z_{eff} compared to their JET-C counterpart when staying above the minimum fuelling level. Measurements confirm that as nitrogen is injected in the plasma, the divertor behaviour is similar to the JET-C N_2-seeded discharges.

In addition to increasing the radiative power and reducing the inter ELM power load, nitrogen seeding has been found to improve plasma energy confinement in high δ ELMy H-modes by raising the pedestal density and temperature. This leads to H-factors only slightly below their JET-C counterparts. The best N_2-seeded pulse in JET-ILW yielded $n_e/n_{GW} \approx 1$ with $Z_{eff} \approx 1.5$.

This is the first time in JET that injection of impurities lead to an increase in global energy confinement. It is important to note that the increase in confinement stems from the pedestal and not from an improved energy and particle confinement in the core plasma, since density and temperature peaking remained unaffected. A similar correlation between nitrogen seeding rate and stored energy has already been observed in AUG and is reported to be linked to a positive correlation between H-factor and Z_{eff}, which is not (yet) found with the JET-ILW.

The JET-ILW results strongly suggest that the carbon impurities played a decisive role in the performance of the highly shaped plasma scenario in JET-C. In JET-ILW plasmas the divertor radiative power and the pedestal confinement increase up to values similar to those in the deuterium fuelled JET-C counterparts as the nitrogen seeding rate is increased. Once the maximum pedestal pressure has been achieved with nitrogen seeding, a further raise of the seeding level leads to a decrease in density and a weaker decrease in temperature, very similar to the behaviour of plasmas in JET-C with N_2-seeding. These observations indicate that the C level and the associated radiation may have been a hidden parameter in the JET-C confinement behaviour in highly shaped, fuelled H-mode discharges, and that the injection of N_2 at least partially recovers this effect.

A direct consequence of the increased edge stability resulting in higher confinement and lower ELM frequency is the tendency for an un-stationary behaviour similar to that shown in figure 2. It is, however, important to note that high-δ ELMy H-modes were not stationary in JET-C either. In fact, ICRH was added to neutral-beam heating as an integral part of the scenario for control of density peaking and sawteeth. In the JET-ILW discharge, first tests with ICRH heating applied to this scenario did not show any benefit so far, probably due to the additionally induced W source.

Although the improvement in confinement was found to be very robust in high-δ discharges it could not be reproduced in low-δ configurations. The range of Z_{eff} values covered with the low-δ configuration was from 1.2 to 1.5 and thereby spanned the important part of the range explored with high-δ plasmas (1.1-1.8). The reason for this different behaviour is not clear, but it reflects to some extent the differences in confinement behaviour already observed in D-puffed discharges in JET-C. In the course of these investigations on low-δ discharges, a vertical target configuration was also tested, whereas in almost all other investigations the outer strike point was positioned on the horizontal bulk W target (‘tile 5’). In terms of divertor geometry the vertical target configuration is much closer to ITER. Interestingly, W contamination in the main plasma was much reduced and the operational window seemed to extend to very low fuelling rates close to levels used in JET-C. Due to the limited amount of discharge time this beneficial behaviour could not be investigated in detail but it will be a top priority for the upcoming campaigns in 2013.

Fusion Technology Tasks

The design review for the AUG-type dust collectors has been completed and the locations of the collectors in the JET vessel are fixed. They are currently being built at IPP. The installation of the dust collectors has been fully integrated into the 2012/13 JET shutdown and is planned for March 2013.

In addition, IPP cooperated with NILPRP (Romania) and DIFFER (Dutch) to perform high heat flux tests of tungsten coatings in MAGNUM PSI and GLADIS with the aim to achieve a further performance improvement of these coatings. In preparation of the 2014 shutdown a new set of 12 bulk tungsten lamellas was coated with Mo/W marker layers at NILPRP in Bucharest (Romania) for erosion/deposition studies. The thicknesses of the marker layers were determined at IPP using ion beam analysis methods and the pre-characterized lamellas were delivered to JET.

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Stellarator Research

Wendelstein 7-X

Head: Prof. Dr. Thomas Klinger

In 2012 the construction and assembly of Wendelstein 7-X went according to plan. Since now five years, the project is on time and on budget. The closure of the cryostat has started, and until the end of the year three out of five module separations have been closed. The three remaining large work packages are (I) assembly the in-vessel elements, (II) assembly of the current leads, (III) assembly of the device periphery.

1 Introduction

Figure 1 shows the organization chart of the project Wendelstein 7-X. The project splits into eight divisions, one of them (division "In-vessel components") being located in Garching. In addition there are two central departments "Quality management" and "Technical Services". In this form the project turned out to be stable and well suited for the purposes of the device construction with emphasis on assembly.

Design and manufacturing of the remaining components of the basic device have progressed according to plan, as described in chapters 2 to 4. The assembly of the stellarator device and the development of the related technologies have made at lot of progress (chapter 5). The efficient work of the divisions "Engineering" (chapter 6) and "Design and Configuration" (chapter 7) is the backbone of the project. Development and construction of heating systems (chapter 8), diagnostics developments (chapter 9) and control systems (chapter 10) have continued as planned. The Wendelstein 7-X device consists of five identical modules (labelled M1 to M5), each of them consisting of two flip-symmetric half-modules.

Quality Management

The Quality Management (QM) department reports directly to the project director via the associate director coordination. The department organises the QM system within the project W7-X and supports the supervision of all external contractors. It has taken over responsibilities for quality assurance during the assembly phase of Wendelstein 7-X. At the end of 2012 the QM system of Wendelstein 7-X has been recertified by the TÜV NORD CERT according to the DIN EN ISO 9001 for the "construction and commissioning of Wendelstein 7-X". The certificate is now valid till 2016. TÜV NORD CERT acknowledged a further improvement of the QM system and the appropriate ability of the project to react to new requirements.

Project Coordination

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

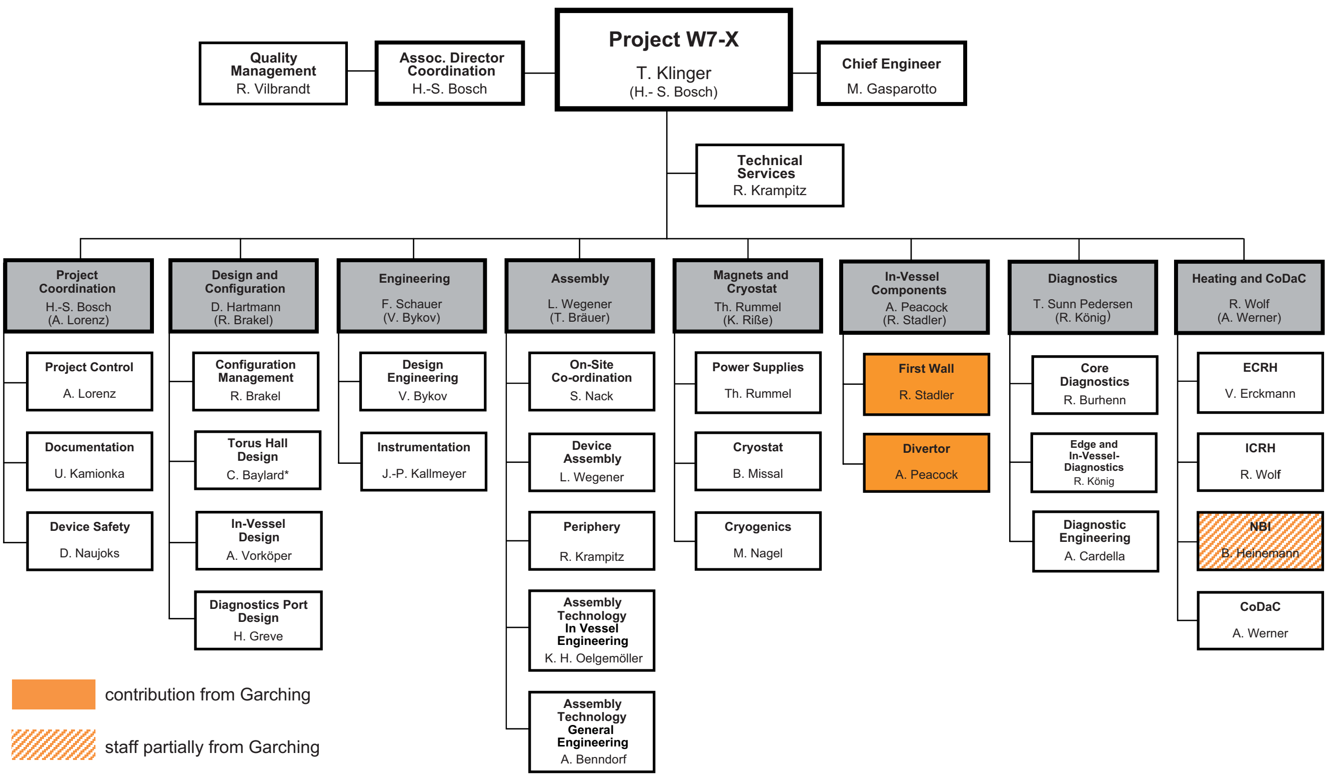

Figure 1: Organigramme of Wendelstein 7-X project as of 31.12.2012.

The department monitors and co-ordinates component delivery and assembly schedules, supports the component responsible officers in the handling of industry contracts; it deals with organisational aspects of the project and is responsible for the reporting to all external supervising bodies, especially the supervising body of the financing institutions (Project Council). The department is using a large variety of planning and controlling tools to co-ordinate and to control the Wendelstein 7-X project progress. Since 2011 the Integrated Planning Tool (IPT), developed up to the end of 2009, is in use. As of now the IPT is the routine tool for the responsible officers, their supervisors, but also for the financial reporting to both the management and the supervising bodies. The concept of establishing links between all sub-projects in a stable and reliable way has been extended in 2012. 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. The documentation department (PC-DO) is responsible for an independent check of all technical drawings and CAD-models and for archiving all documents relevant to the project. An electronic documentation system (now ORACLE-PLM) is used for archiving documents and CAD models (in CADDS5- as well as in CATIA v5-format). All the models in the archive are imaged into a working directory of all W7-X models, the so-called "Wendelstein 7-X assembly". The device safety department (PC-DS) plans, implements and leads the processes that are required to ensure safe operation of the Wendelstein 7-X device. The department participates in the Task Forces "Heat Loads on In-Vessel-Components" and "Wendelstein 7-X Commissioning" established 2011 and 2012, respectively. In 2012, further 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.

Schedule

The time schedule of the co-called "scenario 3" (developed in fall 2007) was the reference plan in 2012 (as the years before). All milestones scheduled in 2012 have been achieved. The port assembly turned out to require more time than foreseen. However, this did not result in any delay to the assembly end date. In 2012, the assembly of the in-vessel components and the diagnostics inside the plasma vessel started, and these processes turned out to require much more time for preparation and for some of the assembly steps. Counter measures are being developed to keep the completion date of Wendelstein 7-X in fall 2014. By the end of 2012, all five magnet modules were installed in their respective cryostat vessel modules. In the first four modules, all ports have been welded; in the last module this process is almost finished. The first three module separation planes have been connected, closing of the last modules separations planes has begun. The detailed planning of assembly packages for the peripheral installations such as supply systems, diagnostics and heating systems has been continued.

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 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. These five trim coils will be located at the outer side of the cryostat and have a relative small cross section but a size of 3.6 m × 3.3 m and 2.8 m × 2 m, respectively.

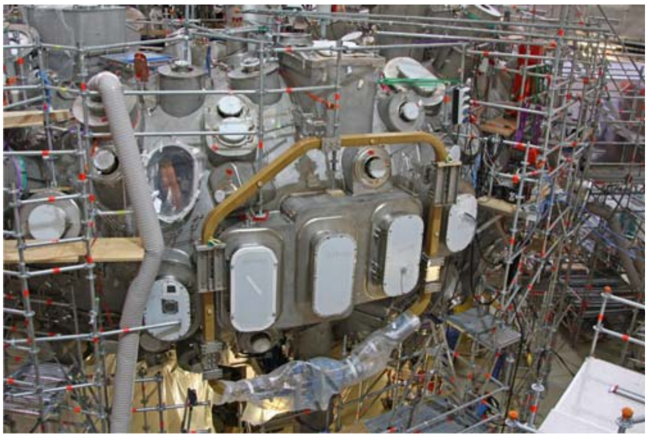

Figure 2: First trim coil of type A installed in module 5.

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 three years grant to participate in the stellarator research at IPP. PPPL contributes in-kind the five trim coils with their power supplies. The manufacturing contract for the coils was awarded to Everson Tesla Inc. (ETI) in Pennsylvania, USA. After procuring the manufacturing tools, materials and conductor, the manufacturing of the first coil started in February 2012. PPPL procured and preassembled the coil service components, which were finally assembly by ETI. The first coil arrived as planned at the end of June 2012. The remaining 3 type A coils were

delivered in August and October 2012. The winding of the B coil started end of 2012 and the delivery is scheduled for February 2013. PPPL has developed an electronic system, which evaluates the sensor and voltage signals coming from the coils. IPP designed and procured the coil supports, which are divided into two parts. Part one is welded onto the outer vessel, part two clamps the coil with a kind of bracket. Until 2012 all clamps were delivered within the required quality. The first trim coil was assembled on the outer cryostat vessel of Wendelstein 7-X in October 2012 (figure 2).
The five trim coils will be supplied with electrical current by five power supplies with maximum ratings of 230 Volt and 2200 Amps. The power supplies are another in-kind-contribution of PPPL to Wendelstein 7-X, whereas the auxiliary systems like input transformer, water cooling system, high power cables and the control system, are in the responsibility of IPP. In 2012 the final requirements of the power supplies were agreed. The tender action has been conducted for the manufacturing and the test of the power supplies The company American Power Systems (APS) in Hicksville, USA, has been selected as contractor. APS has developed the detailed design of the power supplies and production has started after a successful final design review. The first power supply is planned to be tested in June 2013. IPP has started the procurement of the 200 KVA input transformer and the switching units as well as the design of the water cooling system.

2.1.2 Coil Support Structure and Cryo Legs

The support of the magnet system consists of the central support ring, the inter coil supports and the cryo legs. The central support ring consists of ten identical sectors (half-modules) with a total weight of 72 t. It is made from steel plates, cast flanges and cast extensions, which are welded to a half module.

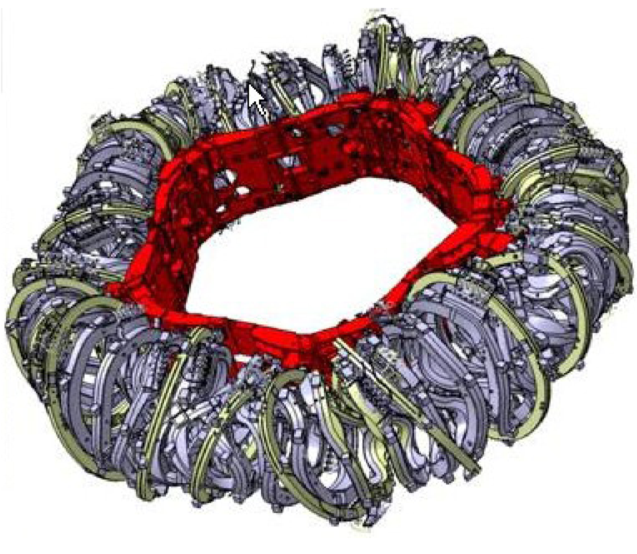

Figure 3: Schema of central support ring complete.

During assembly of the five magnet modules, in each case two half-modules have been connected (bolted) to a module. For the assembly of the modules to a ring, connection elements at the module flange are necessary. These connection elements are composed of several 3-D shims, diamond foils and special bolts. They are to adjust the assembly tolerances and to avoid movement during the operation. Special measurement tools were developed for the fabrication of the shims; three out of the five connections were measured in 2011. In 2012 the remaining associated shims were final-machined and the last two ring modules were assembled to a complete central support ring. Also all different types of support elements like narrow support elements (NSE), lateral support elements (LSE), planar support elements (PSE), contact elements (CE) and lateral support elements (LSE) were completely assembled in 2012.

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, these two vessels create a cryostat, keeping the magnet system at cryogenic temperature. It constitutes the boundary between the Wendelstein 7-X basic device and the external environment. The 254 ports give access to the plasma vessel for diagnostics, plasma heating and supply lines. The vessels and the ports are equipped with a thermal insulation to protect the cryogenic components from the heat load of the warm environment. MAN Diesel & Turbo (MAN-DT), Germany, is responsible for the manufacturing and partly 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; meanwhile the installation of the superconducting coils and the thermal insulation has been completed as well. In end of 2012 four (of five) module connections were welded together. All 15 vertical supports of the plasma vessel have been assembled (welded) successfully in 2011. The installation of the first horizontal support/centring system was finished in 2012.

2.2.2 Outer Vessel

The outer vessel is designed as a torus with an outer diameter of approximately 16 m. The internal diameter of the cross section is 4.4 m. It is made of austenitic steel 1.4429, the same material as the plasma vessel. The nominal wall thickness of the shell is 25 mm. Also the outer vessel is made of five modules; each module 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 were delivered to IPP and upper and lower shells were welded. Until the end of 2012, four out of five module connections were welded together.

2.2.3 Ports

A total of 254 ports are used to evacuate the plasma vessel, to give access for plasma diagnostics and heating, and to connect supply lines and sensor cables. The cross sections of the ports range between 100 mm circular up to 400×1000 mm^2 square. The ports are equipped with bellows to compensate deformations and displacements of the plasma vessel with respect to the outer vessel. All ports are surrounded by water pipes in the bellow-area to control their temperature. The ports and their fixing tools were delivered already until 2007. At some special ports, additional copper stripes between cooling pipes and ports where installed for a better heat transfer. The routing of water pipes in the bellow area has been corrected in all modules. Because of a misalignment of some ports, an enlargement of dome plates was necessary in a few cases. The very difficult space situation required changes in the assembly procedure of the two NBI heating ports AEK-v2 and consequently several reworks of the ports. One port was completely assembled in 2011; the second in the beginning of 2012. Because of increased vacuum requirements, new feed-throughs for sensor cables had to be provided. After detailed a qualification program, all 120 feed-throughs have been ordered and tested and the assembly has been started. To generate ultra high vacuum conditions inside, the bellows have to be electrical heated up to 150°C. The design of the insulation and the heating mats and first assembly tests started in 2012.

2.2.4 Exhaust Gas System

To avoid overpressure in the plasma vessel, safety valves (rupture disc flanges) and a piping system to bring the gas outside the torus hall where designed. The outer vessel is equipped with pressure caps to avoid overpressure. To avoid human hazard by the gas, exhaust gas chimneys were designed. The preparation of the technical specifications of several components has been started. The procurement will start in 2013.

2.2.5 Quench Gas Exhaust System

Helium gas is released by the cryo pipes in case of a malfunction (e.g. in case of a quench of a superconducting coil or loss of vacuum). It is guided to the outside the cryostat via quench pipes. The gas is collected in a ring manifold outside the cryostat and then transported to the gas storage tanks. In the 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. The boundary conditions for the design of the quench gas exhaust system were reworked and the conceptual design was started. The work package is split in two parts to accelerate the design progress. Part one consists of the fitting group with valves, burst discs and safety valves. The fitting group is directly connected to the pipes coming out of the cryostat. Also the ring manifold and the connection pipe to the quench pipe system of the refrigerator belong to the first part. Part two consist of additional safety lines with burst discs and safety valves and seven chimneys that guide the expulsed helium flow in the desired direction within the torus hall. The conceptual design was finished for part one and a design review was conducted. Under specification are now the detailed design of the system, the preparation of the manufacturing drawings, the fabrication and the testing of preassembled parts ready for installation. The call for tender will be launched in the first quarter of 2013. The design work on part two has already started.

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. The fabrication was finished for the port shields of the last module. In 2012 the port shield installation was done for the three last modules. In a next step, the closing of the cryostat at the module separation planes has been started. In close coordination with the installation of the stainless steel adjustment rings, the thermal insulation was applied on the adjustment rings at the outer vessel and plasma vessel. Then the port installation at the corresponding module was carried out. Also the two upper dome shields at the module separation planes were insulated. All three work packages were carried out for three module separation planes. Also the insulation of the adjustment ring at the outer vessel and plasma vessel was carried out for the 4th separation plane. A mock-up for the insulation of the current lead dome for the planar coils was done, similar to the setup for the non-planar current lead-dome. An adaption of the insulation and assembly concept was required, because the access for installation of the insulation is very much restricted in this configuration. The thermal shield has to be installed first before the corresponding segments of the planar current lead-dome can be installed. This requires a special support concept for the thermal shield.

The test was carried out successfully with a scale 1:1 mock-up together with the assembly sub-division and MAN-DT. The design of the thermal insulation was then confirmed and the corresponding CAD models were provided by MAN-DT. A collision control has been carried out by IPP for four modules. The model for one module needs to be checked still.

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 bottom. In total 14 current leads are needed. The production and the tests are being performed by the Karlsruhe Institute of Technology (KIT). In 2012 significant progress has been achieved in the production as well as in testing. A stable production process has been established, accompanied by a suitable quality management system. The production of all 14 series current leads and the two prototypes has been finished in October 2012.

Figure 4: Current leads during the production at KIT.

By the end of 2012, in total 12 current leads have been finally tested under cryogenic conditions. In each test campaign, two current leads are 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. This demonstrates the correct behavior of the electrical insulation. In 2012 the two prototypes and seven series current leads have been delivered to IPP.

2.3.1 Current Leads Mechanical Support

Mechanical supports of current leads are needed to support the current leads at the section between warm and cold side with all the allowable movements arising from the operation. Simultaneously, they are needed to support the bus system up to the central support ring. The mechanical supports consist of the following main parts: domes, which are subdivided into three sections, two bellows to allow movements of the current leads and a support plate in the bottom, the lower supports, which connect the support plate with the domes, the fixing box with the bearings for the current leads, and the horizontal rods to connect the central support ring with the fixing box. All parts have been delivered until end of 2012.

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 have been carried out. The Helium gas inventory was replenished to be able to continue with the commissioning and acceptance test activities. In order to avoid oscillations in pressures and mass flows, Linde Kryotechnik AG (LKT) has introduced convection blocks along the stems for altogether 26 valves (20 control valves and 6 hand valves) located on subcooler box and magnet valve box. After solving this problem, the commissioning of the cold compressors was continued. The acceptance tests have been started, based on corresponding test procedures. The test of the two cold adsorbers was completed. The tests of the four operation modes began with long standby mode (=100 K) and short standby modes (=10 K) for various sub-tests defined for each of these modes, including the regeneration cycle for divertor cryo-vacuum pumps and thermal shield baking at 150 °C. Later began the most critical tests for standard mode (=3.9 K) and peak power mode (=3.4 K), during which the operation of cold circulators and cold compressors were necessary. The mode tests were carried out with and without liquid nitrogen precooling. There were no problems observed. For the cool-down and warm-up test, it was observed that all the consumer circuits were cooled down and warmed up more or less simultaneously. While cooling down it was found that some adjustments with the mass flow would be required for the given cooling power. The test will be repeated by LKT. The warm-up was achieved within the predefined period.

The simultaneous purification of helium together with warm-up was achieved by operating a heat exchanger downstream at relatively higher temperatures. Purification of helium with consumers being at warm condition is still to be demonstrated by LKT. The change of mode test was demonstrated for all modes. For the short standby to peak power mode change, however, the results have to be evaluated. The reaction of the system after alarm and trip signals were demonstrated to be reasonable, some of the failure signals are to be tested. The refrigerator contract is approaching the end with most of the tests completed. The remaining few tests and open items are planned to be finished within first quarter of 2013.

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 in 2005. In order to prepare the system for the operation phase of Wendelstein 7-X, several tests campaigns have been made. To allow a steady state test operation, the room temperature bus bars have been connected together, forming an electrical short circuit. This provides a realistic load circuit in terms of the resistances with respect to the Wendelstein 7-X load. First, the seven power supplies have been operating in test campaigns of several hours at different currents up to the nominal current. Later, a test over 24 hours at nominal current has been performed without problems. During the operation of Wendelstein 7-X it is planned to operate the superconducting magnet system continuously five days a week. Therefore the test duration has been enlarged, reaching finally 100 hours steady state operation at currents, which represents 2.5 Tesla on the magnetic axis.

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 order to provide a redundancy in the quench detection, it was decided to install a back-up quench detection system. It runs in parallel to the original system, but as an additional feature it allows one to detect symmetric quenches in adjacent double layers of the coils. Due to a slightly different cabling concept, the number of necessary units is less than foreseen in the original quench detection system. In total 560 quench detection units are necessary. The quench detection units will be put into 10 so-called subsystems. One subsystem contains up to 64 quench detection units and is equipped with an internal AC/DC power supply combined with an uninterruptible power supply to secure the independent operation of the subsystem. For control and data acquisition an internal controller is installed to evaluate and to transmit the quench signals to the magnet safety system and to allow 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 production of the two interface racks has been finished in 2012. The quench detection system will be controlled by a central control station, which 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 started, a concept has been developed and a first prototype has been built.

4 In-vessel Components

The in-vessel components (IVCs) consisting of the divertor components (target, baffles, and toroidal closure plates), plasma vessel protection (panels and heat shields), control coils, cryo-pumps, port protection and special port liners for the different heating systems together with the complex system of cooling water supply lines continued their detailed design and fabrication in 2012. In particular, the detailed design of the high heat flux divertor continued. The design of the modules of the high iota tail of the divertor was completed with a successful design review and the design of the vertical target modules was started. 2012 also saw the delivery of over 80 % of the 2500 large KiP components for Operational Phase 1 to Greifswald.

4.1 Target Elements

The main building blocks of the high heat flux (HHF) divertor are the 890 target elements being manufactured by Plansee SE. These HHF divertor elements consist of 8 mm thick carbon fibre 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. The contract with Plansee SE foresees the delivery of the elements in two main phases. All of the 282 first phase elements were delivered to IPP in 2011. In 2012 deliveries the second phase elements began with 80 elements being delivered and tested at IPP. One of these elements is shown in figure 5.

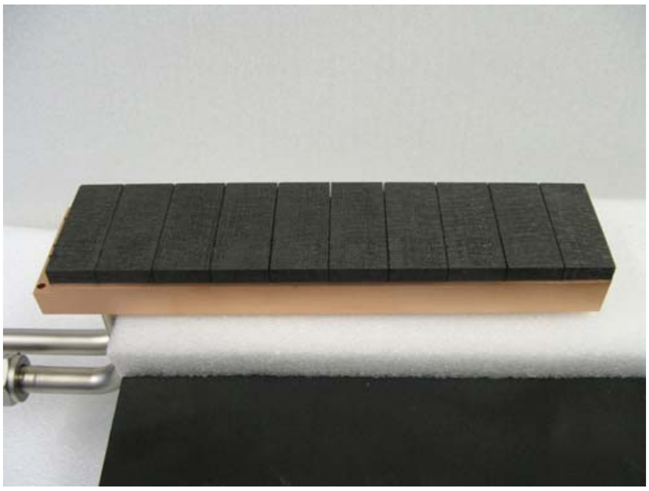

Figure 5: Delivered Element 2012, Type 4B.

All the tests showed that the elements were within the specification. This includes the testing in the GLADIS high heat flux facility. Results from GLADIS are shown in section 5 of this report. The elements in the second phase use a modified procedure to produce the gap between tiles. This uses machine shaped tiles instead of cutting the tiles after the tiles have been jointed to the element. This gives a smaller gap, typically 0.4 mm instead of 0.8 mm and more importantly significantly reduced the failure rate of this manufacturing step. The uniform gap can be seen in figure 5. Production of the remaining elements continues at Plansee with further deliveries expected in 2013 and the final delivery expected in the middle of 2014.

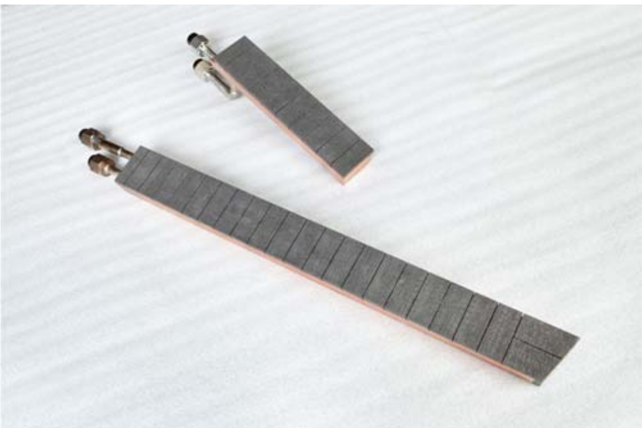

Figure 6: Different element types ranging from the smallest to the largest.

The remaining target elements to be delivered in the second phase of the Plansee contract are longer and in some cases wider than the first phase elements and also have additional tiles on one end of the element, which means that they are more complicated to manufacture and to test. As part of the BMBF funded development programme a number of open issues concerning these elements were addressed and solutions developed. Part of the outcome of the development programme was the qualification of a repair process for the end tiles of the longer elements. The results indicated that the repaired end tiles meet the specification but were not as robust as the original tiles. The range of elements being produced is shown in the figure 6.

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 Wendelstein 7-X machine. For each divertor unit there are 10 such modules. In parallel to the design of the modules TMh7, TMh8 and TMh9, a prototype module of the type TMh9 was produced to demonstrate that the designed modules could be manufactured with the required accuracy and performance. Lessons learnt from the manufacturing process were then fed into the design to reduce costs and manufacturing time. The prototype module was successfully tested under similar conditions to those experienced in operation, i.e. the prototype module was conceived to be tested in GLADIS. No problems were identified during this testing, which also acted as a qualification of the testing procedure for the prototype module. It is planned to test one of the ten series modules of each type in GLADIS. The prototype module was made from prototype elements used for the development of the CuCrZr/CFC joining technology. The use of the prototype elements meant that only the horizontal target module TMh9 (with 12 elements) could be produced since other modules require other types of elements. The complex 3D plasma facing surface of the target modules was also replicated in the prototype module. The prototype module relied heavily on the experience gained during the manufacture of the in-vessel pipe work for the manufacture of the water manifolds and the pipe welding. Since the elements deform under thermal load thermal stresses build up in the module, which have to be allowed for in the design. Bellows were investigated to allow this movement but the resulting water pressure stresses were difficult to resist. The final solution with the long pipes has sufficient flexibility within the pipes to allow for the movements of the elements without causing too high stresses in the sensitive transition where the copper element is joined to the stainless steel pipe work. In parallel to the prototype module production finite element (FE) calculations with a complete model of the module were performed to ensure that there would be no systematic problems with this geometry under the geometric load conditions expected in the W7-X machine. Based on the design progress, the FE calculations and the results of the testing programme a design review was held in 2012. The design of the modules TMh7, TMh8 and TMh9 was accepted and in 2012 the manufacture of these target modules was started.

Since there was still manufacturing of the KiP components going on in the IPP Garching workshops for the first operational phase this work had low priority but will start fully in 2013.

4.3 Test Divertor Unit (TDU)

The interim solution for the Divertor during the first phase of machine operation is the TDU. This has the same geometry as the HHF divertor, which will be installed later but uses inertially cooled graphite tiles instead of water cooled HHF elements. During 2012 the assembly of the modules TMh7-TMh9 was completed. The entire TDU was delivered to Greifswald in 2012 ready for installation. The TDU has been built by IPP Garching and Greifswald in co-operation with external companies.

4.4 Baffle Modules

The design and manufacture of the remaining baffle modules continued in 2012 and by November the whole set of horizontal baffle modules had been completed and were sent to Greifswald. The last vertical baffle modules to be designed are geometrically more complex than the earlier modules. Manufacture of the baffles continued during 2012 and at the end of the year 150 of the 170 Baffle modules had been manufactured by the IPP workshop in Garching. The graphite tiles and the associated TZM screws, which cover the baffle modules are procured externally and the contracts for graphite tile procurement run in parallel to the manufacture of the modules. All graphite and TZM deliveries from external firms were completed in 2012. Figure 7 shows a baffle module of type 7v with a complex geometrical form.

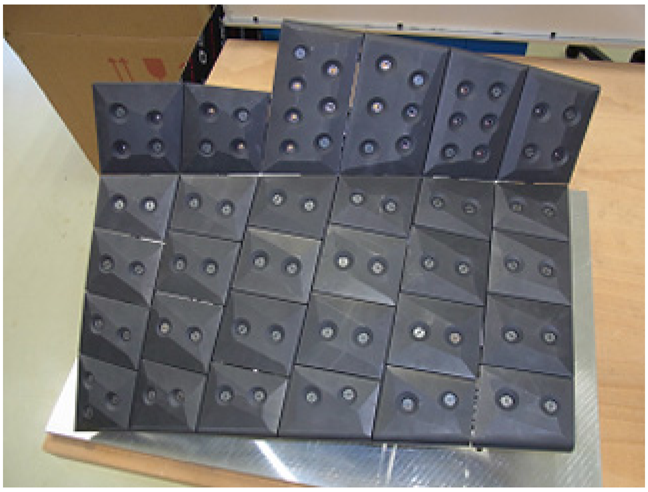

Figure 7: Baffle module Type 7v with graphite tiles showing complex 3-D form.

Close to the baffle modules are the Toroidal Divertor Closure (TDC) plates. These components are used to close the divertor volume and protect the area behind the divertor. Initially it was intended to install these components at a later stage of the IVC installation but the installation sequence was modified and an earlier delivery date was needed. This meant that the manufacturing sequence had to be changed and it was necessary to initially complete 2 of the 10 units early. Subsequently the remaining TDC units were finished and delivered. The design and manufacture of these components was completed during 2012 and the components were sent to IPP Greifswald. These components use baffle technology.

4.5 Wall Protection

Apart from the divertor the IVCs consist of double walled stainless steel panels (covering approx 70 m^2 of the inside of the plasma vessel) and heat shields (covering approx 50 m^2) consisting of water cooled copper plates coated with graphite tiles (similar to the baffles). The delivery of the panels to IPP Garching was completed by MAN-DT including six modified panels for the Neutral Beam (NBI) shine-through area in 2011. The testing of these panels was completed in 2012 and the complete set of panels delivered to IPP Greifswald. In the region of the NBI shine-through the panels were reduced in size as there was a concern that the beam could damage the previously designed stainless steel panels. In this region the heat shields were extended. The design of the heat shields also integrates several plasma diagnostic components as well as mirrors for ECRH heating. By the end of 2012 all of the 162 heat shields cooling structures had been fabricated in the IPP workshops. The procurement of the graphite tiles was also completed. 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. For resource reasons, the manufacture of the port protection panels has been postponed to a later date. Nevertheless, a limited amount of design effort of these protection elements was continued to fix their interfaces and define the routing of the cooling water lines. Since the space behind the wall protection is very restricted, all port protection panels will be later supplied with water from outside. In addition a few port protection panels have been manufactured especially for those regions that will be relatively highly loaded during the first phase. The ports, through which the neutral beams will shine as well as the port for the diagnostic injector need to be protected against energetic particles by CFC and graphite tiles from the beginning of operation. The design work for these port protections is completed, the manufacturing drawings have been prepared and the components were manufactured. Due to the limited space available within the port, scan data was taken of the port to ensure that the port protection would still fit. Due to some distortion within the port it was necessary to modify the design slightly and to qualify the port assembly process in IPP Garching. The assembled segments of the port protection in a dummy port (without the graphite protection) are shown in figure 8.

Figure 8: Graphite port protection support structure during assembly testing at IPP Garching.

4.6 Cryo-pumps

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

4.7 Control Coils

The control coils are supplied by power supplies, which are able to provide direct currents of up to 2500 A and alternating currents up to 625 A with frequencies between one and 20 Hertz in parallel. In 2012 the test operation of ten power supplies were continued by using dummy loads. The power supplies were operated up to the maximum direct and alternating current several times to check the electrical and thermal performance. Also the quality of the closed loop controller was checked and adjusted.

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 ports. These plug-ins consist of a flange, through which welded tubes are mounted to allow water to reach the components and to take the water out. There are eight different types of plug-ins depending on the port they are going through and the components they are supplying. Some plug-ins carry water for components that will take part in the “hot liner” experiments and calculations have shown that in one case, i.e. for the AER port plug-in, additional thermal shielding is necessary to avoid overheating of the port wall by radiation from the hot tubes. All 80 plug-ins have been completed and delivered to IPP Greifswald by the end of 2012.

4.9 Water Supply Lines inside the Plasma Vessel

The cooling supply lines of the in-vessel components run from the plug-ins to a complicated system of manifolds and pipes, which deliver water to the various components via flanges. The manufacture of the pipe work was completed in 2012. In total 308 cooling circuits are foreseen. In OP1 26 cooling circuits will be completed and filled with water. The panels and the heat shields will have their pipework fully welded in OP1 but will not be filled with water as this is not necessary during OP1. However the panel circuits will be filled with inert gas to provide some thermal conduction inside the panels avoiding 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 and to check this software from Flowmaster has been used, which allows the flow in the different cooling circuits to be calculated based on the measured pressure drop in the individual components, also taking into account the pipe work pressure drop. These calculations were also necessary due to the large number of different geometries, which occur as a consequence of local geometry variations. Through the use of this and other calculation methods it was found necessary at a number of locations to build into the cooling system restrictions to balance the water flow. These restrictions were tested at IPP Garching and delivered separately to IPP Greifswald to be introduced into the cooling circuits on installation.

4.10 Glow Discharge System

Each glow discharge electrode is supplied by a separate power supply delivering a voltage of up to 3 kV and a current of up to 3 A. The power supplies have to be combined in one system with one central control unit. The contract for the development, production and test of the power supply system was awarded to the company Puls Plasmatechnik. The whole system was produced, delivered to IPP and finally tested. In 2012 the components were ready for installation at IPP Greifswald. Some final design modification was necessary to limit the effect of ECRH stray radiation.

5 Assembly

In 2012 the qualification and procurement of assembly equipment, and extensive assembly trials have been continued. All magnet modules are completely connected with each other – mechanically, hydraulically and electrically. The associated components of the helium pipe-work and the superconducting bus bar system are accomplished as well.

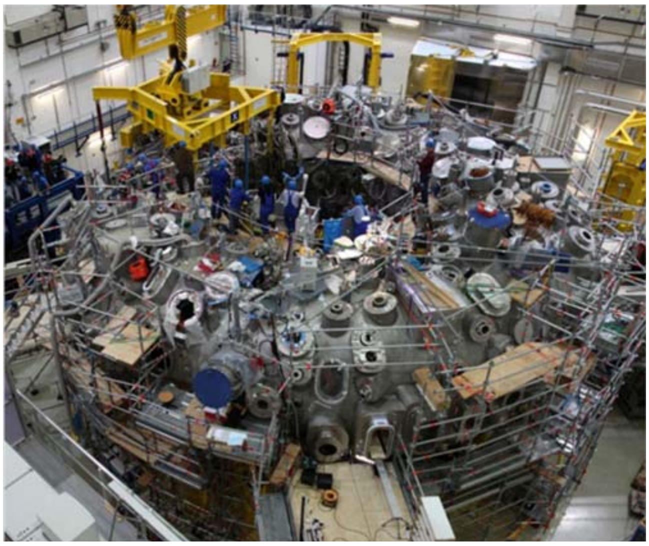

Figure 9: The cryostat of W7-X is closed.

All temporary supports have been removed from the magnet system. The position and the geometrical contour remained within the pre-calculated accuracies. All modules of the outer vessel (cryostat) are assembled; four of them are already welded together (figure 9). 242 out of 254 ports were installed and welded. The technology for the installation of the current leads (CL) was completed and the associated assembly equipment procured. This very challenging development program lasted for about five years, with interruptions. The assembly technology for the in-vessel components (KiP technology) together with the embedded magnetic diagnostics was the second main task in the technology development. In parallel, the assembly of the KiP components was started with at the same time in two modules. The planning and specification of the periphery (installation of feed throughs, cables, pipes, bus bars, platforms and support structures in the torus hall) together with the vacuum systems and cooling systems formed the third main work package. The first installations were continued in 2012. Further comprehensive procurement contracts for the associated periphery-components were launched. The work organisation, the planning and the assembly personnel were noticeably adapted to the changing work-packages. Both the assembly planning and the technology had to work at their capacity limits to cope with the integration of the development programs in the ongoing works and with the start of new work packages. The assistance and service for other divisions of the project were increased. The cooperation with the IFJ in Krakow was successfully finalized with the completion of the superconducting bus bar system at the end of 2012.

5.1 Bus Bar System

In conjunction with the completion of the assembly of the magnet system the last joints between adjacent superconductor bus bars were installed and tested. The works ran routinely as before. However, the associated Paschen tests were organisationally challenging since helium pressurization and the high-voltage application are being more and more complex with the number of connected modules. Development works for the mechanical and electrical connection of bus bars and CL were continued or done. During the assembly the 250 kg CL has to hang at the magnet system in the interior of the cryostat. That enables the assembly of the surrounding CL-dome to the outer vessel, which will carry the CL's deadweight after the assembly. Temporary assembly bearings, bus bar ends, helium pipes and ports hamper these assembly works. A 300 kg dome-section is threaded across the CL once the CL has been connected with both the bus bar and the helium pipe work at its so-called cold end. Thereafter the dome is welded to the outer vessel and two more dome sections are supplemented. At the end a pendulum support is mounted at the bottom end of the dome arrangement and the CL's deadweight is transferred from the suspension in the inside of the cryostat to the outer support. The position accuracy during welding must stay within a few tenths of a millimetre. That avoids clashes between CL and dome at the narrow at their bottom end, which lies 2,5 m away. The opening in the outer vessel must be customized accurately according to the as-built contour of the dome. The dome must be cut to length and shape according to the customized contour of the opening. That causes several weeks of manual work but guarantees a precise welding process. Optimization of the weld fusion-zone, heat control, CO_2-quenching and peening are used in a similar way as it was done at the precise port welding. Two extensive 1:1 mock-ups were used to qualify this technology. The procedures require many auxiliary tools and rigs. The handling and alignment of CL and dome-sections require metrology assistance and a special tool (ramp), which is similar to the one used at the port assembly. This ramp was delivered by Fantini Sud and successfully made ready for use. In two modules a double pair of CLs is to be assembled (seven pairs of CLs in five modules in total). Here the assembly space inside the cryostat is even more crowded. Solutions for an appropriate assembly technology still have to be found. The first part of the installation of the first pair of CLs ran smoothly (figure 10). The tools functioned as qualified and the accuracies lay within the given tolerances of less than 2 mm. The first dome-weld will be made in spring 2013.

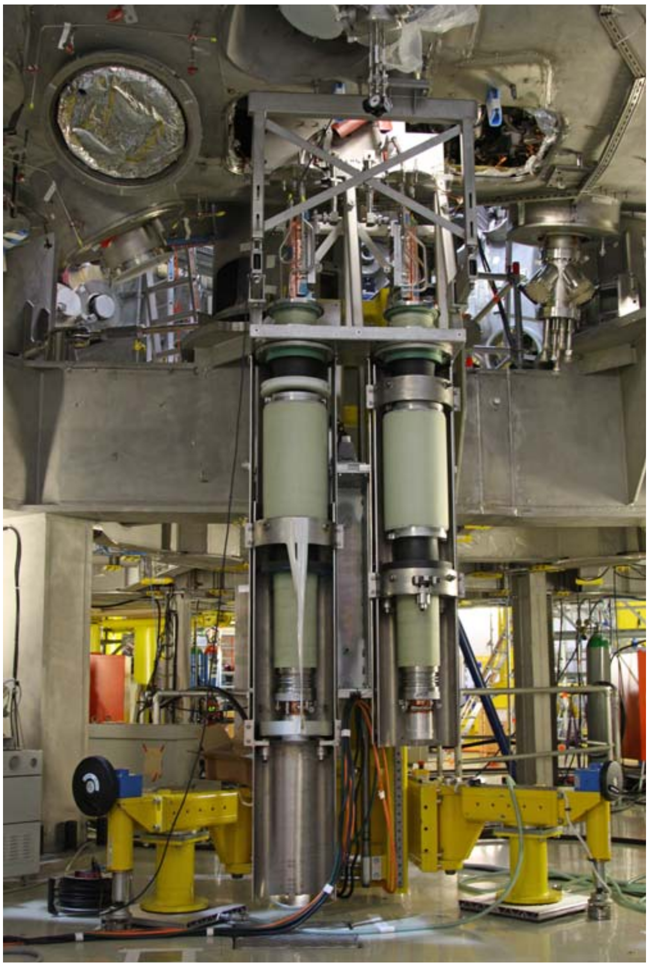

Figure 10: The assembly of the first CL.

However, the process time needed is longer than originally planned. The design of the CL-joint, which is clamped at the CL's cold-end was modified in 2012. The use of solder and flux between SC-strands and inner copper profiles was optimized. The compression was increased during both the soldering process of the strands and the welding process of the joint housing. A first specimen of this design worked as expected during a 4K test at the Efremov Institute. A second specimen is tested at the moment. In contrast to this there are still discrepancies with test results of the KIT in Karlsruhe. The reasons are investigated further.

5.2 Vacuum Technology

The work packages of the vacuum technology group in 2012 were continued as in the years before. An additional leak test tank was set up to support the increasing scope for tests of diagnostics. Main tasks were: leak detection at single components and Paschen tests at components of the magnet system. Particularly tests at the magnet system require that the associated pipe work is being filled and pressurized with helium and high voltage is put on all electrically connected components. That hampers all work around the machine where modules are already connected. A comprehensive work planning, intensive use of the third shift and a strict surveillance of given goels does mitigate the progress risk in this situation. The design of local test chambers as well as the qualification of the practise was continued. Design works on the vacuum systems were finalized, the contracts for nearly all main components were placed and first components have already been delivered and installed. Conceptual designs for controls of the three main vacuum systems were done. The associated procurement specifications are being drafted.

5.3 Wendelstein 7-X Assembly

The preparation of all components for the base machine is nearly accomplished. The external preparation area was reduced accordingly. Only the last 12 ports and 7 domes require extensive steel work yet. Started was the preparation of in-vessel components. For that a special cleanliness-area was set up in front of the torus hall and appropriately equipped. In the final assembly the construction work at the magnet system is complete. Only the current leads need to be installed yet. The geometrical accuracy achieved corresponds to the designed values of about 10E-4. The port installation was continued as in the years before and is meanwhile nearly finalized. Special effort was needed for the assembly of the NBI ports (figure 11) since they have to stay in the contour within 2 mm in addition to their already challenging position accuracies.

Figure 11: The NBI port prior to the assembly.

These ports are split in parts, which have to be welded together once they have been positioned in the machine. Some welds were done twice until the accuracy was achieved. The position of some further ports had to be corrected since the geometry of the plasma vessel was too complex at these spots. Correction measures were successfully developed and performed. These repairs, however, took time, for which no reserves were available. Subsequent work packages were organized more in parallel to compensate for it. Three more module separations were closed at both the plasma vessel and the outer vessel. Domes and ports at these spots were assembled as well. The dome welds caused unexpected large sagging at the outer vessel. They were corrected partially but the majority could be let after thorough geometrical checks. First work was done together with MAN-DT to prepare the connection of the last separation of the vessels. Here the vessels must be spread before the splice plates are put in. That compensates for the later weld shrinkage and minimises inadmissible vessel deviations.

Figure 12: 4 KiP assembly: supports are positioned by means of a manipulator.

Highest priority in 2012 was given to the start of the assembly of the KiP. Despite a lot of tests and qualifications several parts and processes had to be corrected or modified during the first installation. Alone the large number of single components is already a challenge. The positioning of hundreds of different bolts and brackets accurately according to given CAD-coordinates in an as-built environment requires a large effort in technological preparation. The manipulator used for the positioning was intensively tested during the first use, and potential for improvements was identified (figure 12). A second manipulator was specified and ordered with these experiences. The customizing of pre-bent pipes inside the vessel had to be practised intensively. Particularly difficult are the uncomfortable work position and the adaptation of complex 3D-bends. Though intensively qualified, the orbital welds inside the vessel proved difficult. Many of these welds have to be made from the inside of the pipe. The welding heads needed have to be extremely small because of the bad accessibility. Minimal deviations in the pipe's geometry or dimensions lead to malfunctions during the welding. Repairs are very time consuming. Meanwhile these processes are optimized. Some parts had to be adapted first before they were ready for installation. The work is organized in two shifts, 88h per week. At the moment the progress is lower than planned. However, learning curve effects are expected as of the second or third module. The KiP works are separated from the port assembly in neighbouring modules. An extensive cleaning (including CO_2 ice-blasting), a separate ventilation system and special gates at the module's entrance secure the clean interior during the KiP assembly.

The installation of the periphery was expanded. The pipe work for vacuum and water cooling in the close up range of two modules is nearly complete. The manpower was enlarged accordingly. Complex and heavy structures for carrying the pipes, cables and diagnostics in the centre of the machine were specified and ordered from Fantini Sud (Heavy Duty Structure HDS and Thomsen Support Structure TSS). That applies also to the central platform in the torus hall, which was ordered from a local firm. The design of cooling-systems has been expanded and optimized and the associated equipment was specified and ordered. The first out of five trim coils was prepared and assembled smoothly and as planned. The technology used for it was deduced from the experiences gained during the assembly of the magnet system (figure 2). The assembly control and the planning worked routinely as before. The advanced weekly and 4-weekly plans are used as standardised tools. The preparation of the assembly documentation (QAAP, work and test instructions) is ongoing. The manpower for these tasks will be extended. The entire manpower planning was refined and the number of staff was adjusted correspondingly. Quality deviations were reliably handled as in the years before. The assembly schedule was slightly updated. However, a comprehensive update will first be made in 2013 based on the experiences of the KiP assembly. The detailed planning for CL, KiP and the periphery was restructured and optimised. The future assembly-works were further concentrated. The assembly organisation was adapted to the new work packages. Again external manpower was included to ensure the partial two-shift-system and extended working times in the assembly. New engineering staff started the work for the development and qualification of technologies for the KiP assembly. Altogether, assembly has reached the planned progress in 2012. However, the launched KiP assembly might be subject to future schedule risks. As in the years before, new assembly technologies were qualified and successfully tested. Special emphasis was put on the assembly technology for CL and KiP. 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 worked stabile and smoothly.

6. Engineering

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

6.1 Design Engineering

Focus of the EN-DE department's work has been shifted from the basic machine design towards fast analyses of nonconformity consequences, determination of deformations as input for collision checks, and toward additional support of assembly with respect to new or changed procedures. An increasing part of the work is also related to analyses of in-vessel components, diagnostics, periphery, preparation for commissioning, exploration of operational limits of the as-built machine, and evaluation of signals expected from the mechanical instrumentation.

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 a finite element (FE) model tree. Starting points are FE global models (GMs) of a complete module including the cryo-legs. Two FE models created with ANSYS and ABAQUS codes, respectively, have been continuously used to deliver input for refined local models of support structures, cracked structure element regions, winding packs, etc. Parametric studies covering all main uncertainties including the variation of the friction factor at bolted contacts as well as as-built gap variations at the narrow coil support elements have been finished. The ABAQUS model was expanded to encompass the complete torus including the machine fundament (figure 13) in order to cover also 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 are being used for model validation. Local models using both finite element and boundary element method were developed in collaboration with LTCalcoli (Italy) applying the sub-modelling technique in order to assess accepted cracks in the welded lateral support elements (LSEs) between the non-planar coils. The prediction of the envelopes of 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 was finalised demonstrating that the predefined number of load cycles is not jeopardised by any of the observed cracks. The updated procedure to fix the cryolegs on the machine base with bolts only was accepted on the basis of a local model of the cryoleg, which was used to simulate the bolting and loading procedures. Machining and assembly of the LSE D06 and shim plates between the module separation planes of the central support ring was closely supervised.

Figure 13: 360° Abaqus GM model of the magnet system including machine base and temporary supports to predict deformations during torus assembly.

6.1.1.2 Electromagnetic Analyses

Analyses have been started to assess the impact of slightly non-symmetric coil deformations originating from the final torus assembly as predicted by the ABAQUS 360° FE model. Work was also initiated to determine consequences of non-symmetric deformations, originating from magnet system parameter uncertainties, on the magnetic field error and corresponding requirements for the trim coils. In addition, the development of electromagnetic in-house software (ELMA, and a method of secondary sources in ANSYS) and of models in the commercial code MAXWELL 3D (figure 14) is on-going. These programs were used to calculate stray fields and field disturbances at the plasma edge induced by components made of permeable material and by current lines in the torus hall.

The models are also continuously employed to predict eddy currents and corresponding EM forces on the plasma vessel and on in-vessel components and diagnostics due to transient events like fast coil discharges or plasma disruptions.

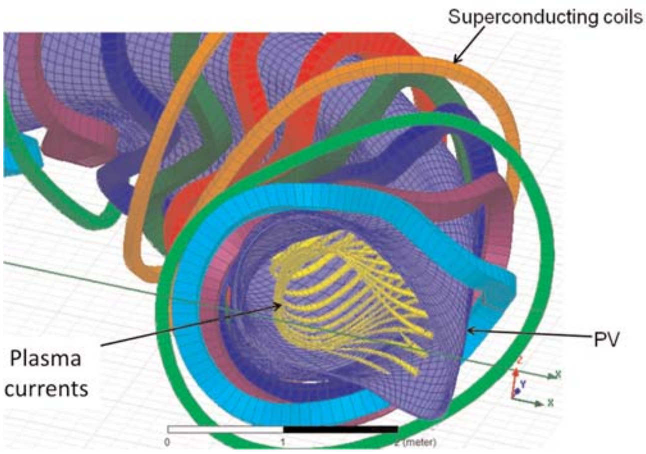

Figure 14: Global electro-magnetic MAXWELL3D model of the PV including the superconducting coils and plasma currents.

6.1.2 Trim Coils

Benchmarking of electromagnetic and thermo-mechanical simulations done by the Princeton Plasma Physics Laboratory was completed (figure 15). The mechanical effect of some design changes of the support structure was shown to be acceptable. Further activities included calculation and optimization of the assembly handling tool, which is used to bring the trim coils into position on the outer vessel whereby the coil deformations have to be kept below allowable limits.

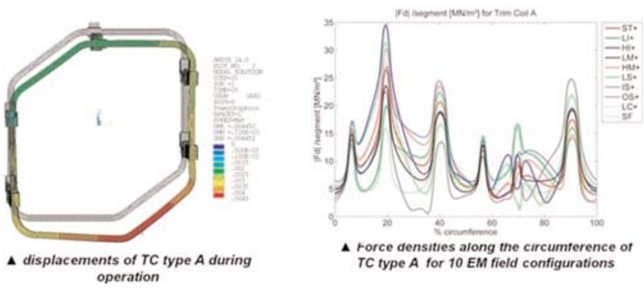

Figure 15: Analysis of trim coil type A. Displacement (left) and forces (right) during different operation scenarios (positive trim coil current for standard, low and high iota, low and high mirror, low shear, inward and outward shift, limiter, and self field).

Another contribution to the trim coil design was the thermo-mechanical non-linear analysis of the winding pack in order to check delamination and local stresses of the turn, pancake and ground insulations. EN-DE defined the pre-stress and tightening procedures of the rubber pads, which are used as cushions to distribute the forces at the clamping supports holding the winding pack. Shear and compression tests were performed on the pads and corresponding re-tightening procedures derived. A fast and simple technique to monitor the pre-stress of the pads during operation was developed.

6.1.3 Cryo-piping

FE-models of the magnet system cooling pipes were updated concerning design modifications near the fixing box in order to provide input for collision checks. The design limits of the potential breakers were defined based on a critical review of test and literature data.

6.1.4 Cryostat

Main application of the ANSYS global model of the cryostat system (GMCS) is to provide input for collision checks, for local analyses of port welds, plasma and outer vessel (PV and OV, resp.) supports, local OV deformations under trim coil loads, port movements, and PV deformations in the location of in-vessel component attachments, etc. In 2012 a new version of the GMCS was created (in collaboration with IGN company, Greifswald) with some 400 modifications as compared to the previous version, taking into account all the design changes during manufacturing and assembly. The model is now easier to handle, and the post-processing capabilities were extended. In an ongoing extensive benchmarking process it was shown that the displacement differences as compared to the previous model version are moderate and acceptable. A procedure was established to define for each port an envelope of relative displacement and tilting over all load cases including plasma vessel sag and required re-adjustment. The results are being used in the design of diagnostics and heating systems within corresponding ports, to assess the reliability of port bellows, to check collisions with the cryo-shield, etc. Further activities in the reporting period concerning the cryostat are listed in the following: (1) Investigation of unloading the PV from the temporary sliding supports to the final pendulum supports has started with the new GMCS. (2) Work continued on evaluation of port tolerance deviations and adaption of dome plates and welds. (3) Thermo-mechanical analyses of closures of the ports, which were skipped in scenario 3 revealed critical loads on the welds in some cases. The design of cover plates to protect those closures from overheating has been supported with design proposals and corresponding FE calculations. (4) Analysis of electrical heating and thermal insulation of port flanges and the contiguous port necks protruding outside the cryostat has been continued with the aim to ensure an adequate temperature distribution during PV and port baking, and to limit the heat loss to the torus hall. (5) Allowable thermal radiation loads on port bellows were specified, and a design proposal was made to monitor the bellows temperature during operation.

6.1.5 In-vessel Components (KIPs)

Analysis activities supporting the design and assembly of KIP components increased further, major examples are listed in the following: (1) EN-DE continued to participate in determining heat loads on the KIPs as well as on the PV and ports due to ECRH radiation and heat radiation from the first wall backside and through its gaps. (2) Gap and step tolerances between wall panels were re-assessed based on the thermo-mechanical behavior of these components under internal pressure, baking and plasma operation. This led to a redesign of the wall panel supports and reconsideration of the positioning strategy in order to allow for larger thermal expansions. (3) A design proposal was made for additional copper shields behind the heat shields for operation phase two (OP2) in order to limit the thermal load onto the PV and diagnostics behind the first wall. (4) Temperatures, thermal stresses and deformations of high heat flux (HHF) divertor module 9 were evaluated for thermal overloads (figure 16).

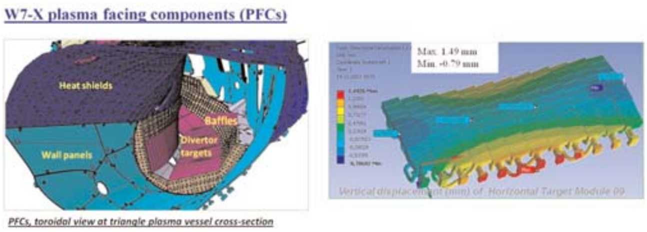

Figure 16: In-vessel component overview (left) and deformation of divertor target module 9 (right).

Module 7 and 8 were assessed by comparison with module 9. (5) Temperatures, thermal stresses and deformations of the baffle and heat shield modules were checked with the result that heat loads onto baffles need to be monitored in OP1. This has to be done to determine any need for modification of the support structure for OP2 such that overloading of the cooling pipe and/or the braze between the pipe and heat sink is avoided. (6) Analysis of convective loads on the divertor and scraper elements as function of magnetic field errors has been performed and benchmarked with results from ORNL (USA). The load redistribution effect of sweep coils was evaluated. (7) The expected surface damage of HHF tiles during machining was considered by an assessment of the damage impact on peak temperatures of the carbon and the cooling structures. Requirements to smoothen the surfaces of some particular damage types were specified.

6.1.6 Diagnostics

Diagnostics, which are exposed 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. Moreover, diagnostics components mainly of copper were checked against eddy current forces caused by fast coil discharges and plasma current decay. Below a list of corresponding tasks is given: (1) Thermal-mechanical simulations of retro-reflectors have been continued with the aim to ensure parallelism of the incoming and outgoing laser beams under reflector deformation. (2) Electromagnetic and mechanical analyses of the diamagnetic loops led to several design changes to cope with electromagnetic forces during fast coil discharges and plasma disruptions. (3) Thermal analyses were carried out on diagnostics that are directly or indirectly exposed to the plasma like the Rogowski and Mirnov coils (figure 17), Langmuir probes, and the soft X-ray multi-camera tomography system. (4) Thermal and mechanical analyses of the port shutter in the AEL port were performed.

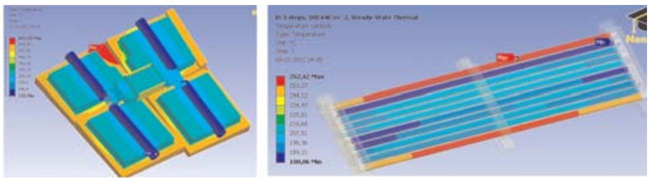

Figure 17: Temperature distributions in Mirnov coil former (left) and Rogowski coil body (right) due to thermal load behind heat shields.

6.1.7 Periphery

Various components in the centre and direct vicinity of the torus were dealt with in 2012. The structural behaviour of the heavy duty structure was analysed, and the results were implemented in the call for tender specification. Also the structural behaviour of the quench gas pipe system and its support structure was calculated. The disturbance effect of increased steel permeability of these structures on the plasma edge field was assessed and found to be acceptable. In addition, electromagnetic and mechanical analyses of the control coil power supply lines including their supports were performed. Finally, heat balance and temperature rise in the torus hall during PV and port baking, normal, and hot liner operation was assessed.

6.2 Instrumentation

The department EN-IN is responsible for the mechanical instrumentation of the magnet system, i.e. measurement of mechanical stresses, strains, forces, deformations and positions. Since 2012 EN-IN is also responsible for the PV sensor data collection (temperature and strain) and for temperature monitoring of the AE- and AF-ports. Main task was the continuation of hardware as well as software implementation for signal sensing, transfer and processing. Development of measurement systems to determine the horizontal loads on the cryo-legs as well as the plasma vessel position has been started.

6.2.1 Sensors

All mechanical sensors within the cryostat were applied and tested. These are approximately 98 % of the mechanical sensors of the whole machine instrumentation. About 0.5 % of them were defective, and in these cases redundant sensors were connected to the vacuum feedthroughs. The strain gauge based system to monitor loads on the cryo-legs was finally applied and set to function. The step by step removal of the temporary magnet system supports, after connection of the respective modules, and the subsequent re-distribution of the weight was successfully monitored. Concerning the plasma vessel position measurement, the development of an extensometer based system has been started. The plasma vessel position, displacements and deformations will be monitored by following the flange movements of the AEU, AFC and AFD ports, which are firmly connected to the plasma vessel without bellows. Extensometers will also be used to monitor the radial movements of the cryo-legs. Work has started on the application of a strain gauge measurement system to monitor the loads on the tie rods fixing the cryo-legs in toroidal direction. This system is similar to that, which was developed for the highly loaded inconel bolts fixing the coils to the central support structure. The technical specification was prepared and released. 25 km torus hall cable to connect the AE and AF temperature sensors from the vacuum feedthroughs at the outer vessel to the corresponding cubicles were tested and ordered. For these and the previously purchased 30 km cables for the mechanical instrumentation the potential fire hazard was determined.

6.2.2 Instrumentation Cubicle

EMI/EMC-tests (electromagnetic interference/compatibility) were performed on the instrumentation cubicle prototype, including the whole measurement chain consisting of sensor, torus hall cable (70 m) and electronics. The torus ground concept was also part of the test. As a result, electronics shielding against radio frequency radiation had to be improved, which was then verified in a subsequent test. The cubicle fulfils now all EMI/EMC requirements with regard to industrial standards, but also concerning the torus hall environment. A technical specification of the cubicle was created and released, its components can be purchased separately and installed in-house. Interfaces for the AE and AF port temperature as well as for the plasma vessel mechanical and temperature sensors were provided. The instrumentation requirements for Wendelstein 7-X commissioning and operation were critically reviewed in order to determine the machine components, which need to be monitored simultaneously in each operational mode and to define the minimal number of the most expensive cubicle components, the signal transducers. This led to a significant cost reduction as compared to the full equipment. Consequently, for some operation conditions the transducers have to be re-plugged to drive and read the corresponding sensors. However, since this has to be done at rare intervals only, it is a negligible operational restriction. Subsequently the electronics was specified and ordered, and part of it is already delivered.

6.3 Reactor Studies

Within the framework of the EFDA "Stellarator engineering scoping studies" (WP12-DAS07) design work on a 5-fold symmetric HELIAS stellarator reactor with on-axis and maximal fields of 5.9 T and 12.5 T, respectively, has continued. The coil geometry was slightly changed corresponding to the latest HSR5/22 version yielding more space between plasma and coils, and this stellarator configuration was named "HELIAS 5-B" (figure 18). The conductor design is, like the one of the ITER toroidal field coil (TFC), based on the superconductor material Nb_3Sn. The current densities and electromagnetic loads per coil are similar in both cases apart from the advantageous fact that the HELIAS coil conductor is exposed to dc fields only. The superconductor behaviour during a quench and subsequent emergency shutdown was re-evaluated, and it was confirmed that the interrelated parameters hot spot temperature, discharge voltage, and switch-off time are less demanding as with the ITER TFC system.

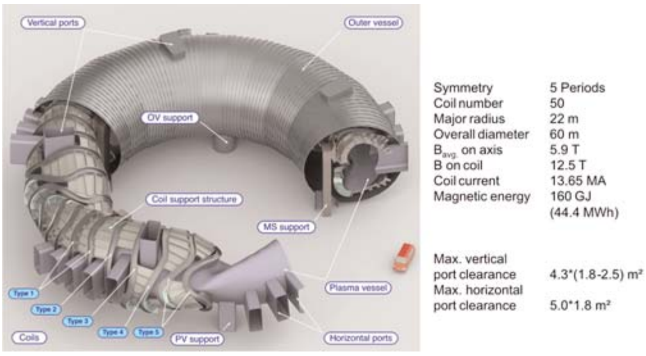

Figure 18: Helias 5-B stellarator reactor overview.

The previously designed building block structure was adapted to the new shapes and forces, and was further optimized for better load distribution and reduced number of joints. Simplified structure panels were introduced with only one or two plates each. In highly loaded areas between the coils two of such panels can now be inserted one on top of the other. The plasma vessel shape was newly created according to the changed coil geometry, and additional mechanical analyses were performed considering the roughly estimated weights of blanket and neutron shield. The large ports were re-arranged to horizontal and vertical orientations only. An additional blanket maintenance concept was devised, which is based on the simultaneous exchange of large segments through five vertical ports. The segments are transported inside the complexly shaped plasma vessel toward these ports by a robot running on rails. Generally, the confidence was further strengthened that a high field HELIAS reactor magnet system and corresponding cryostat could be built with state of the art technology on the ITER level.

7. Design & Configuration

The subdivision “Design & Configuration” provides the configuration management of Wendelstein 7-X, configuration control of the components in the cryostat, the plasma vessel and the components in the experimental area and provides design solutions and fabrications drawings for many components of Wendelstein 7-X. These tasks are taken care of in the four departments “Configuration Management”, “Design in the Torus Hall”, “Design of Port Diagnostics” and “Design of In-vessel Diagnostics”. This department structure is in effect since the beginning of 2011 in response to the near completion of the design activities in the cryostat and the necessity to focus on the design of the peripheral components and of diagnostics essential for the first operational phase of Wendelstein 7-X. This structure maps design areas with, in general, simple geometrical interfaces into areas of design responsibilities in order to ensure proper simultaneous engineering with minimal risk of lengthy iterations. About 60 different projects in the experimental hall require design activities of various extend. The deliverables range from space reservations for components developed, designed and built within the framework of collaborations to concept design and detail design including fabrications drawings for others. In order to ensure that the design activities meet all functional aspects of these projects and are conform to the boundary conditions a 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 matched and adjusted to design solutions. A conceptual design review concludes this activity and freezes the found solution if it has been shown that the major functional requirements and boundary conditions are confirmedly met. After this phase the project is given a conceptual space reservation in the torus hall. This space reservation is then considered during the design of adjacent projects and space conflicts are informally mitigated. During the subsequent 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 space reservation in the torus hall. This space reservation encompasses the actual design space including tolerance areas and additional space needed for minor and major maintenance. The detail design activities finally culminate with the generation of all required fabrication documents and conclude the design.

7.1 Configuration Management

By now the configuration management for system identification, change and deviation management and interface coordination are routinely applied. Currently 958 design change requests are registered in the change data base. 84 % of the requests have been accepted, 5 % are in the decision process and 11 % have either been rejected, withdrawn or became obsolete by revision. 81 % of the accepted change requests have been closed, i.e. the relevant design and assembly documents, computer aided design (CAD) models and drawings have been revised or created according to the change. Highest priority has been given to changes, which may directly affect the progress of Wendelstein 7-X assembly. While in the past interface control had been focused on the components of the W7-X basic device it has recently been extended to the about 60 projects in the Wendelstein 7-X periphery. Thus the Wendelstein 7-X interface matrix increased by 130 additional pairs of components with identified interfaces. The complete matrix now contains about 350 elements, which require a dedicated interface description, 30 % of them already being processed and released.

7.2 Design in the Torus Hall

Within this department design solutions are developed for diagnostics and peripheral components that are predominantly located in the torus hall. In 2012 the guidelines and tools have been further detailed and have now proven to work properly to efficiently and effectively manage and advance the design activities in the torus hall. 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” that 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 solution. The conceptual design that is being developed meets the main elements of the specification, is proven to be integrable in the torus hall, and takes into account further design aspects like manufacturing and maintainability.

After each design step, a final configuration control 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. 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. The department has to cope with a complex set of activities of concurrent engineering and system integration to advance more than 60 projects in various design states and efficiently organize the design activity of 15 designers that operate in the same design volume. To this purpose the department has implemented special tools and procedures (daily CAD data base updates, collision report tools, delivery tools, various exports for communication inside and outside the department, etc.). 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 has been developed, whose interfaces to the other projects are clearly defined and documented further detailing is most often done in other departments or directly by an external supplier. In 2012, a large progress was made in the overall layout of the torus hall: layout principles of major distribution networks (electric, cooling and vacuum distribution) were defined, presented and approved. The preliminary design was performed for the following periphery projects: ground level platform in the torus hall, escape path on the platform, quench gas exhaust system, gas exhaust system (cryostat and plasma vessel), vacuum system (cryostat and plasma vessel including rough vacuum system), the power supplies of trim and control coils, electric distribution system including the cable trays, the grounding systems, the low voltage distribution systems, and the cryo supply line support. The conceptual design has started for the following periphery projects: the fire extinction system, and the cold water system that provides 24 hour cooling water to selected projects. The following diagnostics in the torus hall have been further advanced: the routing of the electron cyclotron emission diagnostic, the conceptual design of the supports of the neutral particle analyzer, the feasibility study of the carbon and oxygen monitor diagnostic, the preliminary and detail design of various components of the Thomson scattering diagnostic, the preliminary design of the one channel interferometer and the conceptual design of the multi-channel interferometer. The best example of an integrated design is the heavy duty structure. This is a multi-purpose support structure in the center of the torus that was conceived, designed and integrated by the department DC-TH to be a central support structure for cooling lines, quench gas exhaust lines, the gas injection system, vacuum lines, the helium transfer lines and further diagnostics. Progress has also been made in the long term activity of positioning and allocating cubicles in the torus hall and the adjacent hall ways. Here, in particular, it was imperative to identify the minimum requirements on functional needs. Figure 19 shows the status of the overall layout and design in the torus hall in summer 2012.

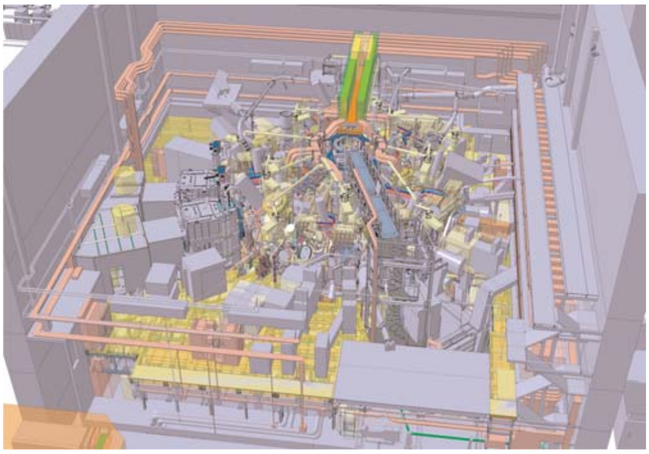

Figure 19: "Torus Hall" – Overview of the layout of the various components in the torus hall.

7.3 Design of Diagnostics in Plasma Vessel Ports

Within this department design solutions are developed for diagnostics whose major part is located in a port. Based on the importance for the first operational phase and the scope of the projects, the design activities of the magnetic flux surface measurement diagnostic, the electron cyclotron diagnostic, the bolometry and the Thomson scattering diagnostic were given the highest priority. By now the principle components of these diagnostics are near completion.

7.4 Design of In-vessel Components

Within this department design solutions are developed for diagnostics that are located in the plasma vessel. In addition, some design work coordinated by the sub-division "components in the plasma vessel" is being performed.

Latter is described separately. Diagnostics that are located in the plasma vessel are the Mirnov coils, the Rogowski coils, the diamagnetic loops, the x-ray multi camera tomography system, bolometer for ECRH stray radiation, the glow discharge electrodes and the plasma video observation. For the most part these diagnostics have to be installed behind the wall panels and behind the baffles. The design of the diagnostics in the plasma vessel is challenging since the space behind the wall panels and baffles is already congested with water cooling pipes and supports. In addition, the high thermal radiation (either directly from the plasma through openings between the wall panels or indirectly from the heated wall panels and baffles) and the ambient stray radiation of electron cyclotron resonance heating require that these components are either actively cooled or are thermally connected to actively cooled structures, e.g. the plasma vessel or the already available water cooling pipes. Thus a number of completed designs were further equipped with shielding structures while still maintaining the sensitivity of the sensors.

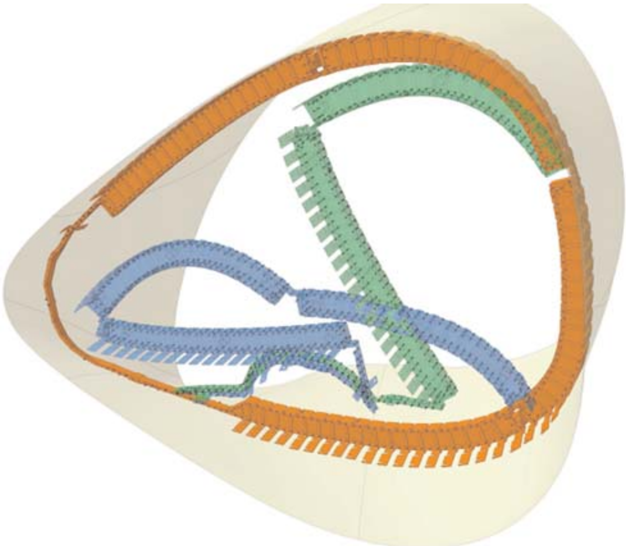

Figure 20: "Diamagnetic Loop" – Vairous stages in the unfolding of the diamagnetic loop and the compensation coils during installation at its location in the plasma vessel.

In 2012 it became apparent that non-negligible poloidal currents are induced in these structures at the time of plasma terminations by the sudden changes in the toroidal plasma currents. These currents together with the ambient static magnetic field lead to forces on the diagnostic and their cable shielding tubes that were approximately normal to the plasma vessel and that exceeded the allowable values. Therefore a number of diagnostics supports had to be redesigned to allow a good thermal contact to the plasma vessel to accommodate the heat loads and to have sufficient rigidity not to deform during a plasma termination. In most cases the number of supports had to be increased. The additionally required space for these supports often required modifications of adjacent components. One diagnostics that was particularly challenging was the diamagnetic coil in the triangular plane. This coil was to be equipped with four additional compensation coils that are designed to correct the signal in the diamagnetic loop for currents induced in the plasma vessel. The diagnostic had to be designed to shield the diamagnetic loop cable insulation against stray radiation of electron cyclotron resonance heating, while still facilitating a sufficiently high time response. The heat load required attachments to the plasma vessel that involve custom made blocks fitted to the scanned plasma vessel surface. The need to simplify the installation in the plasma vessel and to provide safeguard against damages of the most critical parts during installation required a design that could be pre-assembled completely outside the plasma vessel and that could be folded into a compact structure to be transported into the plasma vessel and to its final location. Such a design solution has been found. Various stages in the unfolding process of the loop at the installation location are shown in figure 20 "Diamagnetic Loop".

8 Heating

8.1 Project Microwave Heating for Wendelstein 7-X

The 10 MW ECRH system for Wendelstein 7-X is designed for continuous wave (CW) operation (30 min) at 140 GHz, which is resonant with the W7-X magnetic field of 2.5 T. The total power is generated by ten Gyrotrons and is transmitted to the plasma by a quasi-optical transmission line and versatile in-vessel launchers for both, high field side and low field side launch. ECRH will support also W7-X operation at reduced magnetic field, because the gyrotrons can be tuned to 103.6 GHz with about half the output power. The ECRH-system is being developed and built by the ‚Karlsruher Institut für Technologie' (KIT) as a joint project with IPP and IPF Stuttgart. The 'Project Microwave Heating for Wendelstein 7-X' (PMW) coordinates all engineering and scientific ECRH-activities. The high-field side launchers are being developed and manufactured in the frame of a separate project, which is supported by the 'Bundesministerium für Bildung und Forschung' (BMBF).

8.1.1 The Wendelstein 7-X Gyrotrons

The series production of the gyrotrons at THALES continued and the gyrotron TH1507 SN6 was transferred in January from KIT, were the initial testing took place, to IPP, where the Factory Acceptance Tests was completed by end of March. The Site Acceptance Tests was then completed within three weeks only. This gyrotron was the first one with all improvements incorporated such as advanced beam tunnel, internal shaft coating, window oil cooling, as well as combined vertical and transverse magnetic field sweeping for smooth collector power dissipation. Operation for 30 min with the specified performance could be demonstrated as seen from figure 21. However, the electrical efficiency of the gyrotron was lower than designed and is now being subject to further R&D. The gyrotron was accepted and mothballed.

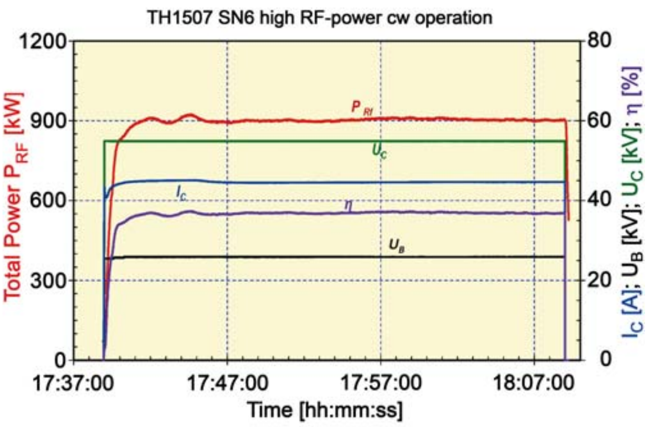

Figure 21: 30 minutes operation of gyrotron TH 1507, SN6: RF-power P_{RF}, beam current I_C, efficiency η, cathode voltage U_c and body voltage U_B, respectively, as a function of time.

All series gyrotrons at the IPP were equipped with a transverse field sweeping system, which, in combination with the vertical field sweeping system, provides a homogeneous power distribution at the gyrotron collector and increases its power operation range by a factor of 1.5. This extends the safety margin for the gyrotrons operation at maximum power and enables a continuous output power variation of about 70 % without overloading the collector. An example is shown in figure 22, where the output power is plotted as a function of the acceleration voltage UACC, which is the sum of both the cathode (UCATH) and body voltage, respectively.

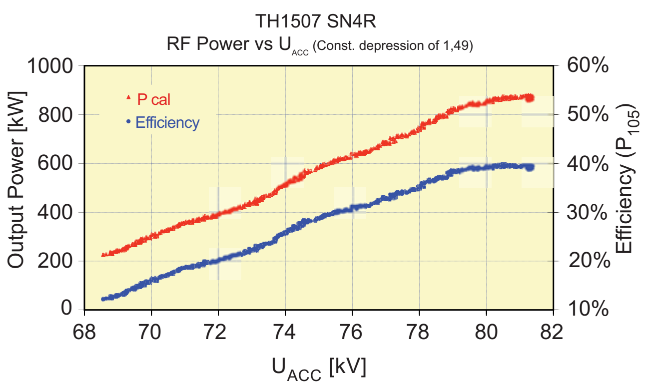

Figure 22: Response of the output power and efficiency of gyrotron TH 1507, SN4R on the acceleration voltage at constant depression ratio of 1.49.

With the newly developed fast control system the depression ratio (UACC/UCATH) was kept constant in order to maximize the efficiency. The acceleration voltage was ramped linearly during a 10 min pulse. The rf-power shows an almost linear response with typically 58 kW/kV. The gyrotron characteristics were determined over a wide parameter range by either tuning the body voltage or the cathode voltage, or both.
The next series gyrotron TH 1507 SN7 was shipped to KIT in early August, but opened a vacuum leak during installation in the KIT test-stand. The tube was shipped back to the factory for inspection and repair. A leaky cooling pipe (internal) was identified and replaced. The repaired gyrotron has passed the bake-out procedure; shipment to KIT is scheduled for mid January 2013. The inspection of the malfunctioning TH 1507 SN5 gyrotron, which showed a strong displacement of the output beam on the diamond window, revealed a misalignment of the internal optics, which is being corrected. The gyrotron is presently being reassembled.

8.1.2 Transmission System

The manufacturing and installation of the components of the basic transmission system has been completed. Cooling tube manifolds to supply the mirrors and stray radiation absorbers in front of the stellarator were installed in the towers. For beam diagnostics and power measurement of the gyrotron beams, linearization amplifiers for the detectors have been developed. The receivers attributed to the directional couplers on the mirrors M14 have been mostly built; present work concentrates on the design of the conical scan mechanics and electronics for the alignment control. The beam characterization measurements for the TED gyrotron SN6 and the subsequent design and manufacturing of the surfaces of the matching mirrors for the transmission line have been performed and were successfully operated. Within the acceptance test of this gyrotron, the "long load" (a 23 m long absorbing stainless steel tube with a water jacket) could be tested further. Successful shots of 910 kW (at the gyrotron output) for 30 min could be demonstrated, see figure 21 CW operation of the calorimetric load, which absorbs the residual power at the exit of the long load, was possible for powers up to 210 kW, qualifying this (originally short-pulse) design also for high-power CW loads.

8.1.3 High-field Side Launch with Remote Steering

Confinement studies with high field side launch of EC-waves are part of the scientific programme of ECRH and ECCD at Wendelstein 7-X. 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 give access to the plasma from the high field side with a weak magnetic field gradient. Access to the narrow N-ports is possible only with "remote-steering" launchers (RSL). The theoretical investigation of the RSL-concept and high power, cw tests are of high importance particularly 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 in the hostile environment of burning plasmas. 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 required therefore 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, a microwave beam at the input of the waveguide (with a defined direction set by a mirror system outside of the plasma vacuum) will exit the waveguide (near the plasma) under the same angle. An application for special support of a consortium consisting of two research laboratories, IPP and IPF-Stuttgart, respectively, and two industrial partners, NTG Neue Technologie GmbH und Co KG and Galvano-T GmbH, respectively, was approved by the BMBF in October 2012 and R&D work on the RSL has started.

8.1.4. In Vessel Components

The ECRH-plug-in launchers were completed and mothballed for later installation in the A- and E-Ports at Wendelstein 7-X. One out of the four launchers was used to test the assembly within similar cramped geometrical conditions as expected for Wendelstein 7-X. An assembly procedure was elaborated together with the assembly department, which insures a reliable vacuum closure with a HelicoFlex-sealing. The quasi-optical front steering launchers allow launching ten wave beams near the equatorial plane with arbitrary polarization in a wide angular range. For high-density operation above the X2 cut-off density, the ordinary wave polarisation is required, were the single pass cyclotron absorption is expected to be incomplete. The electron cyclotron absorption (ECA) diagnostics, which measures the transmitted ECRH power, the beam position and polarization, respectively, was completed. The waveguide vacuum interfaces had been slightly modified. The newly developed CF-type copper sealing with a glued mica window showed a sufficiently small helium penetration rate and a high mechanical reliability. All four modified B-port inserts passed the Wendelstein 7-X vacuum leak test procedure successfully. Outside the vacuum vessel the microwave interfaces will be equipped with filigree components and detectors, which are protected from mechanical damage by a protection bonnet, which also provides electrical connections and mechanical access. The ECA-diagnostic had been formally committed to the assembly department.

8.1.5 Staff

Staff at IPP (W7-X-P 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, P. Uhren, M. Weissgerber.

Staff at KIT (IHM): K. Baumann, G. Dammertz, G. Gantenbein, M. Huber, H. Hunger, S. Illy, J. Jelonnek, S. Kern, R. Lang, W. Leonhardt, M. Losert, D. Mellein, S. Miksch, I. Pagonakis, A. Papenfuß, B. Piosczyk, A. Samartsev, M. Schmid, W. Spiess, D. Strauss, J. Szczesny, M. Thumm, J. Weggen.

Staff at IPF (Stuttgart University): H. Höhnle, W. Kasparek, H. Kumric, C. Lechte, F. Müller, R. Munk, B. Plaum, P. Salzmann, K.-H. Schlüter, U. Stroth, A. Zeitler.

8.2 ECRH Contributions (IPF Stuttgart)

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

For investigations on trapped particles in W7-X as well as a demonstration for a reactor-compatible antenna for ECRH, two N-ports of Wendelstein 7-X will be equipped with "remote-steering" (RS) launchers (RSL1 and RSL5).

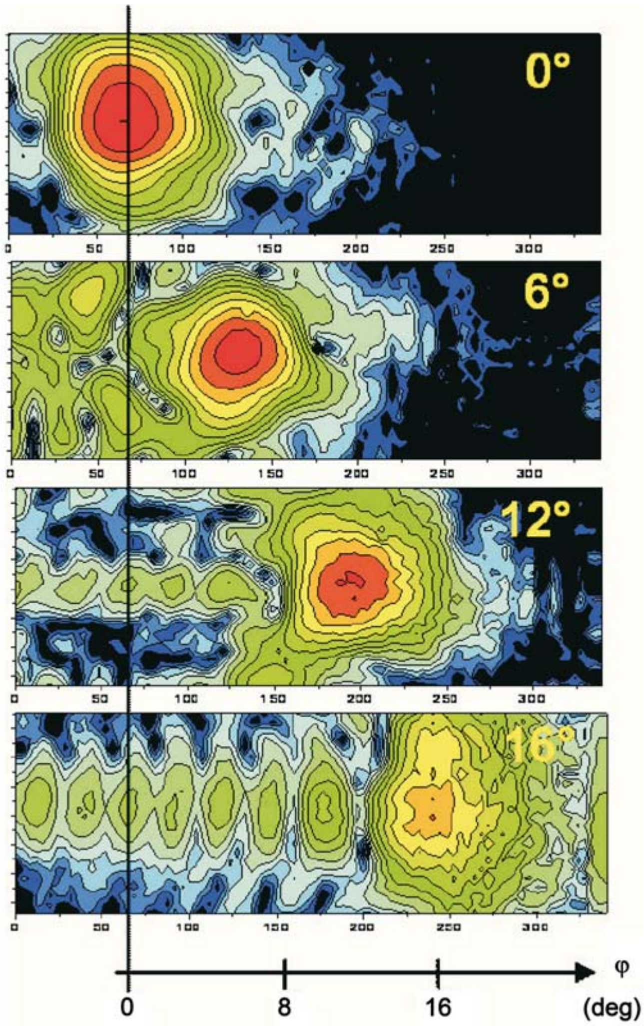

Figure 23: Radiation patterns of a remote steering antenna mock-up with non-quadratic cross-section for steering angle φ = 0°, 6°, 12°, and 16° showing a steering range of -16°<φ<16°. Scale: 3 dB/colour step, field areas: 340 mm × 140 mm.

The remote-steering properties are based on multi-mode interference in a square waveguide leading to imaging effects: For a proper length/width of the waveguide, a microwave beam at the input of the waveguide (with a defined direction set by a mirror system outside of the plasma vacuum) will exit the waveguide (near the plasma) in the same direction. As the imaging characteristics of square waveguides diminish at steering angles >12°, a prototype antenna waveguide with an optimized cross-section (square with outward bulges) with respect to the steering range was manufactured and tested. Antenna patterns recorded at a variety of steering angles (figure 23) show that an increase of the useful steering range up to 16° was reached, however, at the expense of a reduction of the quality of the antenna beam.
A detailed analysis of the radiation patterns showed, that the dispersion relation for the deformed waveguide was optimal for the $HE_{1,n}$ modes, however, $HE_{3,n}$ modes, which also contribute to the antenna beam, did not obey the prescribed ideal dispersion. The results were confirmed by a resonator technique, where the spectrum of the transverse resonances of the waveguide was measured and analyzed. A new simulation code was set up, which allows the simultaneous calculation of all propagation constants in the deformed waveguide; calculations began to find the best-performing RS-waveguide cross-section. Figure 24 shows a result for odd perpendicular modes in a quadratic and a deformed waveguide cross section. In the deformed case, the peaks are shifted, and additional modes are seen.

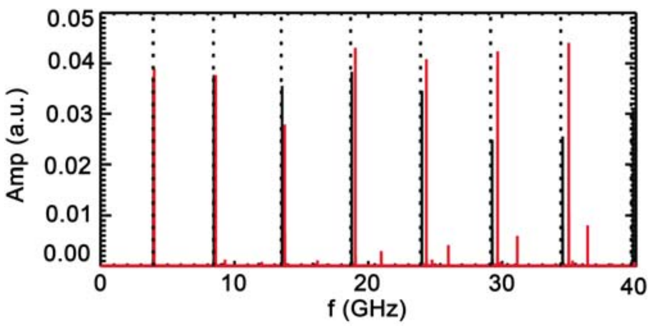

Figure 24: Simulated resonator spectra for the quadratic (black) and deformed (red) waveguide cross section.

Meanwhile, the engineering design and manufacture of the RS launchers was started within the frame of a “Verbundprojekt” funded by the BMBF, including IPP, IPF Stuttgart, and two industrial partners GT Windeck and NTG Gelnhausen (see chapter 8.1.3). The corrugation profiles for the RS-waveguide were optimized with respect to low transmission loss and compatibility with the fabrication by electroforming, and the cooling requirements for the waveguide have been calculated. The conceptual design of the positions and shapes of the mirrors for the feed lines has been performed as basis for the detailed design to be performed at IPP.

8.2.2 Component Development for Plasma Diagnostics

Several antennas were designed for Doppler reflectometry and for ECE-Systems at Wendelstein 7-X. The (smooth-wall!) horn antennas convert the incoming TE11 mode from the waveguide into a Gaussian beam. Given the required parameters (beam waist, frequency range) an optimizer is used to obtain the best horn geometry. These antennas are manufactured at IPF and low-power measurements are done to verify the characteristics. An example of calculated radiation patterns of a horn antenna for ECE at Wendelstein 7-X is shown in figure 25.

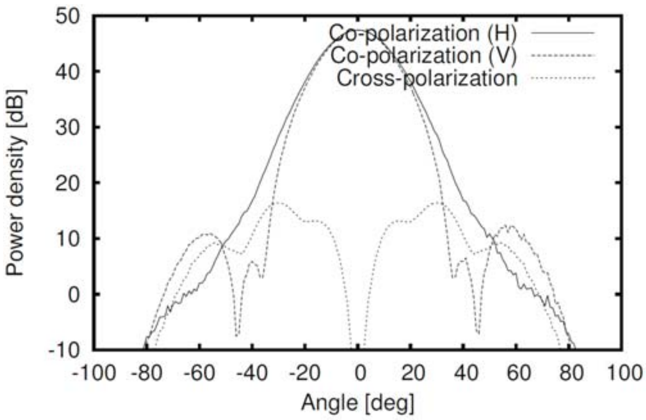

Figure 25: Antenna diagram of an optimized horn antenna for ECE diagnostics at 140 GHz. The antenna is broadband from at least 115 GHz to 155 GHz with similar radiation characteristics.

The development of a frequency-scanned, 32-element array antenna for reflectometry in the W-band has started, and measurements of a pre-prototype gave promising results, with a steering range of at least ± 20°, a beam width below 5°, and a steering sensitivity of 17°/GHz. Further calculations are done to estimate the effects of other components of the transmission lines for plasma diagnostic systems. Since these systems need to be broadband and the length of the transmission lines is several meters, oversized waveguides must be used. The components (e.g. bends and tapers) for these, however, need to be properly designed in order to avoid mode conversions, which can lead to disturbed radiation patterns and erroneous diagnostic signals.

8.3 Ion Cyclotron Range of Frequency Heating

Budgetary and personnel constraints required the project Wendelstein 7-X to focus on the essential components needed for the first operational phase. This led to a postponement of the heating system in the ion cyclotron range of frequencies. Still a stand-alone non-resonant radio frequency (RF) plasma generation system for the purpose of plasma vessel wall conditioning with ambient magnetic field and for the generation of target plasmas for neutral beam injection discharges at magnetic field, for which electron cyclotron heating

(ECRH) is not possible, was considered necessary for the first operational phase. To that purpose a scaled down system with a transmitter power of 3 kW was designed for WEGA. This system went into operation in 2012and successfully demonstrated that fast impedance matching based on feedback loop controlled frequency changes was possible and that wall conditioning showed similar removal rates as comparable ECRH discharges. Meanwhile the project decided to terminate the dedicated RF plasma generation system for operational phase 1 (OP1) based on the operational experience of the Large Helical Device (LHD), Japan, that wall conditioning in large superconducting fusion experiments is not required for obtaining plasmas and that reproducibility of plasma discharges can also be achieved by introducing standard plasma discharges into an experimental program and based on a reduction of magnetic field scenarios to those where an ECRH absorption mechanism exists. The conceptual antenna design for the ion cyclotron range of frequency system for operation phase 2 was further advanced by the Trilateral European Cluster.

8.4. Neutral Beam Injection

The Neutral Beam Injection (NBI)-system for Wendelstein 7-X is planned to be available in the summer of 2015. Initially available will be 2 ion sources on one box and it is planned to finish installation of a further 2 sources on the second box as soon as funding can be made available. The box-duct interface passed its formal design review this year and is approved for construction. The NBI group is responsible for the design of the interface components between the injector and the machine as well as for the internal protection of the bellows and insulator between the torus gate valve and the KiP port protection (see figure 26).

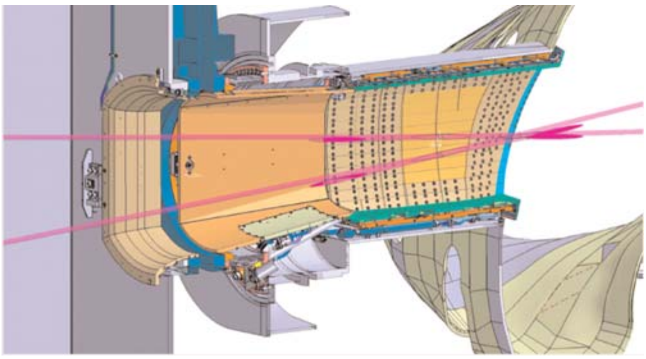

Figure 26: Figure shows a CAD model of the box-torus interface that has passed its design review and has been approved for construction. The pink lines indicate the axis of the four ion beams.

The NBI group has also been asked to take over responsibility for the construction and installation of two machine safety diagnostic systems: the heatshield thermography system (HST) and the thermocouples installed in the beam dump and duct regions. These are a new combined project (P008) for the machine. The collaboration with the Polish National Centre for Nuclear Research has progressed well. The upgraded and new gate valves have been delivered to Poland from VAT, the company PREVAC has been awarded the contract to provide the valve heating system. The contracts have also been awarded for the other work and delivery of all components will occur in 2013 (box support structures (see figure 27) from the firm TEPRO, upgraded and new magnet from TESLA, and the cooling water plant from INSS-POL). Work has proceeded on schedule for the assembly of the two injector boxes in the NBI assembly hall.

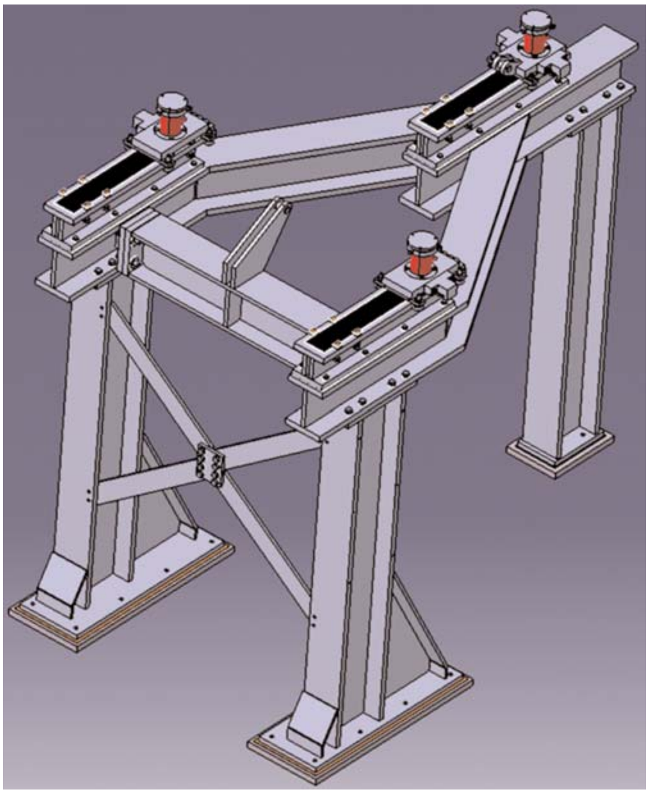

Figure 27: Figure shows a CAD model of the box support structure to be built by the Polish firm TEPRO.

A great deal of preparatory work has been accomplished towards the goal of installing the boxes in the torus hall in 2013. The CAD design has been updated to conform to the newest Wendelstein 7-X information and includes details of the support services routing. The torus hall water supply system has been planned, procured and awaits installation. A crane support capable of holding the weight of a box was designed, and constructed this year and has passed its acceptance trials. The magnetic shielding house for the ion sources have been manufactured and delivered this year. The box internal magnetic shielding is still undergoing manufacturing but is expected to be installed early in 2013.

The low voltage distribution boards (400 V/750 V) have been assembled in their own room in the cooling plant area. The high voltage cages for each box now have the internal components installed and are ready to be connected to the HV power supplies. The LR&FE snubber has been fabricated and is undergoing acceptance testing. The gas system for the boxes has started to be assembled and the interfaces with the main Wendelstein 7-X have all been defined with the connection lines from the main distribution valves now detailed. Essential to the operation of the injector is a pumping system capable of dealing with the amount of gas necessary for operation (~20,000 Pa-l/s). At AUG DC current heated titanium sublimation pumps are used.

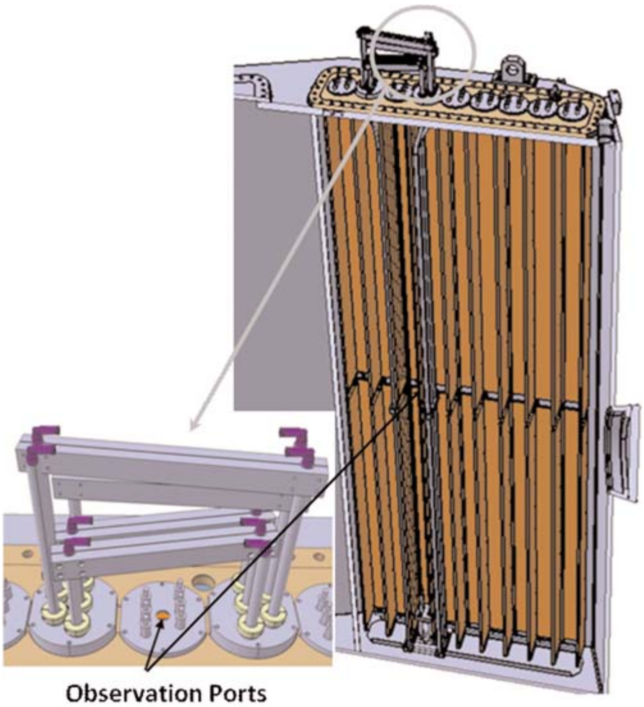

Figure 28: Figure shows the modifications made to the existing titanium sublimation pumps to allow testing of the AC heating concept on the old MANITU test stand. The observation ports will be used to observe the motion of the wire during heating in the presence of a magnetic field.

In Wendelstein 7-X, due to the main magnetic field always being present during a shot day, DC current heating of the 4 m long titanium wires is not technically feasible. Alternatively it is under investigation now if AC heating of the wires can be utilized within a magnetic field. To answer this question the test stand MANITU at IPP Garching has been repurposed with a modified full size titanium sublimation pump that now includes a pair of coils simulating the stray magnetic field of Wendelstein 7-X. A variable frequency AC power supply has been purchased and is being commissioned on the new test stand. All necessary mechanical modifications have been completed and the test stand should enter into operation in early 2013. (As an example the modification made to the existing pump to both generate the magnetic field and also observe the motion of the heated rod are shown in figure 28.) It has proven necessary this year to reduce the number of ion sources and injectors going initially into operation to free up funding for this effort.

9 Diagnostics

The work focused strongly on the set of start-up diagnostics. These are the diagnostics that are necessary for safe operation and control of the machine, or are indispensable for the physics goals of the first operational phase. The following sections briefly summarise 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 tender procedure for a long pulse compatible IR/visible endoscope system for divertor target temperature control and interference filter based divertor plasma observation has been completed. A contract will be placed early 2013 for development and manufacturing of two such systems – with an option for 8 further systems to be delivered before the beginning of operation phase 2 (OP2) in 2019. Los Alamos National Laboratory (LANL), USA will supply the two IR-cameras for the OP1 system. The first of these is presently being tested at LANL. Furthermore, a contract for manufacturing of 8 simplified IR/visible observation systems, for OP1 only, has also been placed and the delivery of the vacuum interface components is expected early 2013.

9.1.2 Video Diagnostic

The video diagnostic developed by MTA WIGNER RMI, Budapest, Hungary, will be located in the same port type in all 10 half modules of Wendelstein 7-X and will enable the observation of almost all of the plasma facing first wall. The design of the whole diagnostics was completed in 2012 and an assembly test of one complete system at one port location on Wendelstein 7-X has been performed, in which the field of view, the optical resolution and the reliability of the docking system of the camera carriage have been successfully field-tested in-situ with two different cameras (EDICAM and PCO PixelFly QE), together with the specially developed lens system for observation through a pinhole. The EDICAM system has been irradiated by hard gamma radiation at the Training Reactor of BME (Budapest), demonstrating its successful operation in a radiation environment comparable to Wendelstein 7-X deuterium operation.

The development of the new intelligent firmware for EDICAM continued throughout 2012 and a first demonstration of its operation is expected in early 2013.

9.1.3 Magnetic Diagnostics

The detailed design of the cable routing for approximately half of the Mirnov coils has been completed. The ceramic (AlN) coil bodies for all Mirnov coils have been manufactured and the first batch of 20 coils assembled and handed over to assembly for mounting to the wall protection elements. The copper shielding tubes for in-vessel signal cables, the diamagnetic loops and the in-vessel Rogowski coils were revisited for electromagnetic forces compatibility in case of a fast shutdown of the magnet system or a fast plasma decay at the end of a high-performance discharge. Several elements had to be added to the design to reduce these forces or to withstand them. An integrated design concept for the fast diamagnetic loop and its compensation loops for the triangular plane has been developed, taking into account the requirements of low thermo-voltages, mountability, good thermal contact to the plasma vessel wall, small eddy currents in the housing in order to maintain a high time resolution, and low electromagnetic forces in case of a fast shutdown of the magnet system or plasma decay. The detailed design of this important diagnostic has proceeded quite far. The first 110 (out of 650) in-vessel Rogowski coil rods have been manufactured and are ready for pre-assembly.

9.1.4 Flux Surface Mapping

The design of the plasma facing diagnostic frontend, the port shutter and the vacuum interfaces is still ongoing. The optical fibre based spatial reference system for the video observation of the fluorescent rods has been manufactured and the first components were installed in the plasma vessel. The mechanical tests of the prototype manipulator in vacuum have started showing that improvements on the bearings of the push rods are still required. A large vacuum tank for the integral tests of the manipulators has been modified by integrating an additional flange. The tools required for installation and alignment of the manipulators have been designed. The CoDaC department has started with the development of the control and data acquisition system.

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 to measure erosion of the divertor and to gain information on transport and re-deposition of the divertor and wall materials. The final prototype, with an improved design, as well as a possible later W-coating, has been successfully tested in GLADIS.

9.1.6 Target Integrated Flush Mounted Langmuir Probes for TDU Phase

All cable protection tubes as well as the cable connector unit, which will be mounted on the plasma vessel and inside the ports have been manufactured. The assembly of the complete tubing as well as the threading of the signal cable bundle has been successfully tested. The target finger modifications necessary for the flash mounted Langmuir probes are being designed, together with the cabling up to the connector plug.

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. A fast linear probe carrier is being developed at FZ Jülich. 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. The flexible design of the transfer system will allow it to be used also as a carrier for other systems, like plasma surface interactions samples or a quartz microbalance (QMB).

9.1.8 Neutral Gas Pressure Gauges

Design improvements were made following experimental results of a prototype in WEGA. All electronic blocks have been manufactured and tested.

9.1.9 Thermal Helium Beam and Divertor Gas Fuelling System

In a collaboration with FZ Jülich, the thermal helium beam plug-in has been designed. It will be a versatile gas inlet manifold. Two such gas manifolds will be mounted at the end of one island chain in n/m=5/5 vacuum configuration. This setup will allow monitoring of the local plasma parameters at the island divertor downstream positions at one upper and one lower divertor module. Each gas manifold consists of five piezo-valves, which can individually be activated. The gas pressure can be varied from 1 to 63 bar and thus gas flows between 1018 to 1023 atoms/s achieved. The gas inlet system can therefore be used to create a thermal helium beam, for island divertor impurity seeding, and divertor hydrogen gas fuelling, alike. Both gas manifolds including the entire gas feedthroughs and the vacuum adaptation systems are being manufactured at ZAT at FZ Jülich.

9.1.10 Thermal He-beam and Visible Spectroscopy Systems

FZ Jülich is developing endoscopes as versatile observation systems. A conceptual design has been developed. The development of the optical setup, supported by plasma and impurity emission modelling with EMC3-Eirene, is still ongoing. 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.

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, allows for an intermittent signal loss during long-pulse discharges and has a very compact optical set-up. The laser beams of the Thomson scattering system and the single-channel interferometer, which serves as the primary density control system, share the same port combination, thereby enabling easy cross calibration of the two systems. The vacuum interfaces for the ports involved have been prepared and the interferometer, its beam position control system, and its digital data acquisition as well as the phase measurement have been set-up and successfully operated in the laboratory. The design of the mechanical support structures in the torus hall has been completed and their manufacturing started. For the first operation phase (OP1) also the first four channels of the multichannel dispersion interferometer will be installed. All four modules have already been successfully operated on TEXTOR at FZ Jülich. These systems require high-heat-load compatible retro-reflectors to be integrated in the carbon-tiled heat shield of the first wall.

9.2.2 Electron Cyclotron Emission (ECE)

The ECE system allows measurement of the electron temperature from the blackbody cyclotron radiation emitted by the plasma. For the calibration optics and transmission lines in the torus hall, the conceptual design has been finished and the manufacturing of associated vacuum flanges and waveguide feedthroughs started. For the high-field side antenna, which will be integrated into a carbon tile of the first wall, the waveguide components have been designed. Some of the components are already on site. In combination with the already manufactured and tested in-vessel ECE mirror optics, this additional antenna allows measurements of the non-thermal part of the electron distribution function.

9.2.3 Reflectometry

Reflectometry measures plasma density profiles, fluctuations and their propagation velocity by microwave signals reflected from the cut-off layers in the plasma. A versatile in-vessel optics combining x-and o-mode launch for density profile and Doppler reflectometry measurements has been designed in cooperation with CIEMAT in Spain. The port design includes space reservations for two further advanced antennas, namely a fast angular scan Doppler antenna as K-spectrometer for turbulence measurements and a correlation reflectometry array. They are being prepared together with the University of Stuttgart and the FZ Jülich respectively, both within the framework of the new Helmholtz Virtual Institute on advanced microwave diagnostics, which was approved in June 2012.

9.2.4 Thomson Scattering

The preliminary design of the ìThomson bridgeî support structure has been completed. The bridge serves as central support structure for the Thomson diagnostics, supports the retro-reflector of the single-channel interferometer and provides the access to the W7-X machine centre. The low cobalt, low μr SS material required for its construction has been delivered in December 2012. Its detailed design and manufacturing has started at an external company (Fantini, Italy). The two Nd-YAG laser systems were installed in the Thomson scattering laboratory where the automated laser beam steering and control system will be tested next.

9.2.5 Stray Radiation Testing in MISTRAL

In preparation for long-pulse operation, diagnostics and other in-vessel components are being qualified with respect to their absorption of non-absorbed ECRH heating power. The experiments performed in the Microwave STray RAdiation Launch facility (MISTRAL) were bundled in two campaigns, which focused on dedicated ceramic in-vessel components, magnetic diagnostics, gaskets for Wendelstein 7-X and a mock-up test of a possible ITER bolometer prototype.

9.3 Core Spectroscopy

9.3.1 RuDI-X, CXRS, NPA

The acceptance test of the high-voltage power-supply for the Russian Diagnostic Injector for Wendelstein 7-X (RuDI-X) took place in June 2012. This system provides an energetic beam of neutral particles required for active charge exchange recombination spectroscopy (CXRS) and charge exchange neutral particle analysis (CX-NPA). Testing of the entire injector system started in December 2012 with encouraging initial results. Watercooling and gas-supply systems have also been completed. The design of the CXRS vacuum barrier has been finalised and tests of fibre and optics were successfully accomplished.

9.3.2 HEXOS

A mechanical unit for adjustment of the two calibration sources in front of the VUV/EUV spectrometer system HEXOS had been designed, manufactured and delivered to FZ-Jülich in summer 2012. Using this device, HEXOS has been calibrated in autumn 2012. In parallel the Wendelstein 7-X data acquisition and control system has been successfully developed by FZJ at TEXTOR using a CoDaC mobile station provided by IPP.

9.3.3 X-ray Imaging Spectrometer

The X-ray imaging spectrometer at TEXTOR has been modified to Wendelstein 7-X requirements by FZ-Jülich and delivered to IPP in autumn 2012. It will provide spatially resolved core ion temperature measurements, as well as plasma rotation measurements. The spectrometer has been re-assembled and re-aligned at IPP in cooperation with FZJ.

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 manufacturing of the actively cooled detector holders for both systems, consisting of SS water cooling pipes welded into the high thermally conducting CuCrZr holders, has been completed. The main components of the vertical camera system have also been manufactured already. In tests it has been demonstrated that the diagnostic positioning accuracy meets the bolometer requirements. For the horizontal bolometer system the manufacturing drawings of the camera head have been completed.

9.3.5 XMCTS

The manufacturing of the individual components of the series cameras for the in-vessel soft X-ray multi-camera tomography system (XMCTS) has been completed and are currently being assembled. The specially developed custom-made electrical vacuum feedthroughs for the detectors have all been welded into the electronics boxes and successfully UHV-leak tested. The design of the preamplifiers inside the electronics boxes has been completed, a prototype been tested and the series preamplifiers all been delivered. The components for the support frames are presently being manufactured externally while the pre-assembly stand is being manufactured by the IPP workshop. Both are expected to be delivered in January 2013. The port plug-ins for the media supplies are manufactured at ITZ in Garching. All other components will be assembled on the pre-assembly stand in time for the planned integration of the XMCTS in-vessel components in June 2013.

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

The Agreement of Cooperation between IPP and the IPPLM, Warsaw has been renewed. The manufacturing drawings for both systems, PHA and MFS, have been completed and manufacturing and delivery of parts for the PHA-system are ongoing at IPPLM. The filter control mechanism by a wobble stick has been successfully demonstrated with a prototype setup.

9.3.7 Neutron Counters

Two outer neutron monitors will be installed along the torus and one above its centre. In order to match their dynamic ranges for neutron flux densities from 5 10^3 up to 10^9 cm^{-2} s^{-1}, the outer ones will be equipped with four counter tubes, the central one with five. The positioning and geometries of the monitors has been optimised and a concept for their support on the cryostat vessel been developed. The proper functioning of the counting tubes and their preamplifiers has been tested in a magnetic field of up to 50 mT.

9.4 Collaborations

FZ-Jülich, Germany: HEXOS, 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
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

10. CoDaC

The subdivision Control, Data Acquisition and Communication has focused its work on accomplishing the control and data acquisition of CoDaC frontend systems, i.e. diagnostic, heating and other auxiliary systems, which are required for the first W7-X plasma. Beside these activities, the software development continued on the envisaged improvements as a consequence of the operation experience at the WEGA stellarator over the past seven years.

10.1 IT/EDV

Wendelstein 7-X CoDaC has introduced a new IP network design that is capable of streaming data up to 30 GByte/s continuously and that meets the requirements of new data center technologies and the IT security standards. It is based on a virtualization strategy, which separates the organizational from the physical structure of the system and, therefore, enables to adapt the organizational structure without affecting the physical network layout. Wendelstein 7-X CoDaC contains three network units, the realms for the experiment, the data center and the offices. Each of them is equipped with a virtual router function (VRF in figure 29) being interconnected via firewall instances for security purposes.

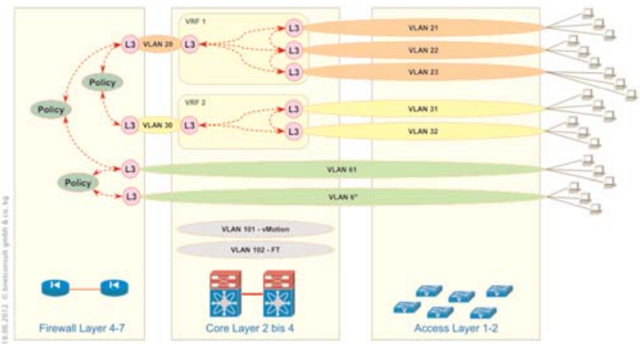

Figure 29: Network concept for Wendelstein 7-X.

All layer 2 network segments are implemented by using VLANs (virtual LAN). In preparation for the experiment archiving system, the first GPFS (0.25 PByte) mass storage disk system has been installed with the strong support by the RZG. The local tape library is now routinely used for server and virtual machine image backups.

10.2 Control and Data Acquisition

10.2.1 Central Control and Frontend Systems

Finishing the planning phase for the central safety system and the central operational management, the assembly of the hardware has been started. A new programming tool PCS7 was introduced as a standard for PLC based control systems at Wendelstein 7-X for an increased PLC programming efficiency. A new version of the trigger-time-event card (lTTEV2) is under development. The detailed specification has been finished and the FPGA program has been implemented and tested using a prototype board in cooperation with University of Rostock. Based on this prototype a new printed circuit board for the lTTEV2 card is being designed. The central gate valve and shutter control system, which is needed to control and observe all gate valves and shutters of the Wendelstein 7-X torus for diagnostics, heating systems NBI and ECRH, and the gas inlet system, controls 102 gate valves and 188 shutters. The production of the control cabinets for the PLC based control system and the pneumatics is almost accomplished. The data acquisition systems for all gyrotrons of the ECRH system have been designed and implemented. The commissioning and test of the system is in progress. The data acquisition and control system for the diagnostic HEXOS (VUV spectrometer) has been finished. The commissioning was done in collaboration with the Forschungszentrum Jülich by using MobileCoDaC. Furthermore, systems for the diagnostic neutral beam RuDiX (in cooperation with Budger Institute, Russia) and the flux surface measurement system achieved essential progress in 2012. The Wendelstein 7-X ground fault detection system has been further developed and an appropriate signal acquisition hardware and computation platform was procured. The software algorithm for signal filtering has been modified to fit to a multi-core CPU system. Some diagnostics need a position control of their laser beams, e.g Interferometry and Thomson scattering. After being tested for Thomson Scattering, the Laser Beam Position Control was adapted to the needs of Dispersion Interferometry. The data acquisition system of the latter is based on a FPGA solution. Its prototype has been developed within a graduation project (Instituto Tecnológico de Costa Rica) and operated successfully. In the context of a collaboration with IST (Instituto Superior Técnico) in Lisbon a high-speed data acquisition system based on ATCA industry standard was developed. A first 64-channel version has been installed and successfully integrated in the Wendelstein 7-X CoDaC environment. Final performance tests are expected to be finished in early 2013. Necessary preparations for the upcoming series manufacturing of ATCA ADC-boards have been taken.

10.2.2 MobileCoDaC

MobileCoDaC allows in situ testing and commissioning of components. Its main purpose is to establish an environment of central services as needed by CoDaC frontend systems. It consists of a transportable rack system, the CoDaC server infrastructure (Wendelstein 7-X time server, configuration database, archive server, data access web server, documentation, messages server, software deployment server), the network infrastructure (LAN, real time network if applicable, Wendelstein 7-X timing network) and the software stack providing the user tools for experiment preparation (Xedit), operation (Xcontrol, logbook), trouble shooting (Xnote) and data access (DataBrowser, Data Access framework).

Figure 30: MobileCoDaC (right) and HEXOS data acquisition (left cubicle).

Additionally it provides remote access possibility for maintenance by the CoDaC staff and it is comprehensively documented allowing external developers efficient handling of the system. MobileCoDaC has been used successfully for tests and commissioning of the HEXOS diagnostic at FZJ (figure 30).

10.2.3 Software Projects

The development of the CoDaStation (Control and Data Acquisition Station) software has been focused on the new version 2. This version provides a higher level of modularization and more clearly defined interfaces. The benefits are better testability and more flexibility regarding the integration of third party software. Due to the system independent interface definition for configuration and archive storages it is now possible to switch between different database systems. Mockup implementations of the new interfaces allow the definition of more complex tests without dependencies to actual runtime systems. For the TDC (Time to Digital Converter) new hardware device drivers were developed to support the Microsoft Windows 7 and Windows Server 2008 operating system, both in 32-bit and 64-bit versions. The configuration database and the accessing applications are subject of a major refactoring endeavor. All Control and Data Acquisition software packages are reorganized to a layered architecture. It clearly separates the concerns of persistence, business processes and application logic to layers with distinct interfaces between each other. Thus, testability and maintainability are greatly improved and further development is facilitated. Application logic and persistence of data in a database is now completely decoupled. Furthermore the persistence layer is based on a vendor-independent database interface (Java Data Objects) by using the open source persistence framework DataNucleus. This eases the use and change of different database systems. Currently the schema-less, document-oriented database system MongoDB is prepared for productive usage. By these steps the software becomes independent to a single, proprietary database system (Objectivity) and is being optimized with respect to the data structures of the configuration database.

10.2.4 ArchiveDB

The Wendelstein 7-X scientific archive will contain all acquired, analyzed and machine operation related data and is therefore a crucial project. Activities aimed to provide a portable and reliable data archive solution based on publicly available software and replace the existing proprietary ObjectivityDB. Therefore a comprehensive requirements and use case analysis has been accomplished. Fundamental functional requirements are to write mass data continuously in parallel, i.e. parallelization of the network and data server capacity (expected storage rate for Wendelstein 7-X operational phase OP1 is up to 30 Gbyte/s; data capacity is about 1.8 Pbyte per year), and to read mass data synchronized. Performance is achieved by a coordination mechanism providing read operations on many logical data sources scattered over several physical storage locations. Work has been identified, planned and started to improve the software architecture by strict consideration of scalability (size), maintainability (layered structure) and usability (API design) requirements. The prototype database servers will be replaced by a scalable storage system and a scalable network for increasing demands on data rates. A new backend software layer StreamAccess, unifying the access to the existing old and planned new archive, has been defined and the development has been started. To improve usability a new end user programming interface SignalAccess has been designed and partly been implemented. It allows unified access to all archived data using a signal concept, which considers ADC channel, image, analysis result and parameter commonly as signals.

10.2.5 Service Oriented Architecture

A part of the private cloud system will be used as a cluster for modeling and analyzing of scientific data associated to W7-X. For an easy integration, the software on this cluster is implemented as Webservices according to the principles of Service Oriented Architecture (SOA). By the usage of SOA/Webservices, it is foreseen to provide a way to combine theory and experiment data analysis software and make them in this way reusable for a wide range of scientists working on Wendelstein 7-X. For integration of legacy implementations, like Fortran codes, a service wrapper is a suitable option. A prominent example is a webservice implementation that wraps the VMEC2000 equilibrium code. One common tool for integration of services is the Enterprise Service Bus (ESB), which is now being operated routinely in CoDaC. An ESB introduces an abstraction layer between client and server in a SOA and handles common tasks, like load balancing, message transformation and security, in a centralized manner. Thus it is possible to make a top-level parallelization of software calls, which is suitable for many scenarios. For these integration tasks, the open source WSO2 ESB was chosen, after an evaluation of commercial and open source products. Parallelization scenarios were tested for services for field line tracing and the PIES EXTENDER code, as well as for Monte Carlo simulations for the Wendelstein 7-X helium beam diagnostic.

10.3 Software Quality Management

Software development for Wendelstein 7-X is based on industrial process models (ISO 15504-5, RUP) providing a means to achieve well defined product quality (ISO 25000). Experiment operation and maintenance is based on quality of service standards (ISO 20000, ITIL), which is under implementation for all CoDaC services including IT/EDV. The implementation focuses on automation, use of formal models, templates, software metrics and agile management. The quality assurance for development covers review and tracing of developed artifacts and installed equipment as well as automated software builds, integration tests, application of quality metrics, report generation and deployment.

For operation, the quality assurance comprises the survey processes for availability of server infrastructure (data acquisition, development tool chain, database and archive servers) based on Nagios, the automatic verification of quality requirements like, synchronization precision of the timing system, consistency checks of acquired data and consistency checks within the configuration Database. Furthermore, a ticket system for users of experiment systems has been introduced for improvement of the operation services.

10.4 External Contributions and Collaborations

CoDaC received contributions by the XDV group of the RZG (see RZG section), the University of Rostock for the lTTEv2 development, FZ Jülich for HEXOS setup, an ATCA based ADC prototype by the Instituto Superior Téchnico (Portugal, Lisbon) and the Instituto Tecnológico de Costa Rica (graduation project, Humberto Trimiño Mora) for the FPGA based dispersion interferometry data acquisition. A master thesis on software architecture for a data monitoring system (FH Stralsund Master Thesis, Frank Engel) and two bachelor thesis on controller for the gas inlet system (FH Stralsund, Ulli Stutz and Matthias Wiese) have been conducted.

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Other Activities in Greifswald and Berlin

In 2012 the experimental program at WEGA and VINETA were carried on. The international Stellarator/Heliotron database and the cooperation with LHD on 3D effects were continued. Construction work has started for creation of the first electron-positron plasma on earth (APEX project). Substantial external funding has also allowed to continue the activities in electron spectroscopy.

WEGA

Head: Dr. Matthias Otte

A new plasma radio frequency heating method could be established. This non-resonant method distinguishes itself as robust and flexible. The bulk plasma is heated by collisions with relativistic electrons with MeV energies. Those supra-thermal "runaway" electrons with parallel momentum are well confined in a stellarator field, but their drift surfaces strongly deviate from the magnetic flux surfaces. The drift surfaces are outward shifted and their low field side parts concentrate at the plasma edge on the equatorial plane close to a open circular waveguide antenna, where the electron are accelerated by stochastic interaction with the electric field at the antenna mouth. The high field side part of the drift surfaces cross the central flux surfaces, where the supra-thermal electrons interact with the bulk plasma. Since no plasma waves are involved in the heating process the magnetic field and the plasma parameter can be varied over a wide range. The energy of the fastest runaway electrons was determined from their synchrotron radiation to about 2 MeV. This result is supported by the measurement of γ-rays in the 0.5-1 MeV range, originating from the collision of MeV electrons with the in-vessel components, which are closest to the plasma. The confinement time of those particles is only a function of the density. Decay time constant of up to 0.9 s could be achieved. The acceleration process was identified as a tail formation in the energy distribution function by stochastic interaction. Its characteristic time constant of 0.5 ms could be verified by power modulation experiments.

During the future operation of W7-X the existence of the permanent magnetic field prevents using DC glow discharges for cleaning the first wall. Instead alternative plasma heating methods by means of ICRH or ECRH have to be applied. In cooperation with the T. Wauters from the Laboratory for Plasma Physics – ERM/KMS and P. Urlings from TU Eindhoven a comparative study on the efficiency of different wall conditioning methods was initiated at WEGA. For this purpose a 6 MHz RF system (3kW, cw) with a single strap antenna was installed additionally to the existing 28 GHz ECRH gyrotron (10 kW, cw). In order to create a defined contamination level of the vessel wall a droplet of water was evaporated into the vessel before plasma operation. In a first campaign helium plasmas were created by the two heating methods and the temporal release of water, hydrogen and other gases from the wall was measured by mass spectroscopy. Generally, highest efficiency was obtained in a repeated modus of a plasma discharge of a few seconds followed by interval without plasma allowing the recombination of the released impurity molecules and their subsequent pump out. This confirms previous results from tokamak operation. Comparing ECRH and RF discharges, highest water release per unity of emitted energy was observed for RF discharges. In this case the plasma was generated outside the confinement region so that the interaction zone of the plasma with the wall was large. In contrast the centrally heated 0.5 T ECRH discharges with a small interaction zone of the strike lines with the wall were less efficient. However, when increasing the interaction zone by varying the magnetic configuration or by applying an off-axis heating scenario a much higher hydrogen release was observed.

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 conducted (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. Differences of radial electric field measurements with ambipolar fields in LHD are being assessed to result from non-local neoclassical effects. A documentation of the particle transport at similar parameters is being prepared.

3D Effects in Tokamaks and Stellarators

Joint experiments within the ITPA Transport and Confinement group have been initiated (LHD, W7-AS, KSTAR, DIII-D, TEXTOR, ASDEX Upgrade). Main focus is led on so-called pump-out with RMPs and the impact of low order rational surfaces. The benefit of joint experiments both in tokamaks and stellarators is to assess RMP effects in well reproducible discharges with equilibrium not resulting from plasma current density profile. Extensive studies of LHD divertor heat flux pattern were conducted in collaboration with the NIFS. A thorough analysis of this data and a comparison to modelled divertor loads with a fluid code (EMC3) revealed influences of the stochastic edge magnetic field on the edge energy transport. Multi-peak structures due to whisker-shaped flux tubes intersecting the divertor seem correlated to fast electrons accumulated on long field lines, which stay close to the LCFS.

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VINETA

Head: Dr. Olaf Grulke

Magnetic Reconnection

One new direction of research is the experimental study of driven magnetic reconnection. The original VINETA device was modified by adding one vacuum module housing the conductors for the reconnection drive. The experimental setup and diagnostic tools have been finalized. In contrast to the original approach using two parallel axial conductors, in which a sinusoidal current is driven, the concept has been changed to systematically separate the generation of a magnetic X-point configuration from the reconnection drive amplitude and timescale. Therefore, a third axial conductor has been installed carrying the sinusoidal current, thereby driving the reconnection process, whereas a steady-state current in the other two conductors forms the magnetic X-point configuration. The setup is schematically depicted in figure 1a. These modifications allow to study, e.g., guide field effects separately from the drive. Various theoretical studies predict that two fluid effects considerably influence the reconnection structure for small magnetic guide fields. Indeed, preliminary experimental results indicate that the magnetic guide field strongly alters the topology of the current sheet that forms in response to the magnetic reconnection process. For large guide fields the current sheet is mainly determined by the geometry of the plasma gun, which provides the electron current. However, if the guide field strength is comparable to the reconnection magnetic field a so-called neutral sheet forms with an elongated current sheet as shown in figure 1b. Investigations of the guide field dependence will be one major objective in the upcoming experimental campaigns. The results will be compared with numerical simulations, which were established in close collaboration with the Ernst-Moritz-Arndt University, Greifswald (Prof. R. Schneider).

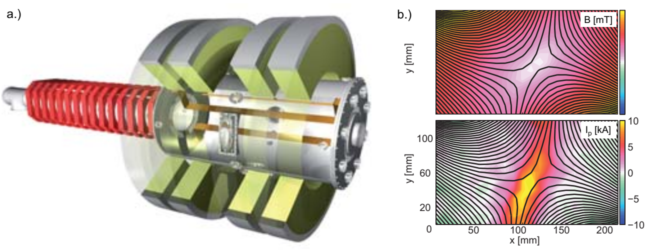

Figure 1: a.) VINETA II device for the studies of magnetic reconnection showing also the internal axial conductors for the reconnection drive. b.) Measured magnetic field topology and plasma current in an azimuthal cross section.

High Density Helicon Discharge

The helicon discharges commonly used at VINETA are characterized by very efficient plasma production. At moderate rf power levels of a few kW plasma densities comparable to the scrape-off layer of fusion devices are achieved. This property is already used in various applications, as e.g. material research and advanced plasma propulsion schemes, which rely on high ion fluxes. Since the helicon dispersion relation has no intrinsic density cut-off, discharges with even higher plasma densities are principally possible. A new experimental device was set up for a proof-of-principle study, if plasma densities required for novel plasma-based accelerator concepts of $n \approx 10^{20}$-10^{21} m^{-3} can be achieved using helicon discharges. The research is embedded in a large collaboration (AWAKE) aiming at the development of the first proton-driven particle accelerator. The device consists of a homogeneously magnetized vacuum glass tube (length 1 m) and m=1 helicon waves are excited by external helical antennas. Low-power operation yields plasma densities in the range $n \approx 5 \cdot 10^{19}$ m^{-3} and are in good agreement with power balance and helicon dispersion calculations. Multiple distributed antenna operation has been successfully shown, which is important to scale the helicon discharge length. The device is currently modified for high power operation to increase the plasma density. For high-density operation a CO_2 laser interferometer system has been installed to study the evolution of the plasma density with operational parameters.

Fluctuation-driven Plasma Flows

Previous investigations showed that the formation of localized turbulent structures is related to the generation of velocity shear layers driven by turbulent plasma fluctuations. The studies were mainly based on the results obtained from numerical simulations of drift wave turbulence, which are carried out in close collaboration with the DTU (Dr. V. Naulin). In the VINETA experiment turbulence-driven shear layers have been observed as m=0 perturbations of the plasma potential fluctuations, accompanied by peaking of the radial divergence of the measured Reynolds stress. However, a correlation of the shear layer formation with the formation of isolated turbulent structures could not be experimentally established yet. The probe diagnostics has been extended to measure the individual radial momentum transport contributions to directly compare the experimental results with numerical simulations.

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PAX, APEX

Head: Prof. Dr. Thomas Sunn Pedersen

APEX (A Positron Electron eXperiment) aims to create plasmas of electrons and positrons, that is, of equal amounts of matter and antimatter, for the first time in the laboratory. Due to their perfect mass symmetry, they are predicted to have fundamentally different behavior from regular electron-ion plasmas. In nature, they are believed to exist around astrophysical objects such as neutron stars and accreting black holes. Also, simulation codes for fusion plasmas can be benchmarked against observations on a pair plasma.
Although their unique and interesting behavior has been predicted for over 30 years, no such plasma has been created in the lab yet. The challenge is (at least) three-fold: 1. Having enough low energy positrons to ensure they behave as a plasma (collective behavior). 2. Having a trap that can simultaneously confine positrons and electrons. 3. Being able to bring the electrons and positrons into the trap with sufficient efficiency. We have developed scenarios, under which a meaningful plasma can be produced from existing positron sources (T. Sunn Pedersen *et al*., New J. Phys. **14**, 035010, 2012). A back-of-the-envelope calculation shows that for a plasma volume of 10 liters, 10^{11} positrons are needed to display plasma behavior. To account for losses in transfer and injection, we have set ourselves a target of 10^{12} cold e^+ stored prior to the creation of the pair plasma. Comparing to conventional laboratory source rates of 10^6 e^+/s one sees the challenge.
In figure 2, a sketch of our planned experiment is shown. It will use one of the most intense sources of slow positrons today, the NEPOMUC beamline at the FRM-II nuclear research reactor in Garching, with a flux of 3×10^9/s cold positrons (figure 2, A). Even with this source, an accumulation and storage system must be developed (PAX, Positron Accumulation eXperiment) before the positrons are injected into APEX.

Positron Accumulation

Major elements of the set-up sketched in figure 2 have been acquired in 2012, namely the buffer gas trap (figure 2, B) and the accumulator (C). These two components will trap the positrons provided by NEPOMUC, and cool them down to sub-eV temperatures. A laboratory source enabling positron experiments in Greifswald has also been acquired.
Part D of figure 2 depicts an assembly of multiple Penning-Malmberg traps that will be filled sequentially and will accomplish a long term, low loss storage of the positron cloud. The main component of this system, a 5 T magnet (figure 3), has become available by a cooperation with Greifswald University (Prof. L. Schweikhard, Dr. G. Marx). Further development of the high field trap will be done in collaboration with UCSD (Prof. C. Surko, Dr. J. Danielson).

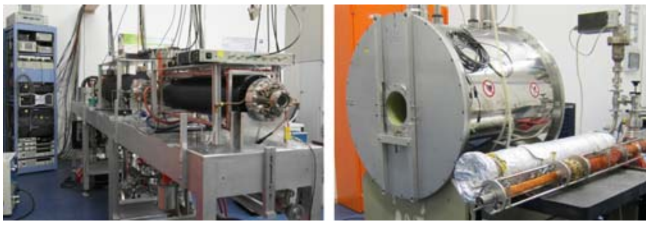

Figure 3: The buffer gas trap and the positron accumulator in the newly established PAX laboratory (left). The 5 T superconducting electromagnet (Oxford Instruments) to be used for positron storage (right).

APEX

Two scenarios for confining the electron-positron plasma have been developed: The first geometry studied is a stellarator with two interlocking coils, similar to the Columbia Neutral Torus (CNT) (figure 2, E.). Design studies for a CNT-like device employing superconducting coils have started. As an alternative, positron injection into the dipole field created by a levitated, superconducting current loop is being considered.

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T. S. Pedersen, U. Hergenhahn, N. Paschkowski, X. Sarasola, E. Stenson.

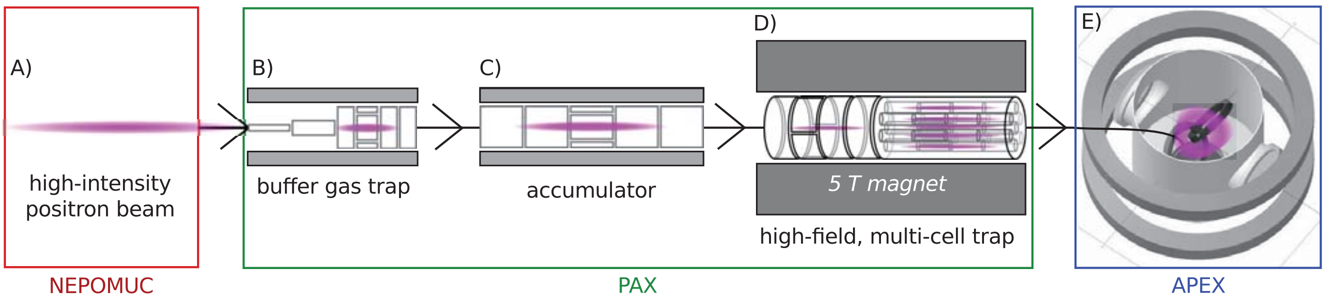

Figure 2: Experimental set-up for creation of an electron, positron plasma.

Electron Spectroscopy

Head: Dr. Uwe Hergenhahn

The electron spectroscopy group is carrying out an internationally recognized research programme on excited state relaxation dynamics in weakly bonded systems, e.g. van-der-Waals clusters and liquids. Equally important, work is done in high-resolution, quantum state resolved molecular Auger spectroscopy.

Intermolecular Coulombic Decay

Interatomic/Intermolecular Coulombic Decay (ICD), since its experimental demonstration by the electron spectroscopy group ten years ago, has become a topic of broad, interdisciplinary interest in AMO physics, physical chemistry and ultrafast dynamics.

In ICD, an excited state decays via energy transfer to a neighbouring atom or molecule, thereby effecting its ionization. Interestingly, meanwhile also the inverse process of ICD has been considered theoretically (C. Müller *et al.*, Physical Review Letters 104, 233202, 2010). In this so-called two-center dielectronic recombination (2CDR), a free electron is captured by an ion, with a partial transfer of the excess energy to a neighbouring atom or ion, which becomes excited. 2CDR is predicted to be an important recombination mechanism in dense, not overly warm plasmas (‘warm dense matter’).

Experimental work of the electron spectroscopy group in 2012 has focussed on ICD as a tool for structural analysis. Similar to earlier work, clusters were produced by supersonic expansion through a cryogenically cooled nozzle. Excited states were then created by photons from synchrotron radiation, and their decay was monitored by energy resolved electron, electron coincidence spectroscopy.

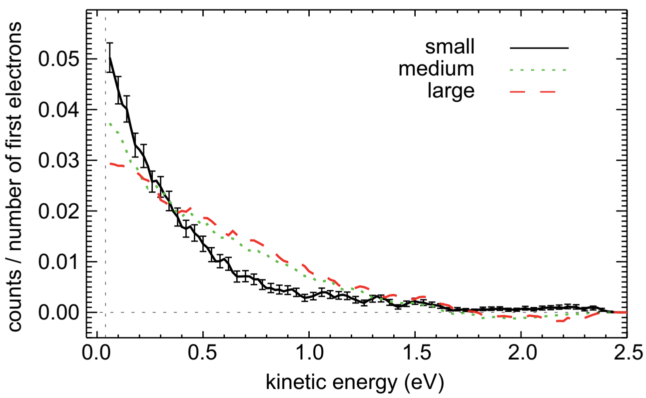

Figure 4: Autoionization spectra of Ar $3s^{-1}$ vacancies in mixed ArXe clusters. Clusters designated as ‘big’ consist of about four layers of Xe surrounded by an Argon layer. ‘Small’ clusters contain on average one-two Xe atoms, which are surrounded by Ar. ‘Medium’ clusters are in-between the two regimes. Intensity is given as number of secondary (ICD or ETMD) electrons collected per primary (photo)electron and energy interval.

As an example selected results for a study on ArXe are shown. For ArXe after Ar 3s photoionization, a competition between ICD and non-local autoionization involving charge transfer, so-called three center Electron Transfer Mediated Decay (ETMD(3)), has been predicted. The fact that Ar 3s vacancy states, which are long-lived in pure Ar clusters, become autoionizing by a Xe admixture, has been established already (Melanie Mucke, IPP Report 16/23). To clarify the nature of the autoionization process, we have now recorded electron spectra from a series of ArXe clusters condensed from different gas mixtures (figure 4), and carefully monitored their composition via outer valence photoelectron spectroscopy at the same time. It is well established that condensation of an ArXe mixture leads to clusters that consist of a Xe core surrounded by Ar layers. Assuming this structure, the composition and the mean size of the clusters can be inferred from the intensities of the Ar and Xe outer valence photoionization lines.

For ETMD(3) to occur, the presence of at least two Xe atoms near to the initially excited Ar site is necessary. Therefore, this mode of autoionization is most probable in ‘big’ clusters (‘big’ referring to the legend of figure 4), while the ‘small’ clusters hardly contain sufficient Xe. The competing decay via ICD requires just a single Xe atom as partner. Due to energetical constraints, a distance of more than one layer to the initially excited Ar site is needed though. From that, autoionization of ‘small’ clusters strongly favours ICD, or is not possible at all. Indeed, the autoionization probability has been found as > 90 % for ‘big’, but only 70 % for small clusters (±10 %). In bigger clusters, a true Ar-Xe interface forms. Excited Ar atoms will therefore have several Xe neighbours available, which increases the number of channels available to ETMD(3).

Further interpreting figure 4 it is seen that ETMD leads to higher kinetic energies than ICD, in line with very recent theoretical work.

The ICD Network

The Electron spectroscopy group has initiated a german-austrian network for research on ICD and related processes. Funding for this research unit (http://www.icd.uni-frankfurt.de) has been approved by the DFG in 2012.

Scientific Staff

U. Hergenhahn, M. Förstel.

ITER

ITER Cooperation Project

Head: Dr. Hans Meister

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

Introduction

The many efforts made within the ITER cooperation project at IPP during the last year were rewarded by some pleasant news towards the end of 2012: The test facility ELISE has been commissioned and officially started operation in November. Also, IPP and its partners have been awarded the Framework Partnership Agreement (FPA) on the development of the ITER diagnostic pressure gauges by F4E in December. Our response to the Call for the FPA on the development of the ITER bolometer diagnostic is still under negotiation, but R&D efforts at IPP continue with national funding. The investigations related to the ITER ICH antenna within the CYCLE consortium and those related to the ECRH Upper Launcher within the ECHUL consortium continue. Furthermore, IPP concluded the investigations on a dust monitor for ITER, contributes to the development of the ITER CODAC system, to simulations of ELM effects on ITER performance, to the development of fusion materials and performed Paschen tests for cables for JT60-SA. Additionally, IPP is leading or 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 2012 with the final assembly and commissioning of the new ELISE test facility and with basic experiments as well with the continuation of diagnostic development at BATMAN and at the University of Augsburg (see corresponding chapter), accompanied by modelling of the processes leading to negative hydrogen extraction and electron suppression.

ELISE is now fully assembled. Due to different problems in manufacturing of components, the start of the experiments is delayed in total by about twelve months. The main issues have been in the manufacturing of the grid holder boxes, the coating of the large plasma grid (PG) and bias plate segments, some defects in the cryo systems – although that was used already at MANITU – and, finally, problems with the manufacturing of the diagnostic calorimeter. The latter is still in the prototype evaluation phase, so that for the start of the experiments a simple beam dump with rather limited diagnostic capabilities has been installed. The F4E service contract was prolonged by twelve months in order to ensure the two year experimental phase. The commissioning has started with HV grid conditioning (see figure 1) and the cool down of the cryo pumps.

But due to several leaks in the source and the calorimeter, the RF and beam commissioning is delayed.

In the upcoming experimental phase, ELISE will address the missing operational links between the experience that was gained with the small IPP prototype RF driven ion source at BATMAN and MANITU and the large ITER-like source. The main difference is the different magnetic and electric field maps in the boundary region near the plasma grid, where almost all processes leading to negative ion and electron extraction occur, due to the different bias plate geometry and the creation of the filter field by a PG current. The experiments in the next two years are supervised by the new ELISE program advisory committee being initiated by F4E and consisting of European neutral beam experts. The first meeting of this committee in November 2012 was accompanied by an official opening ceremony celebrating the end of the assembly and commissioning phase.

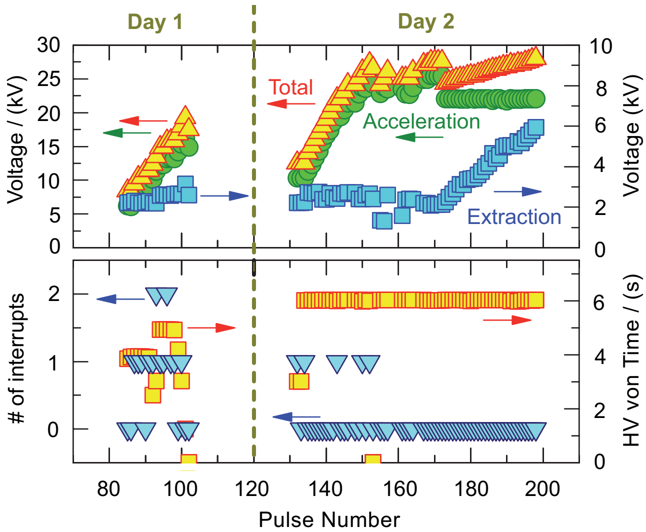

Figure 1: Progress of ELISE grid conditioning during the first two days. Final goal is 60 kV total and 10 kV extraction voltage.

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 IPP test facilities has now been started; tests of SPIDER diagnostic tools like CFC calorimeter targets and flat Langmuir probes have been performed together with RFX personnel at

BATMAN and GLADIS, with a total visiting time of almost twelve person-months. IPP personnel is also further involved in the tender and procurement of the SPIDER ion source. Similar supporting activities are still under way with the Institute of Plasma Research in Bhat, India, which is responsible for the construction of the ITER diagnostic neutral beam.
The other experiments at the BATMAN test facility continued on studies of the effects of the magnetic field structure on the source performance, now with an emphasis on deuterium. Similar correlations, but with larger magnetic fields, of the extracted ion density and the amount of co-extracted electrons have been found as for hydrogen. In order to have a validated input for models, the detailed diagnostic campaign for spatially resolved measurements of the plasma parameters from the driver to the plasma grid was continued in deuterium by using movable Langmuir probes and optical emission spectroscopy with a special emphasis on the still unresolved question of the large surplus of co-extracted electrons in deuterium compared to hydrogen.

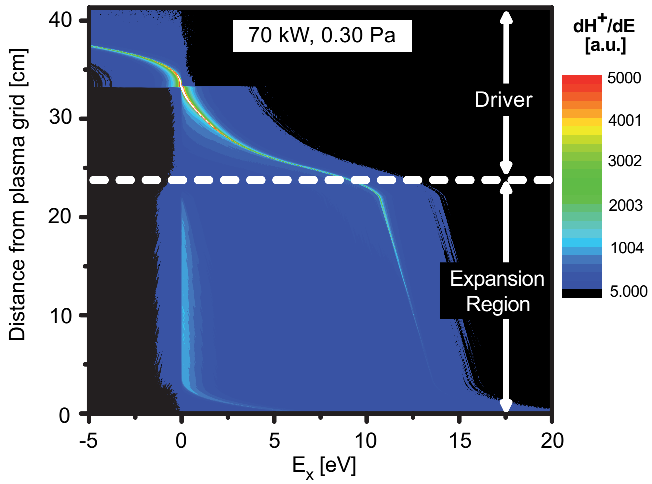

Figure 2: Calculated positive ion energy distribution across the IPP prototype source.

The IPP modelling activities of the processes in the boundary layer near the plasma grid where the negative ions are generated are concentrated on electron suppression, Cs distribution and beam diagnostics, also by collaborations with French groups at the Universities Toulouse and Paris-Sud. The latter collaboration resulted in a two-year Alexander-von-Humboldt scholarship for ion source modelling at IPP. The strength of the IPP modelling activities is the close connection of models with the experiments at the IPP test facilities. This ranges from modelling of diagnostics – e.g. Langmuir probe measurements or beam emission spectroscopy – to 2D or even 3D Monte-Carlo particle-in-cell codes of the processes inside a negative hydrogen ion source. An example is shown in figure 2 where the plasma potential distribution measured at BATMAN is used for the calculation of the positive hydrogen ion energy distribution. The calculation shows that the ion energy at the plasma grid is a few eV only and thus too low for a major contribution of positive ions in the negative hydrogen ion generation; the conversion of neutral hydrogen atoms to negative ions is the dominant process.

Design of the ICRF Antenna for ITER

The contract of the CYCLE consortium with F4E for the design of the ICRF antenna for ITER started in March 2010. IPP contributes to the design of the ICRF antenna through the consortium. Following the CDR (conceptual design review) in May 2010, IDRs (intermediate design reviews) in November 2010, May 2011 and October 2011, the PDR (preliminary design review) was successfully concluded on the major components of the antenna in May 2012. Following a PDR of the Faraday screen in February/March 2013, the grant is due for completion in March 2013. A final report has been submitted for comments to F4E.
Negotiations in 2012 between CYCLE, F4E and IO led to the agreement that future work should take place through a framework contract, which is being drafted. Work will concentrate on still needed basic R&D, prototyping and integration, as well as operational testing. IPP plans to keep involved in this work at the level of 1 ppy.

Upper Launcher for Electron Cyclotron Waves

The work on the physics performance of the upper EC antenna has been performed as part of the commitments of the ECHUL-Consortium Agreement in the frame of Grant 161 of Fusion for Energy. During 2012 a revision of the stabilization criteria for Neoclassical Tearing Modes (NTMs) has been performed. This analysis shows that the requirement, that the ratio η_{NTM} between EC-driven current density and bootstrap current density should exceed a threshold value (usually set to 1.2), applies to cases, in which the width w_{CD} of the EC deposition profile is larger than the marginal width w_{marg}, while a condition on the product $\eta_{NTM} \times w_{CD}$ (that has to be larger than 5 cm) has to be applied in the opposite limit $w_{CD} < w_{marg}$.
A numerical evaluation of the Rutherford equation has been implemented in a routine used to post-process the results of beam tracing codes. On the basis of the computed width and height of the driven current-density profile for a given toroidal angle and rational surface, the injected power is increased until unconditional stability is achieved. This procedure has been employed in the analysis of a simulated plasma discharge for the standard 15 MA ITER scenario, which has been made available in June. Beam settings have been taken from previous analyses, as the new mm-wave design is still not available. The steering range is found to be sufficient to reach the relevant flux surfaces except for the very early

phase of the current ramp up. The power requested for stabilization is well within the capabilities of the system during the current flat-top. The numerical results indicate that the maximum requested power occurs just after the H-L transition at the beginning of ramp-down.

ECRH Assisted Plasma Start-up

In order to quantify the requirements for ECRH assisted breakdown in ITER, F4E issued a call to develop a reference scenario for ITER focusing on a prediction of the necessary power and possible damages to the first wall, especially for the first plasma when most shielding components are still missing. This task separates into a review of the existing experiments and models, the set-up of a specific data base and the development of a quantitative model. The contract was issued to CNR (Italy). IPP contributed as third party to the initial review and supplied existing AUG data to the data base. CNR supplied FTU data. The quantitative modelling is done by CNR together with other third parties. A report is expected early 2013.

Diagnostics

ITER Bolometer Diagnostic

In June 2012, the Call for the Framework Partnership Agreement (FPA) for the R&D tasks on the ITER bolometer diagnostic has finally been published. IPP submitted a proposal with its partners Wigner RCP, IMM, MTA EK and KIT. The total estimated budget is ~9 M€, out of which 40 % will be funded by F4E. After answering to a request for clarification in November, the ITERBolo consortium is now waiting for the next steps to be taken by F4E.

Meanwhile, the R&D activities for the ITER bolometer diagnostic at IPP – still being supported by national funding – have continued their efforts in the areas detector development, prototype design and testing, and integration in ITER. The main focus of the investigations in 2012 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). The main challenge for this development is the mechanical stability at high operating temperatures. To this aim, several samples with different detector geometries have been produced and subjected to thermal cycling up to 450 °C. The variations included absorber shapes featuring edge corner radii between 0.2 mm and 0.8 mm, up to elliptical shapes, and absorber sizes between 0.95 mm × 2.2 mm and 1.9 mm × 4.4 mm. Furthermore, SiN membranes of 1.5 μm, 3 μm and 4.5 μm thickness have been tested as well as a Si membrane of 50 μm thickness. In all cases the mechanical stability proved to be insufficient. From the results of the various thermal cycling tests it could be concluded that in the case of the Si membrane the failure could be attributed to the low yield stress of Si. In the case of SiN membranes the thinner samples coped with a higher number of cycles. In combination with results from finite element analysis a fatigue cycle could be identified: due to the intrinsic stress from the deposition of a Pt absorber on the SiN membrane, the membrane is deflected in one direction; at elevated temperatures the deflection changes direction because of the different thermal expansion coefficients of Pt and SiN. The conclusion from these extensive tests is that the material chosen to support the detector needs to be ductile enough to take up the deflection induced by the material stresses and the thermal expansion. Efforts are ongoing to identify suitable materials as well as further designs for the the support of the absorbers.

The laser-trimming procedure of the meanders could be improved so that the resistance of all four meanders within one detector channel can be matched to within an accuracy of 1 Ω, or equivalently 0.1 %. This will help to reduce thermal drifts in the measurements to a minimum. However, the trimming process depends strongly on the individual sample and the parameters have to be adjusted for each lot.

In cooperation with the Physiklisch Technische Bundesanstalt (PTB) the sensitivity of two prototype detectors with 4.5 μm and 12 μm absorber thickness have been calibrated in the energy range from 3 eV up to 25 keV. A first overview already indicates that a 12 μm thick absorber can detect ~80 % of the incident radiation at an energy of 20 keV. Reliable statements will be available after the evaluations of the measurements have been concluded.

During the last year several prototypes for collimator and mini-camera housing have been tested in the laboratory. The investigations on the damping of microwaves by the camera housing have been complemented by another test in the MISTRAL facility, confirming the enhanced damping factor (~ factor of 2 with respect to previous designs). The test facility IBOROB (ITERBolo robot) for the automated measurement of line-of-sight properties is now able to routinely measure the transmission functions of collimator prototypes. Series measurements of several collimators and using different variations of apertures helped to identify design improvements for reducing stray light. A detailed discussion is given in chapter 'Technical University of Munich'.

The design of the diagnostic components concentrated on the development of housing and mounting bracket for a bolometer camera suitable for placement in a divertor cassette behind the vertical targets. The extensive application of finite-element-analysis tools helped to improve the designs and optimise the thermal heat transfer to the cooled structure of the cassette body. The maximum temperature expected for a design version without active cooling is ~370 °C (see figure 3) and can be handled well by TZM, the material proposed to be used. However, the boundary conditions applied to the simulations still need to be checked and some input parameters refined.

In particular, this applies to the thermal load due to neutrons, which has increased after a re-design of the divertor cassettes. Thus, the final decision whether active cooling is required for the bolometers in the ITER divertor is still open.

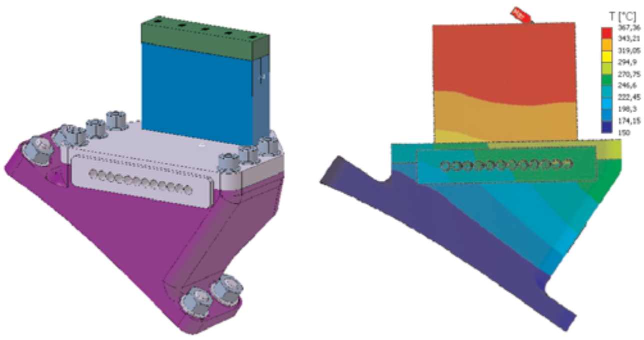

Figure 3: Design of a bolometer camera for the ITER divertor and results from a thermal analysis.

ITER Diagnostic Pressure Gauges

In March 2012 IPP responded to the Fusion for Energy Call for Proposals for a Framework Partnership Agreement (FPA) for the R&D of the Diagnostic Pressure Gauge for ITER, F4E-FPA-364(DG). This diagnostic shall measure in-vessel neutral pressure at several locations in the divertor, main chamber and pump duct regions, with and without plasma, and it will be used mainly for physics studies and advanced plasma control. The present baseline design is based on the so called ASDEX pressure gauge, an ionisation manometer adapted for operation in strong magnetic field, continuously developed since the 1980's at IPP. A consortium was formed under the lead of IPP including Karlsruher Institut für Technologie (KIT) and the engineering company Sgenia Solutiones (Spain). After a lengthy review and approval process the FPA has been awarded to the consortium and finally signed in December. The work will be developed over 4 years with a total budget foreseen of about 6.3 M€ and includes a team of roughly 17 persons for a total effort of 44 ppy with various competences and roles (administration including project management, physicist and engineers, various technical personnel). The main deliverable of the project is the documented designs and technical specifications for the DPG sensor head assembly and of the DPGs power supplies and electronics up to the level where built-to-print drawings and manufacturing specifications for hardware can be produced by economic operators. The call for the first specific contracts, concerning the production of the detailed project plan and organisation of the "Coordination Office", are expected during January 2013.

Dust Detector for ITER

Two capacitive dust monitors (CDM), as proposed for safety diagnostic in ITER, have been installed below the roof baffle in the divertor of AUG and investigated within the framework of a Grant by F4E. They were operated during the experimental campaign to prove the ability of this kind of instrument for reliable measurements in tokamaks. Both sensors were preloaded with 300 mg to allow to measure drifts of the readings. During baking of AUG the signal changed significantly, presumably due to changes in the cable capacity. The instruments were operated for 150 days in AUG. During this time the reading of the instruments was stable with a standard deviation of 6 %. During a plasma discharge, the signal is strongly disturbed by electromagnetic interferences generated, in particular, by plasma heating systems. But the reading in between discharges is not affected. Those experiments indicate that this technique seems suitable for in between shot dust measurement, as required for a safety diagnostic in ITER. Based on experience regarding dust production and deposition in AUG, suitable locations in ITER have been, by analogy, identified and an outline design for integration in ITER produced. It was proposed to install monitors in at least three different cassettes at four different poloidal locations. Efforts have also been made to estimate the cost expected for implementation on ITER. The detection limited of the present instrument will be at 10 % of the allowed ITER dust inventory, minor geometrical changes will extend this limit to 0.1 %.

Control and Data Acquisition (CODAC)

IPP participates in the design and development of a Plasma Control System Simulation Platform (PCSSP) for ITER, together with CREATE / Università di Napoli (I) and General Atomics (US). Based on the requirements and interface specifications compiled during the previous phase, a functional specification was developed, and the preliminary architecture for major components of the PCSSP was devised. It features a plant simulator and PCS simulator components, to model diagnostics, actuators, and plasma controllers in the required detail. Depending on the simulation goal, the control loop is closed via simple plasma models, or by interfacing to detailed external plasma models. Simulation input and output managers provide settings and commands, or archive and visualize computed data and results. To test real-life behaviour, an Event Generator allows simulation of the occurrence of off-normal situations: it triggers diagnostics, actuators or plasma models to compute data typical for plasma instabilities or plant system degradation, so that the control response can be studied. The analysis of such simulation runs will allow to iteratively improve the pulse supervision functionality within the plasma control, so that the exception handling required for ITER's high performance and long pulse discharges can be developed to sufficient maturity in time. By the end of 2012 the PCSSP preliminary architecture was under review at ITER.

To assist ITER in the preparation of the Plasma Control System (PCS) conceptual design review in July 2012 F4E entrusted CREATE / Università di Napoli (I) as consortium lead and IPP as co-lead to coordinate the EU contribution, with participation of CEA Cadarache (F), CRPP (CH) and CCFE (UK). Based on the broad EU expertise from ASDEX Upgrade, JET, TCV and Tore Supra, control use cases for nominal and off-normal operation scenarios were systematically captured and analysed to derive the control functionalities required during various phases of a discharge. From these, a conceptual architecture for the ITER PCS was designed, with particular focus on a universal control framework to coordinate dynamically changing sets of control units, a pulse supervision layer to take case specific exception handling decisions how to steer a discharge, and an actuator sharing concept to optimize the control of many variables with a limited number of actuators. The extremely demanding time schedule could only be met with an excellent cooperation among all the EU and US experts, and the ITER staff. Thanks to the team effort, the ITER PCS CDR was successfully passed in November 2012.

Simulation of the Effect of ELMs on ITER Performance

Within the framework of an F4E Grant (F4E-GRT-267) the effect of mitigated ELMs on ITER performance is investigated with the combined effort of members of several divisions of IPP, including both theoretical and experimental groups from the ASDEX Upgrade project. Four major topics are investigated within this framework:

First, a demonstration is required that the more recent version of SOLPS used at IPP is compatible with the older version used at ITER. Towards this aim good agreement has been achieved in 3 of the 4 cases provided by ITER, and work is continuing on the 4th case.

Secondly, SOLPS simulations with a mix of D, T, He, Be, Ne and W need to be performed to provide a pre-ELM steady state, and then to perform ELM simulations (1 MJ corresponding to mitigated ELMs, 10 MJ corresponding to unmitigated ELMs). SOLPS5.0-B2 simulations implementing the requested mix of species for the 100 MW full power case have been performed, and cases for the low-activation phase (40 MW, with predominant hydrogenic species and with predominant helium) have been started. For a subset of the cases, ELM-like enhancements of the radial transport coefficients have been performed. In order to include the effects of W prompt re-deposition, the re-deposition model of Dux has been implemented in the sputtering model of SOLPS5.0-B2. As expected, the re-deposition in ITER can have a large effect, lowering the steady state W concentration in some cases by more than a factor of ten.

Thirdly, the issue of neoclassical effects on W transport in the pedestal have been examined. For the pedestal profiles provided by ITER, no W impurity accumulation in the pedestal is found using STRAHL, unlike the situation found for ASDEX Upgrade. W accumulation can be encountered if the density gradient is steepened with respect to the cases provided by ITER.

Lastly, the effect of the mitigated ELMs on the plasma performance are to be examined. The core cases provided by ITER (steady state) have been repeated with ASTRA, and cases with similar performance have been found with ELMs. The next step is to take W sources obtained from the SOLPS modelling and include them in coupled ASTRA-STRAHL calculations.

Development of Fusion Materials

In order to assess the tritium removal procedure currently suggested for ITER – wall baking at 513 K (240 ºC) for the main chamber and 623 K (350 ºC) for the divertor – deuterium retention in and release from beryllium-containing mixed material layers were investigated within the framework of an F4E Grant (F4E-OPE-347). The maximum D concentrations due to implantation with 200 eV per D of all investigated mixed-material systems are comparable to or lower than published values for pure Be. It appears that low impurity concentrations (< 10 %) of the investigated impurities C, W and O lead to a reduction of D retention.

TDS analysis after D implantations at elevated temperatures showed that deuterium retention in the investigated Be layers is in good agreement with previous studies. D trapping in and release from Be/W- and Be/O-mixed layers are quite similar to those in pure Be. But carbon incorporation in Be can introduce additional C-related binding sites, which require relatively high temperature (above 600 K) for the D release.

The tritium removal efficiency of the baking operation will strongly depend on the wall temperature during implantation, i.e. during the ITER discharges. In the case that D is implanted at moderate temperatures (300 to 400 K), which would correspond to the "cool divertor" scenario in ITER, a large fraction of retained D is trapped in low-energy traps. In this case, wall baking will remove most of the retained tritium. If D is implanted at temperatures above 500 K, corresponding to the "hot divertor" scenario, the amount of retained D is roughly a factor of 5 to 10 lower than for implantation at 320 K. In this case, however, even baking at 623 K is not sufficient to remove tritium with high efficiency.

F4E Support – Paschen Tests

A proper electrical insulation is indispensable for a reliable operation of fusion magnets. Especially magnets in tokamaks are regularly loaded with high electrical voltages during ramp-up, ramp-down and during fast safety discharges.

Wendelstein 7-X has collected large experiences in high voltage testing during the production, the tests and the assembly of the W7-X superconducting magnets. High voltage (HV) tests under reduced air pressure (Paschen tests) have been identified as powerful method to check the quality of electrical insulation. IPP has been selected for the HV tests on a four wire quench detection cable for the JT-60SA superconducting magnets provided by JAEA through F4E. The tests have been performed in a special vacuum test chamber, in which the pressure can be controlled between ambient pressure and 10^{-4} mbar. HV feed throughs allow the application of up to 30 kV to the components to be tested. In case of a fast discharge the JT-60SA TF coils may experience voltages up to 1.4 kV whereas the PF coils may reach 10 kV. The test voltage for the TF coils is therefore 3.8 kV and for the PF coils 21 kV. The tests were performed at 3.8 kV and 21 kV in a helium atmosphere in the range between 10^{-4} mbar and 50 mbar. During all tests at 3.8 kV the currents stayed below 0.02 µA in the whole pressure range. Also, during the tests at 21 kV the currents stayed below 0.4 µA. In conclusion it is stated that the tested cable is able to operate at Paschen conditions in JT-60SA.

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 contributed to by several Associations and led by IPP – 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 ‘ASDEX Upgrade’, ‘DEMO’, ‘Plasma-facing Materials and Components’, ‘Theoretical Plasma Physics’ and ‘Energy and System Studies’.
The overall effort involved in the 69 tasks active in 2012 accumulated to 18.5 ppy, the maximum contribution by EFDA will be 544 k€. Half of the effort was invested in investigations for ITER Physics Support Projects (IPH; 38 tasks), for which a significant contribution for experimental hardware was granted in addition to the one for personnel. The remaining contributions are related to activities for Integrated Tokamak Modelling (ITM), Materials R&D (MAT), Design Tools and Methodologies (DTM), Socio-Economics (SER), Power Exhaust (PEX), System Code (SYS) and Design Assessment Studies (DAS).

Advancement of Young Scientists

The FUSENET project, which started in October 2008, has developed an active European network on fusion education. IPP was strongly involved in several packages, including the leadership of one work-package and membership in the executive board. To further explore a number of actions, which were initiated during the project, it was extended by one year until October 2013. To make the project sustainable, a legal entity has been created, the FUSENET association, where IPP is also strongly involved, among others through membership in the Board of Governors, and the Academic Council.
In 2012, nine fellowships have been granted in the first cohort of the FUSION-DC funded project. Five 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 with common meetings of the six trainees (one IPP, one KIT and four RFX Padova). The IPP trainee was strongly involved in the construction of ELISE and of the W7-X neutral beam system. The IPP trainee was exchanged as the former one was promoted with a permanent position at IPP indicating the success of the program.
The LITE (Lower hybrid and Ion cyclotron Technology) project ended. The IPP trainee, which gained extensive experience on RF generators, was hired by an industrial company, which has a contract with the Indian Association, responsible for the ITER RF generators.

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ECRH: E. Poli, J. Stober, H. Zohm.
EFDA Tasks: 70+ Scientists.
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ICRF: J.-M. Noterdaeme , K. Winkler.
ITERBolo: A. Gavrilova, L. Giannone, M. Kannamüller, J. Koll, T. N. Le, H. Meister, D. H. Ngyuen, A. Pathak, F. Penzel, T. Trautmann, M. Willmeroth; P. Detemple, S. Schmitt (IMM); H. Langer, C. Zauner (KRP Mechatec); S. Kalvin, G. Veres (Wigner RCP).
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DEMO

DEMO Design Activities

Head: Prof. Dr. Hartmut Zohm

The project ‘DEMO Design Activities’ continued to work on aspects of physics and technology relevant for both tokamak and stellarator DEMO designs. The links to FZJ and KIT within the ‘German DEMO Working Group’ proved to be very important to establish an integrated treatment of the area. Many of the activities were carried out under the EFDA PPP&T 2012 Work Programme, where substantial collaborations within the EU exist. Contributions in this field were presented at various conferences.

Physics Base for a Tokamak DEMO

The physics base for operation scenarios of a tokamak DEMO has been investigated establishing physics rules by which kinetic and current profiles are established from 0-d systems codes design points. This was done using the ASTRA transport code in conjunction with the SPIDER free boundary equilibrium solver. Profiles were set up assuming operation in the ‘improved H-mode’ scenario assuming flat monotonic q-profiles in the core with q>1 everywhere and temperature profiles not exceeding the critical temperature gradient and density profiles with peaking consistent with first principles predictions. The pedestal parameters were chosen to match overall confinement compatible with stable improved H-mode operation, i.e. H=1.2. These profiles also served as input for the heating and current drive assessment described below. The 0-d systems code TREND developed at IPP (see also ‘Energy and Systems Studies’ section of this Annual Report) was successfully benchmarked against PROCESS and HELIOS. TREND incorporates the ‘DEMO Physics Base’ that has been compiled in the EFDA PPP&T programme under leadership of IPP.

In the exhaust area, work is still ongoing to model better radiation losses as well as the power balance in the divertor. Here, it has become clear that DEMO must operate at least under partially detached conditions, but simple scalings for divertor power loads given a certain P_{sep}/R do not exist. This part of the work is closely related to the exhaust studies on ASDEX Upgrade reported in the corresponding part of this Annual Report. Finally, we have also assessed the possibilities of establishing an advanced divertor geometry, the so-called ‘snowflake’ divertor in a DEMO-like geometry with PF coils located outside the TF coils. This turns out to be very challenging due to the high currents required to create a higher order multipole null. An assessment has hence to be made how large a gain in flux expansion can be achieved with reasonable PF coil currents.

Heating and Current Drive Assessment

Using the above mentioned methodology to generate 1-d kinetic and current profiles consistent with 0-d output from the PROCESS systems code, a local analysis of the CD capabilities LHCD, ICCD, ECCD and NBCD was carried out under an EFDA PPP&T task together with CCFE, ENEA and ERM under leadership of IPP. For a conservative tokamak DEMO based on ‘improved H-mode operation’ (R_0=9 m, a=2.25 m, I_p=14 MA, $n_{e,lav}=8.8\times10^{19}$ m^{-3}, β_N=2.2, leading to P_{fus}=1.6 GW and $P_{el,net}$=500 MW), ICCD is mainly suited for on-axis CD, while LHCD can exclusively drive far off-axis (ρ>0.7) current for the profiles studies. For both systems, CD local efficiencies can be of the order of γ=0.3. Due to the constrained radial range, both systems cannot be used to individually synthesize the ohmic contribution to the current profile under consideration in this study. Combinations of systems have not been studied so far.

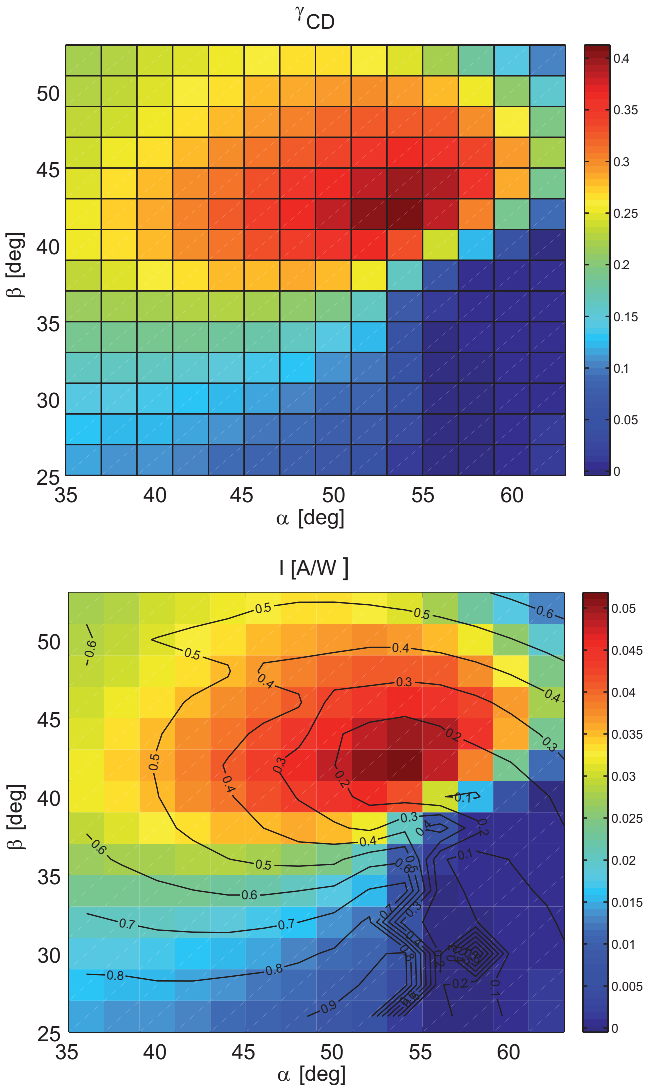

Figure 1: ECCD efficiency for top launch in DEMO (above). The plot below shows the driven current as well as contours of the deposition radius.

ECCD and NBCD show more flexibility, provided a careful optimization of the launch geometry, indicating that for NBCD, there is not much flexibility, while ECCD can in principle be flexible if steerable launchers or tuneable gyrotrons are used. Local on-axis CD efficiencies are of the order of γ=0.4-0.45, with off-axis (ρ=0.4) values dropping to γ=0.25-0.3 for ECCD while NBCD efficiency increases up to γ=0.55 in the best case. Consequently, NBCD has a global CD efficiency of $<\gamma>$=0.4 to replace the missing Ohmic current in DEMO1 while ECCD has a lower efficiency of $<\gamma>$=0.31. However, these values for ECCD are more than 50 % higher than previous estimates, which is due to a new optimization of the launch geometry: in our studies, the microwaves are launched from above the plasma to largely avoid parasitic absorption by downshifted higher harmonics in the hot DEMO plasma. The efficiencies are shown in figure 1.
In these studies, the ECCD frequency was chosen to be 280 GHz and the beam energy 1.5 MeV. Both choices present a significant challenge to technology and it should be evaluated what the impact of reducing these values to ones that seem more in reach of the technological development is.

Stellarator DEMO Studies

The stellarator line offers solutions to overcome specific risks in the more mature tokamak line. While many technical and engineering advances can be applied to both the tokamak and stellarator lines, certain stellarator-specific issues remain: burning plasma issues can neither be addressed with present predictive capabilities nor can be accessed in W7-X experiments. Hence, the nonlinear physics of α-heating in stellarator geometry will likely require experimental demonstration in an intermediate device with considerable Q but could be realized with reduced technical challenges by taking advantage of the nuclear technology developed by ITER and DEMO. Therefore, it appears to be a viable strategy to take the step from a burning plasma physics stellarator experiment (called 'HELIAS-ITER' in figure 2) to a first generation power plant. In particular, the demonstration of tritium self-sufficiency in a tokamak DEMO should validate the engineering tools to a degree that they are directly applicable to the stellarator power plant. The overall strategy is shown schematically in figure 2.
First design studies on such a HELIAS-ITER indicate that it could be operated with coils employing ITER technology and a first assessment of the maintenance properties looks promising. Cooperation with KIT in stellarator reactor technology is being discussed, also with regard to 3D blankets and shields. On the physics side, evaluation of the confinement database taking into account the different degree of neoclassical optimization of the participating devices (see section 'WEGA') has shown that this configuration parameter may play a crucial role in determining the size of the next step. W7-X will play a major role in reducing the uncertainties and clarifying the relation between neoclassical and turbulent transport in a HELIAS-type stellarator. In order to allow for more detailed consideration of different options and lines, an integration of a physics relevant stellarator module into a system code suite (PROCESS, collaboration with CCFE) is being addressed.

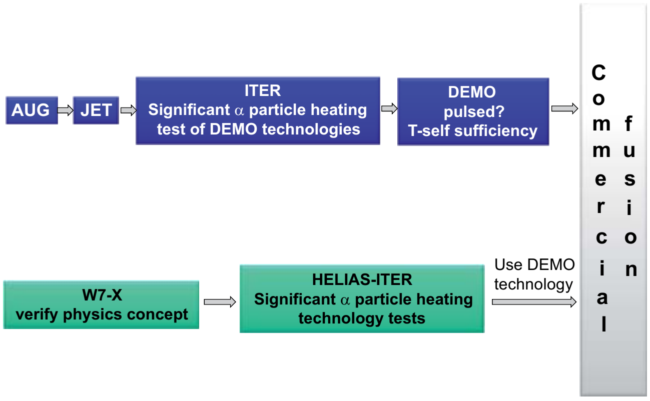

Figure 2: A possible roadmap to a commercial fusion reactor based on the stellarator principle.

DEMO Technology Studies

The assessment of the reliability, availability, maintainability and inspectability (RAMI) of a possible NBI system for ITER has been continued. Small lab experiments at the University of Augsburg (see corresponding chapter) regarding the neutraliser efficiency by laser detachment have been started for increasing the wall-plug efficiency by a factor of two, which is mandatory for using a NBI based CD system. Other activities aim at an increase of the reliability of the RF system by investigating new highly efficient coupling schemes and an assessment of the Cs consumption of a DEMO negative hydrogen ion source and possible alternative schemes for negative hydrogen ion generation without the need for a regular maintenance.
In the framework of the EFDA PPP&T activities, an assessment of the suitability of different engineering computer tools for integrated use in a DEMO design activity was carried out, building on the expertise gained in W7-X construction.

Scientific Staff

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Plasma-wall-interactions and Materials

Plasma-facing Materials and Components

Head: Dr. Wolfgang Jacob

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

Surface Processes on Plasma-Exposed Materials

Experimental Determination of the Resolution of D and H Depth Profiles from Nuclear Reaction Analyses

Well defined test samples were produced to investigate how the analysis depth and the matrix material influence the depth resolution of nuclear reaction analysis techniques. The D(^{3}He,p)α reaction was used to measure D depth profiles. By covering 10 nm thin deuterated amorphous carbon (a-C:D) films on silicon with tungsten (Z_W=74) and titanium (Z_{Ti}=22) at various thicknesses between 500 nm and 8 µm the influence of atomic number and overlayer thickness on the depth resolution could be assessed. The depth profiles resulting from the evaluation of the acquired spectra with NRADC represent response functions of the applied method. The apparent widths of the D-containing layers correspond to the depth resolutions that can be achieved experimentally under optimal conditions and with state-of-the-art data analysis. Their absolute values are in the same range as the theoretical optimum calculated with RESOLNRA. For measuring H depth profiles, the reaction p(^{15}N,α,γ)^{12}C was used at the RUBION device in Bochum. This method allows a determination of H depth profiles in W with an accuracy of 60 nm at a depth of 450 nm. This is better than the resolution of the ^{3}He method for D at a similar depth in W by a factor of 6.5.

Measurements of Net and Gross Erosion of Beryllium under High Flux Plasma Impact

A series of systematic experimental investigations were conducted in collaboration with the University of California, San Diego. The PISCES-B facility allows to expose Be samples under well controlled conditions in terms of particle energy and flux under ITER-relevant conditions. By introducing Be impurity ions into the plasma, it is possible to simulate a controllable and adjustable amount of redeposition without affecting the background plasma. By altering the amount of impurity ions depositing onto the target surface the relationship between gross and net erosion can be investigated. The measurements indicate that the simple definition of net erosion being equal to gross erosion corrected for redeposition is insufficient to explain the results. An increase, by an order of magnitude, in the re-erosion rate of the depositing species, compared to the bulk material species, is necessary to interpret the results.

Deuterium Trapping in and Release from Single- and Polycrystalline Beryllium

The first wall of ITER will mainly consist of metallic beryllium (Be). Hydrogen isotopes (D and T) from the boundary plasma will impinge on the first wall causing implantation and retention of D and T in Be. Atomistic processes relevant for retention and release of D in Be were investigated by comparing well-defined experiments on Be(0001) and Be(11-20) single crystals, and polycrystalline Be to simulations. Be has a hcp structure. Be(0001) and Be(11-20) are the two orientations with the basal planes of the unit cell oriented parallel and orthogonal to the surface. The experimental desorption spectra are modelled as a coupled reaction diffusion system (CRDS). The single atomistic steps are described by a set of rate equations. At low D fluences one single D release peak around 750 K is observed. Peak shifts of some 10 K are observed for different implantation depths and crystal orientations. D retention in Be(11-20) and polycrystalline Be is close to 100 %, whereas in Be(0001) only about 60 % are retained. The reduced retention in Be(0001) is attributed to anisotropic self-interstitial diffusion influencing the availability of mono-vacancy traps during implantation. Additionally, desorption spectra with various temperature ramps recorded on polycrystalline Be were successfully reproduced with the CRDS code. D_2 release from polycrystalline Be occurs at lower temperatures than from the single crystals. This is attributed to fast D diffusion along grain boundaries.

Sticking of CH_3 Radicals on Amorphous Hydrocarbon Films

The sticking of methyl radicals on amorphous hydrocarbon (a-C:H) films was studied using molecular dynamics simulations. The simulations show drastically different sticking probabilities on differently prepared a-C:H surfaces that are created either by bombarding the original surface with thermal hydrogen atoms or with energetic argon atoms. An algorithm based on potential energy analysis using hydrogen atoms as test particles was developed. This algorithm allows identifying the sticking locations of methyl radicals within the film. The mechanism of sticking is found to be the direct incorporation of a methyl radical on such sticking locations at the surface of the film. Different types of sticking locations were identified, which were found to play a crucial role in determining the reactivity of individual surfaces.

Migration of Materials in Fusion Devices

Long-term Erosion of Tungsten Layers with Different Surface Roughness in ASDEX Upgrade

W-coated marker tiles were exposed to plasma discharges at the outer strike-point of ASDEX Upgrade during the 2010-2011 experimental campaign. The campaign-integrated erosion of the different markers was determined by Rutherford Backscattering Spectroscopy. The W coatings were initially 2 µm thick and consisted of three poloidal stripes with different surface roughness. The original roughness values R_a of the stripes ranged from 0.4 to 6 µm. The net erosion rates of rough W coatings are 5-10 times smaller than those of smooth layers. This is most likely due to considerable re-deposition in valleys shadowed by protruding surface features on a rough surface. The rough markers also showed noticeable carbon- and boron-rich deposited layers on them. The surface of the rough coatings was largely modified, especially in the region closest to the strike point, while the smooth coatings had suffered from severe delamination in the same region.

Blistering and Re-deposition on Bulk Tungsten Exposed to ASDEX Upgrade Divertor Plasma

Tungsten bulk material is foreseen to be used in future plasma-facing components for JET and ASDEX Upgrade. In laboratory experiments various modifications of the surface morphology were observed after hydrogen plasma exposure showing a strong dependence on exposure conditions. On the other hand, on technical rough surfaces re-deposition occurs in fusion plasma devices even in erosion dominated regions.

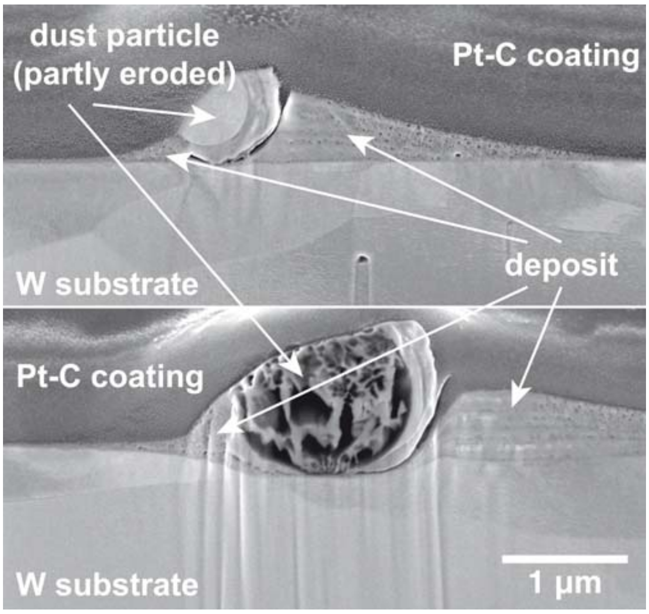

Figure 1: Scanning electron microscopy cross-section images of two spherical dust particles, which are partly eroded from the left side. The Pt-C coating is intentionally deposited and is required for the cross-section preparation. Top: Solid tungsten sphere with a spherical coating that had to be deposited prior to deposition on the surface. Bottom: Porous particle composed of tungsten, carbon, boron and oxygen. The deposition around the particle was probably deposited after landing on the surface. Both particles show a layered deposition in the plasma shadow zone on the right side.

In order to investigate blistering of tungsten and the re-deposition behaviour in AUG, a well-polished and pre-characterised polycrystalline tungsten specimen was exposed to the outer divertor plasma of ASDEX Upgrade close to the strike point for 510 discharges in the campaign 2011 by using the divertor manipulator system accumulating a fluence $\approx 6\times10^{25}$ m^{-2}. The exposure to the divertor plasma with a mixture of hydrogen and various impurities also led to blistering of tungsten. Apart from that the exposure parameters were comparable to those used in blistering studies of tungsten under laboratory conditions. Furthermore, spherical dust particles formed by the strong plasma contact were transported and deposited onto the nearly vertically oriented specimen. In subsequent discharges, these particles were partly eroded. In addition, in the "shadow" of the roughness introduced by the dust particle, a microscopic pattern of layered deposits was formed around them with an elongation rotated ≈40° to the projected B-field-line direction (see figure 1). After observing these patterns from dust particles, comparable features were also found on other AUG tiles with technical surfaces.

Tritium Inventory – Understanding and Control

Hydrogen Isotope Exchange in Tungsten

In ITER, the tritium inventory is limited by safety regulations and active measures need to be taken to stay below that limit. Hydrogen isotope exchange was proposed as one possibility to recover the tritium retained in the walls by plasma operation with pure deuterium. A dedicated laboratory study was performed with re-crystallized polycrystalline tungsten to determine the efficiency of that process and its dependence on target temperature. First deuterium was implanted from a low-temperature plasma source into mirror-polished W samples. Subsequently H was implanted with a mass-separated ion beam at different ion fluences. Elastic recoil detection analysis (ERD) with ^{4}He and nuclear reaction analysis (NRA) with D(^{3}He,p)α were applied to determine the surface concentration and the D depth profile. Thermal desorption spectroscopy was used to determine the total amounts of H and D. The reverse sequence of hydrogen isotopes loading and exchange allowed the analysis of the replacing isotope. Both sequences together deliver not only the efficiency of the exchange process but elucidate the dynamics of the underlying processes. Hydrogen isotope exchange has therefore shown to be an important tool for the understanding of hydrogen diffusion, retention and release in general.

Very efficient replacement of D in the near-surface layers by H or vice versa was observed. Already at a H fluence of 1/5000 of the initial D fluence about 30 % of the retained D was released. The release of D is balanced by the uptake of H. Consequently, retention is close to 100 % for these low fluxes in pre-loaded W compared to only 5 % in pristine W. Depth profiling of D in samples without and with subsequent H implantation at 320 K shows strong replacement close to the surface, but little exchange in deeper layers. In contrast, at 450 K exchange is quite effective in all analyzable depths (<7.5 µm). In figure 2 D depth profiles are shown for samples that were preloaded with H before D implantation. One can clearly see that deuterium does not freely diffuse through the initially hydrogen saturated layer to find traps deep in the bulk. In contrast, with increasing D fluence a D retention front moves into the bulk indicating that every H-containing trap is a potential trap for D. Consequently, transport is a sequence of trapping, de-trapping and diffusion events.

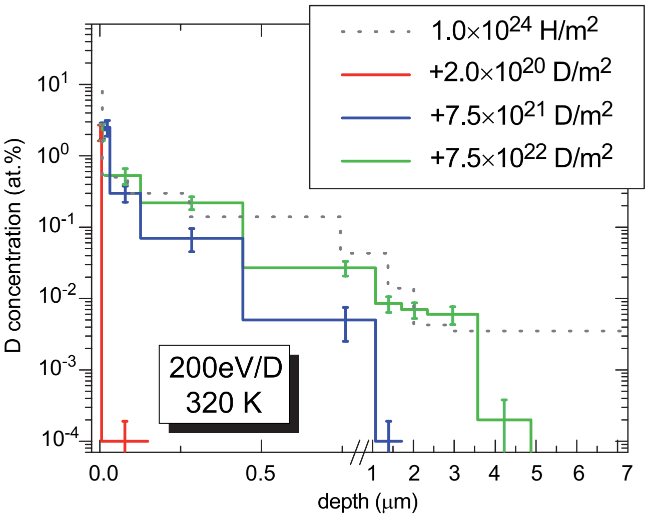

Figure 2: NRA depth profile of deuterium implanted into recrystallized, polycrystalline tungsten for different fluences. Samples were first saturated with hydrogen with a fluence of 1×10^{24} H/m². The hydrogen saturation zone is indicated by the dotted line.

The difference between surface and bulk exchange efficiency suggests that two types of de-trapping mechanisms have to be assumed: The high efficiency of the near surface process could be partially attributed to kinetic energy effects within the ion range. By applying diffusion/trapping models it was shown that beyond the implantation range the isotope exchange can be explained by thermally activated de-trapping of occupied sites.

Although the application of the present results to ITER conditions is difficult, the data indicate that in specially tailored, pulsed discharge scenarios in H or D – avoiding high recycling of the released tritium – near surface concentrations of tritium can be exchanged very quickly with high efficiency. However, this inventory is expected to be re-established equally efficiently after the start of subsequent discharges. Therefore, hydrogen isotope exchange is not an option to extend the operation time until the tritium inventory limit is reached, but appears to be a valid method for reducing the tritium inventory before major interventions or at the end of an operation period.

Saturation of Deuterium Retention in Damaged Tungsten Exposed to High-flux Plasmas

Deuterium retention in damaged tungsten at very high deuterium fluxes was investigated in collaboration with FOM DIFFER. Polished and annealed tungsten targets were damaged at IPP Garching by MeV W ion implantation up to a damage level corresponding to 0.45 dpa. Deuterium was implanted into these damaged samples at FOM DIFFER using high-flux plasmas in Pilot-PSI (~10^{24} ions m^{-2}s^{-1}) up to fluences of 4×10^{27} ions m^{-2} at surface temperatures of 400-500 K. Deuterium retention was studied by NRA at IPP and by temperature programmed desorption (TPD) at FOM DIFFER. Saturation in deuterium retention was observed at very high plasma fluences of about 2×10^{27} m^{-2}. At such high fluences all traps created by the tungsten pre-irradiation that can be decorated by deuterium are occupied. The local D concentration in the damaged region is 1.4 %. Scanning Electron Microscopy revealed large blisters being present at the surface. The dominant trapping sites for deuterium are damages created by MeV ion irradiation, which is only present in the first 1.5 µm below the surface.

Deuterium Retention in Tungsten Films: Comparison of Two Quantitative Methods

Tungsten (W) films with thicknesses between 1 and 12 µm deposited by magnetron sputtering on silicon substrates were used as a model system for comparing D retention measured by both TPD and NRA. Samples were loaded with D ex-situ from a plasma at 370 and 600 K with an energy of 38 eV per deuteron. To avoid diffusion of D into the silicon substrate and to increase adhesion a copper interlayer was applied. The results show that all implanted D atoms were retained exclusively in the W films. The distribution of D is homogenous throughout the W layer with an atomic fraction of $3\pm0.4\times10^{-3}$. With increasing W thickness the D profile extends to correspondingly larger depths with practically identical D concentration. For W films with a thickness lower than the NRA information depth of about 8 µm the total retained D amount measured by TPD and NRA is in excellent agreement. As expected, for films thicker than the NRA information depth, TPD deviates from NRA. The excellent agreement can be considered as a confirmation of the correctness for the quantitative evaluation procedures for both methods.

Materials and Components

Influence of D Implantation on Plastic Properties of W

Implantation of hydrogen isotopes into tungsten causes severe microstructural damage in the near surface layer. The evolution of H-induced damage is often observed to be promoted by local plastic flow. Since solute H tends to soften metals, the question arises as to the extent of tungsten softening due to implanted hydrogen.

The change in slip resistance (i.e. yield stress) of tungsten single crystals after D implantation was investigated in nano-indentation tests. The so called pop-in stress at the onset of crystal slip was measured for 3 different crystal orientations. The pop-in stress represents the inherent plastic strength of a given slip system. At first, specimens were heated at 950 °C for 12 h prior to implantation to outgas the initial H impurity and to remove oxide films. The annealing reduced the H concentration in the bulk from 1.7×10^{-3} at.% to 7×10^{-4} at.%. Subsequently, D was implanted into tungsten from a plasma with an ion energy of 38 eV and a fluence of 6×10^{24} D m^{-2}. NRA analysis of the D depth profile showed that the majority of the implanted D is in a near surface layer corresponding to a mean concentration of about 5 at.% in the top 20 nm.
A clear effect of trapped D was found for all orientations: The pop-in stress decreased significantly after D implantation. On the other hand, the pop-in stress was not affected by heat treatment. This result delivers an evidence of hydrogen-induced plastic softening. In addition, the distribution of the pop-in stresses was found to be dependent on crystal orientation: the (100) orientation showed the highest pop-in load range whereas the (111) orientation the lowest.

SiC Fibre-Reinforced Copper Matrix Composites

In the divertor design for a DEMO reactor, the requirement of effective power exhaust is a critical issue. Currently, the water-cooling concept is gaining wide acceptance owing to its large heat removal capacity. The design of a water-cooled divertor is based on a dual-material joint consisting of W armour and CuCrZr alloy as heat sink material. One problem is that the copper alloy becomes softer owing to ageing and operation at elevated temperature. It remains a challenge to enhance the high-temperature strength of heat sink components. In this context, IPP has been working on the development of novel copper-based composites reinforced by strong SiC fibres.
In 2012, extensive thermal and mechanical tests and characterisations were carried out to evaluate the materials. Many specimens spanning a wide range of fibre volume fractions were fabricated based on the metallurgical process developed at IPP. The measured data of tensile strength and heat conductivity agreed well with the rule-of-mixture predictions indicating excellent quality of the samples. The full capacity of strengthening could be realized by fibre reinforcement with optimised interface coatings. For instance, the tensile strength for the fibre content of 40 vol. % reached 1200 MPa at room temperature. At 300 °C, it exceeded 800 MPa for a fibre content of 30 vol. %.
Thermal degradation was investigated after long-term heat treatment in vacuum at the relevant foreseen operational temperature of 550 °C for 400 h. Damage of the fibres was sporadically observed after the heat treatment. The damage initiated at the outer carbon coating leads to diffusion of Cu into the SiC fibre and reaction with the free Si in the silicon rich outer mantle forming a brittle silicide. This brittle phase leads to a cracking of the fibres and overall degradation of strength. Further optimisation of SiC fibres and characterisation are still ongoing.

High Heat Flux Test Facility GLADIS

The heat flux test facility GLADIS is used to investigate plasma-facing components as well as small test samples under fusion-relevant heat and particle loads. In 2012, the GLADIS contribution to W7-X was dedicated to the assessment of the first manufacturing series of the high heat flux divertor and the technology development for the 2nd series (see Wendelstein 7-X, section 4.1). The investigation of tungsten components focussed on the study of surface morphology changes during hydrogen and mixed H/He loading.
To ensure a constant high thermal performance of the installed W7-X HHF divertor a final assessment of the delivered elements with operational heat load is indispensable. As reported in the previous years, a statistical quality assessment method has been developed for the series manufacturing. The method is based on the analysis of the local temperature evolution ΔT of individual CFC tiles loaded with 100 cycles at 10 MW/m². A temperature increase ≥75 K is a clear indication of a defective CFC bonding.

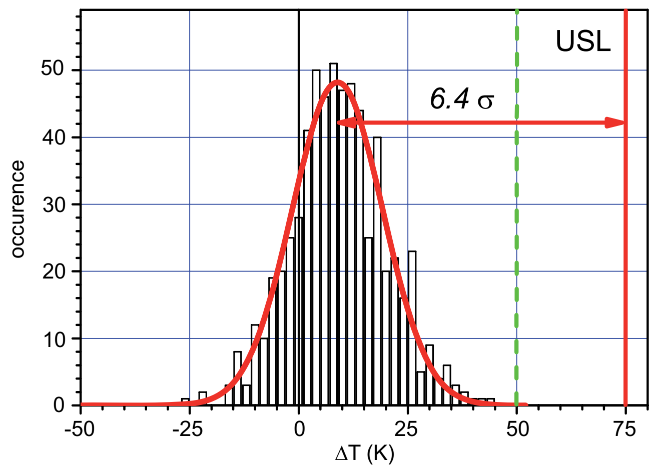

Figure 3: Histogram of ΔT for all tested CFC tiles of manufacturing phase 1 after 100 cycles at 10 MW/m². The dashed line at ΔT=50 K marks the region for tiles without any indication of a defect.

A stable industrial manufacturing of a high number of components gives products whose measurable properties correspond to a Gaussian distribution characterised by the two parameters μ (mean) and σ (standard deviation). Six σ distance from the mean to the upper specification limit (USL) results in a very high reliability of the production quality with only two defective parts per billion. In total, 13 % of the series I elements were tested. The analysis of 320 CFC tiles in figure 3 shows that the distribution of ΔT can be matched well by a Gaussian. All tiles clearly fulfil the specification. According to the measured distance of 6.4 σ between mean and USL the risk of an undetected defective tile is very low. This analysis confirms a high thermal performance of the delivered elements and the stability of the manufacturing process. Quality deteriorations would be detected by a change of the parameters of the Gaussian.

Tungsten Erosion under Combined Hydrogen/Helium High Heat Flux

Tungsten is considered to be of vital importance for the design of well performing and sufficiently long-lived divertor components for future fusion reactors. The plasma in the divertor of a power reactor will be comprised of a D/T mixture with a concentration of helium in the range of 5 to 10 at%. The formation of surface and near-surface features with typical dimensions in the range of nanometres to micrometres under irradiation with He or H/He mixtures has been reported. The resulting morphology after irradiation with a H/He mixture is distinctly different from the morphology after irradiation with the pure species. The question how this morphology influences the erosion behaviour of tungsten was investigated applying a newly devised method. This method allows to directly measure the erosion on actively water-cooled test components exposed to a mixed H/He beam at a power density of 10 MW/m^2. It is based on using a focussed ion beam (FIB), which is implemented in a scanning electron microscope (SEM): Prior to exposure markers are engraved on the samples using the focussed ion beam. By analysing the marker positions with respect to the tungsten surface before and after exposure we can directly measure the material loss on a scale of micrometres.

The experiments were performed in the GLADIS facility. GLADIS is operated with hydrogen, helium, or mixtures of both with particle fluxes on the order of several 10^{21} $m^{-2}s^{-1}$. In up to 600 pulses – lasting 30 seconds each – samples were exposed to a hydrogen beam with 6 % of helium reaching stationary surface temperatures after a few seconds. The surface temperatures were varied from 600 to 2000 °C covering the reactor-relevant range. Since there is massive grain growth at high temperatures during the exposure, our method measures the erosion of individual grains. To obtain information on the crystal-orientation-dependent variation of the erosion we investigated the surfaces by confocal laser scanning microscopy after exposure, which yields 3D topographies. The measured erosion exceeds the amount predicted by numerical data on physical sputtering by a factor of two. Scanning electron microscopy of cross sections of the samples prepared with the focussed ion beam show the temperature and fluence dependence of the formation of the surface morphology in depth in the fluence range of 2×10^{25} m^{-2} to 7×10^{25} m^{-2}.

Integration of and Collaboration in EU Programs

EU Task Force on Plasma-Wall Interaction

The project continues to support the EU Task Force on Plasma-Wall Interaction. IPP supplies the TF leader and the expert group leaders for “Fuel Retention” and “ITER-relevant mixed materials” are members of the project at IPP. 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 the EU Topical Group “Materials” on W materials development and high heat flux investigations. Within the EFDA Fusion Programme the Project provides two mid-size facilities: The High-Heat-Flux Test Facility GLADIS and the Integrated PWI Facility.

EFDA PPP&T Task “Bare Steel Wall”

Within the EFDA work programme 2012 on Power Exhaust (PEX) the project participated in the task agreement “Bare Steel Wall” as the coordinating partner. The purpose of the task agreement is the investigation of the potential direct usage of unprotected low-activation steel as plasma-facing surface material. At IPP the two main activities are the inclusion of steel as a plasma-facing material into the ASDEX Upgrade programme as well as initial laboratory studies on its erosion behaviour. Both activities are to be extended in 2013. In the ASDEX Upgrade programme it is foreseen to use the steel P92 as a substitute for the European low-activation material EUROFER. For the application of the ferromagnetic P92 steel in ASDEX Upgrade in larger quantities the experimental determination of its magnetic properties as well as a finite element study on the resulting forces and magnetic perturbations were performed. In addition to the activities at IPP the coordination of the task also included the activities of five further associations.

Scientific Staff

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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

Tungsten samples were irradiated by 20 MeV W^{6+} ions in order to create radiation-induced damage as a proxy for radiation damage by neutrons, the damaged zone was investigated by Transmission Electron Microscopy (TEM). The extension of the damaged layer is in good agreement with SRIM calculations, the defect density varies with distance from the sample surface. At 0.01 dpa the TEM images are dominated by small defects with sizes below 20 nm. At 0.1 dpa these small defects begin to form "chains" and a web-like structure of defects emerges, at 0.89 dpa a further coarsening of the defects is noticeable.

Atomic and Low-energy Plasma Interaction with Damaged Tungsten

Tungsten samples were irradiated by 20 MeV W^{6+} ions to create radiation-induced damage. The samples were then exposed to a deuterium atomic beam and to a low-energy deuterium plasma (~5 eV to ~20 eV) at sample temperatures from 500 to 900 K. D retention in the damaged zone is similar for the low-energy plasma and the atomic beam exposure at identical fluences. The rate of deuterium decoration of defects depends on ion energy, ion flux, and temperature. The total retention and the penetration speed into depth depend on the dpa level. D retention in damaged W is one to two orders of magnitude higher than in undamaged W and decreases with temperature.

Annealing Behavior of Radiation-induced Defects in Tungsten

Tungsten samples were irradiated by 20 MeV W^{6+} ions to create radiation-induced damage. This damage was subsequently annealed up to temperatures of 1200 K, the remaining damage was decorated with D in a low-temperature plasma discharge. A significant decrease in the amount of retained D was only observed at pre-annealing temperatures above 800 K. But even after pre-annealing at 1200 K D retention is still about two orders of magnitude higher than in undamaged W.

Deuterium Retention in Doped Tungsten Materials

Deuterium retention in tungsten doped with 1.1 wt% TiC and 3.3 wt% TaC (manufactured at Tohoku University, Japan) was investigated after irradiation by 200 eV/D ions and by 38 eV/D deuterium ions from an ECR plasma. The retention was found to be about the same as in stress-relieved pure tungsten at the highest fluences at low temperatures, while retention after irradiation at 600 K to the highest fluence was several times higher than that in stress-relieved undoped tungsten.

Deuterium Retention in Undamaged and Damaged EUROFER and RUSFER

Reduced-activation ferritic/martensitic steels (RAFMs), such as EUROFER and RUSFER, are candidate structural materials for future fusion reactors. The hydrogen isotope accumulation was measured by exposing samples to a low-energy D plasma or to D gas. The amount of D retained in both steels significantly increases with temperature, while the dependence of D retention on gas pressure is very weak. The amounts of deuterium retained in RUSFER and EUROFER are comparable. The differences are related to the surface conditions of the samples, which are determined by the treatment during manufacture. The estimated value of the gas-driven permeability through RUSFER is about one order of magnitude smaller than for EUROFER.
To simulate fast neutron damage, samples were irradiated by 20 MeV W^{6+} ions. The steady-state concentration of deuterium in radiation-induced traps in EUROFER is considerably lower than in W. Three D binding energies were found in EUROFER for undamaged and damaged samples: This indicates that irradiation of EUROFER produces the same trapping sites for deuterium, which already exist in the unirradiated material.
In order to study the influence of damage by high heat fluxes, EUROFER and RUSFER samples were exposed to energy fluxes of 0.5 MJ/m^2 from radiation heat in 0.5 ms at the QSPA facility at TRINITI. These heat fluxes are higher than the melting threshold, and a melted and resolidified layer with a thickness of 10-20 μm is expected. The exposures of the damaged specimens to deuterium gas and plasma are planned for 2013.

Deuterium Retention in and Permeation through Low-activation Vanadium Alloys

The deuterium retention in a V-4Cr-4Ti alloy (produced by Bochvar Institute, Moscow) was investigated under gas loading and low temperature plasma irradiations. The absorption rate of deuterium at gas loading increases exponentially with increasing sample temperature from RT-700 K, the maximum deuterium inventory was 10 at.%. The permeating flux through the material is three orders of magnitude higher than for RUSFER steel under comparable conditions.

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Plasma Theory

Plasma Theory and Computational 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 Computational Plasma Physics, of two Junior Research Groups, and of the HLST Core Team of the EFDA HPC Initiative. It is also a major partner in the new Max-Planck-Princeton Center for Plasma Physics.

Tokamak Physics Division

Head: Prof. Dr. Karl Lackner

Tokamak Edge Physics

Axisymmetric Scrape-off Layer Modelling

Significant effort went into supporting and developing the SOLPS package. Work continued on the project extending the SOLPS5.0 simulation domain to cover the whole vessel (in collaboration with CNRS LSPM, Paris). The B2.5 plasma fluid solver was modified to support the more complex cut-cell type grids generated by CARRE2. First simulations with simplified boundary conditions were performed.

Poloidal distributions of plasma parameters around the separatrix position under the conditions of high temperatures and sharp radial gradients of density and temperatures present in H-modes were modelled with the 2D fluid code EDGE2D. Large in-out (high field side – low field side) asymmetries, but small up-down asymmetries, of plasma density, pressure and electric potential just inside of the separatrix follow from the code. The absence of up-down pressure asymmetries contradicts one of the assumptions of the heuristic Goldston model for the power decay length at the divertor target yielding a scaling λ_q~q/B. The results of the EDGE2D modelling suggest an alternative explanation, related to the stability of ballooning modes around the separatrix position, for the narrow power deposition footprints at divertor targets observed in ASDEX Upgrade and in JET.

In preparation for improving power exhaust predictions for DEMO, dedicated N-seeding experiments have been performed in ASDEX Upgrade and JET for validating radiation models in the scrape-off layer and divertor. SOLPS5.0 simulations have been prepared to describe these experiments, using the highest level of physics description available in the code package: multiple impurity species, kinetic neutral description and activated drift and current terms. Extensive scans of the incremental effects of seeded impurities have yielded radiation patterns and in-out asymmetries qualitatively similar to those observed in the experiments.

Turbulence in the Near-separatrix Region

A 3D turbulence code for the edge-SOL is being developed within a PhD project with emphasis on the effects of the X-point. For a start a simplified physical model (Hasegawa-Wakatani) is used and a Cartesian grid can solve the problems, which usually arise in field aligned coordinate systems. The discretisation of the perpendicular gradient operators is straight forward, while the discretisation of the parallel operators is done via field line tracing and interpolation. The application of the support operator method for the parallel operators suppresses the spurious numerical perpendicular transport. This has been shown using a model 3D diffusion equation. Benchmark runs of the turbulence code give promising results. Further testing and improvement of the code concerning the physical model and performance is being pursued.

MHD Theory

Non-linear MHD

Experimental investigations of ELMs in TCV have shown strong low-n components in the magnetic signals, which are even dominant in many cases. This cannot be explained by linear stability analysis, which typically predicts harmonics with toroidal mode numbers of order ten to be most unstable. We could, however, reproduce a strong n=1 component in the early phase of an edge localized mode (ELM) in realistic tokamak geometry using the non-linear MHD code JOREK. The n=1 perturbation is driven by three-mode coupling with strongly unstable modes with adjacent n-numbers of order ten.

Many large-scale instabilities, like resistive wall modes, vertical displacement events, or disruptions are strongly influenced by conducting structures close to the plasma boundary. This can considerably alter linear growth rates and non-linear behaviour of the modes. The Green's function based algorithm previously used only in linear models to include this effect has been used also for the nonlinear MHD code JOREK by coupling it with the code STARWALL. First benchmarks against linear codes have been performed in limiter geometry revealing good agreement for a tearing mode, a resistive wall mode, and a vertical displacement event.

The nonlinear response of tokamak plasmas to applied resonant magnetic perturbations (RMPs) is studied numerically by using both the single and two-fluid equations. The following two issues are investigated: 1) Shear Alfvén resonances: It is well known that shear Alfvén resonances on the two sides of the resonant surface can be induced in a rotating plasma by applied static RMPs. The transition from shear Alfvén resonances to forced magnetic reconnection is studied. It is found that for sufficiently low magnetic shear and/or high plasma rotation frequency, shear Alfvén resonances exist if the applied RMP amplitude is not too large. With increasing RMP amplitude, however, shear Alfvén resonance is changed to forced reconnection due to the decrease of the local plasma rotation frequency by the electromagnetic torque. 2) Particle and energy transport in a stochastic magnetic field, generated by applied RMPs of different helicities, are studied.

It is found that the results are similar to that of a single island with no stochasticity. The electron density and temperature can be either decreased or increased by RMPs, depending on the difference between the plasma rotation frequency and electron diamagnetic drift frequency, transport coefficients, plasma viscosity, magnetic Reynolds number, and on other parameters. In the frame of a PhD thesis we are currently using the nonlinear 3D code XTOR to extend these studies from straight cylindrical plasmas to realistic, finite aspect ratio equilibria.

Equilibrium Calculation and Stability

Additional non-axisymmetric fields produced by magnetic perturbation coils like recently installed in AUG can cause stochastization and island formation in the plasma boundary region. Simply adding these fields to computed axisymmetric equilibrium fields overestimates stochastization and island formation, because the plasma shielding effect is neglected. Therefore three-dimensional, ideal, free-boundary equilibria (β_N=1.54) have been calculated with the 3D NEMEC equilibrium code for various perturbation fields (n=1,2,4, even and odd parity). Since the NEMEC code is an ideal code that assumes nested flux surfaces, stochastization and island formation inside the plasma are excluded. However, the response of the plasma to the perturbation field leads to poloidal and toroidal deformations of the flux surfaces. These deformations are largest at the plasma boundary close to the upper MP coils. The deformation is largest for n=1 perturbations and can give rise to deviations of the 3D plasma boundary from the corresponding average axisymmetric boundary by more than 1 cm.

Modern poloidal divertor tokamaks, such as ASDEX Upgrade (AUG), are unstable against vertical displacement. The growth rate of this 2D instability in the presence of stabilizing passive conductors (PSL) with finite resistivity was calculated for 5416 AUG equilibria, using a general ideal MHD code package (NEMEC, CAS3DN, STARWALL), which is able to take into account the 3D structure of the PSL. The comparison of the resulting growth rates with those from the previously used rigid displacement model shows that the latter can be misleading, predicting a stabilising effect of the triangularity. This is in line with the experimental observation on AUG of an increasing discrepancy between previously predicted and observed growth rates for strongly triangular plasmas.

Energetic Particle Physics

The non-linear hybrid code HAGIS has been extended in order to include a finite perturbed parallel electric field. The motivation for this generalisation is the fact that both Alfvén and Alfvén-Acoustic modes and their energetic particle branches can have a substantial parallel electric field that changes the resonance condition and therefore the mode growth and saturation. Successful consistency tests and first runs with fully gyrokinetic LIKGA eigenfunctions were carried out. Furthermore, the non-linear transport and loss of energetic ions in ASDEX Upgrade scenarios were investigated. High resolution runs allow to directly Fourier transform the energetic particle losses and compare to the spectrograms from the fast ion loss detector. In addition to very good quantitative agreement for the pitch angle and the energy of the lost ions, a reasonable qualitative match is found in multi-mode scenarios for the losses modulated with the beat wave frequency of toroidal (TAE) and reversed-shear Alfvén (RSAE) eigenmodes.

A project starting in 2012 focuses on the nonlinear interaction of Alfvén instabilities (AI) with energetic particles. As tool the nonlinear gyrokinetic PIC code named NEMORB (electro-magnetic, multi-species version of ORB5) is used for the self-consistent modelling of AI driven by fast ions, together with the linear gyrokinetic code LIGKA. This year, we have started the benchmark of NEMORB on electromagnetic instabilities with the goal of modelling beta-induced Alfvén eigenmodes (BAE) observed in ASDEX Upgrade, which show a peculiar chirped-frequency character, footprint of a strong nonlinear interaction with energetic particles. We have also built an analytic model for these chirped-frequency BAE, in the framework of the generalized fishbone-like dispersion relation. Finally, we have started an analysis of AI observed in ASDEX Upgrade in absence of NBI, but in presence of turbulence with LIGKA, to be completed with NEMORB in the near future. A complete understanding of this novel drive mechanism could help explaining the complex behaviour of AI in the presence of both NBI and turbulence.

Modelling of Massive Gas Injection

A simple new model has been developed to understand the dynamics of the gas penetration during Massive Gas Injection experiments at ASDEX Upgrade, when high Z material is injected at a rate larger than 10^{24} particles/s. The 3D phenomena were simplified and implemented in a combined 1D radial and two-cells toroidal model. A beam model is used to describe the flow of the neutrals towards the plasma centre, while the transport of the ions resulting from the hot plasma-beam interaction is described by a 1D diffusion model. The electron temperature inside the partially ionized gas cloud is determined by the dynamics of the cloud itself and by the toroidal free electron flux of the background plasma in the collisionless limit and by the Spitzer theory in the collisional limit. The model was first applied to calculate the penetration of Neon into an ASDEX Upgrade H-mode discharge and to determine the thermal quench time. The calculated thermal quench time is of the same order of magnitude as in the experiment. To allow for a better comparison and understanding, more physics effects need to be added to the model.

Kinetic Theory and Wave Physics

The package TORIC-SSFPQL has been improved during the year, and in particular self-consistent simulations with whole antenna spectrum can now be performed. Comparisons of simulations done with all relevant toroidal modes with those done using the fields of a single "representative" toroidal mode have shown that the effects of taking into account the whole antenna spectrum are visible, although they are not large. It is more important to perform the consistent loop between the full-wave and Fokker-Planck solvers. As a spin-off, the algorithm for the Hilbert transform developed in TORIC for general plasma dispersion functions has been optimized with fast Fourier transform, and proposed as a fast algorithm for general applications of the Hilbert transform, for instance in signal processing.

On the theory of high-frequency wave propagation, the relation between the direction of energy flux and the extended rays calculated in the frame of complex geometrical optics for diffracting beams has been investigated. A corresponding calculation has been implemented in the frame of the paraxial approximation used in the electron cyclotron (EC) code TORBEAM. These extended rays are used to couple TORBEAM with the Fokker-Planck code RELAX (see ALPS group report). TORBEAM has been employed also to study the current-drive efficiency achievable by means of EC waves in a high-temperature tokamak reactor. The best performance is reached for injection from an elevated position and at high frequencies. With this set-up, the path through parasitic (2nd harmonic) absorption region is reduced and the beam energy is deposited on higher-energy (lower-collisionality) electrons (see DEMO activities). A revision of the stabilization criteria for Neoclassical Tearing Modes used up to now to develop the EC Upper Launcher for ITER has confirmed their validity, highlighting their range of applicability (see ITER activities). TORBEAM has taken part in the European code benchmark performed within the Integrated Tokamak Modelling activity.

We continued our studies of neoclassical physics in the pedestal region of a Tokamak H-mode plasma: The neoclassical transport of trace impurities was studied with guiding centre particle simulations. A two-step procedure was used: First the flow of the main ions was calculated neglecting impurity effects, then simulations for different impurity species were made including the collisions with the main ions. The main results are: The parallel impurity velocity deviates from that of the main ion velocity. The deviation is much stronger on the low field side than on the high field side, leading to a strong poloidal variation of the parallel impurity velocity like that observed in the experiment. The deviation from the main ion velocity and the poloidal variation are stronger at lower collisionality. There is a strong poloidal variation of the density. The peak is on the high field side at the edge and moves towards the top further inward.

A slab version of the gyrokinetic code GKW has been developed to investigate the properties of magnetic islands in this limit. Consistency checks regarding the matching of island and particle motion for imposed island width and rotation have been successfully performed (see Collaboration with University of Bayreuth).

Transport Analysis

Impurity Transport

An important part of the research activities has been dedicated to both theoretical and experimental aspects of impurity transport. For low mass impurities, a database of observations of boron density profiles in ASDEX Upgrade H-mode plasmas has been built and correlations among theoretically relevant parameters have been identified. The peaking of the boron density profile exhibits a strong anti-correlation with the plasma toroidal rotation. Linear and non-linear gyrokinetic calculations have been performed and found to quantitatively reproduce the observed correlations within the estimated uncertainties. The theoretically predicted transport mechanism of roto-diffusion is required for the modelling to reproduce the hollowness of the boron density profile observed in the presence of strong plasma rotation. Roto-diffusion provides an off-diagonal component to the radial impurity flux due to the presence of a gradient of the toroidal rotation velocity, which is directed outward in the presence of ion temperature gradient turbulence. For heavier impurities, theoretical investigations have been dedicated to the impact of a small poloidal electric field generated by poloidal asymmetries, like those produced by centrifugal effects, on the turbulent transport. An analytical model has been derived, which recovers the numerical results in the experimentally relevant conditions where the centrifugal effects are large only for heavy impurities in trace concentration. This has allowed a thorough theoretical characterization of the centrifugal effects on turbulent impurity transport, a step, which was required towards the planned comparison with the experimental observations.

Transition Region from Core to Edge

Recently much attention has been paid to the fact that, in the plasma region from the core to the edge, transport levels about one order of magnitude smaller than those experimentally observed in L-mode on DIII-D were predicted not only by quasi-linear transport models, but also by a set of nonlinear gyrokinetic simulations (the "shortfall" problem). This has motivated a large international validation effort, strongly promoted by the ITPA, to which also IPP has contributed. Several options have been considered as cause of the under-prediction of transport. At IPP, the investigations have focused in establishing whether nonlinear effects, which are known to occur in edge turbulence, become important also in the transition region from the core to the edge.

To this end, comparisons among quasi-linear gyrofluid modelling with the TGLF model, nonlinear gyro-fluid simulations with the GEM code, and nonlinear gyrokinetic simulations with the codes GENE and DFEFI have been performed. While the studies of validation and benchmarking are still in progress, there are already a set of conclusions that can be drawn at the present stage. Comparisons performed so far between ASDEX Upgrade data and both gyrofluid and gyrokinetic nonlinear simulations did not show a significant under-prediction of transport. The same result has been obtained for an extended set of simulations with GENE of a DIII-D case, where transport is under-predicted only by less than a factor 2 (and not by an order of magnitude), and the actual ion heat flux can be matched with an increase of the ion temperature gradient by only 20 %. When running the GEM nonlinear gyrofluid code in transport mode (matching the applied heat fluxes), consistently with experimental measurements, no evidence is obtained in the temperature profiles of strong gradients developing at the edge (and consequent shoulders developing just inside). In contrast, these features are regularly obtained when transport is under-predicted, as for instance with the quasi-linear model TGLF, particularly for discharges at high q_{95}. The properties of these gyrofluid and gyrokinetic nonlinear simulations are presently under investigation. GEM gyrofluid and DFEFI gyrokinetic simulations, adopting circular geometry, show the effect of a nonlinear interaction between the drift-wave part of the spectrum and the longer wave length shear Alfven component of MHD, which is a well-known signature of the strong non-linearity of finite beta edge turbulence, as also reported in the turbulence theory section. The strength of this effect depends on parameters and increases approaching the edge. Gyrokinetic simulations with GENE of actual ASDEX Upgrade discharges for r/a=0.8 have shown so far more conventional types of turbulent spectra. The presence of trapped electrons in the gyrokinetic models makes a significant quantitative difference to the GEM model. Moreover in realistic geometry, subtle geometrical effects can affect the turbulent state at the same kinetic parameters. Future studies are planned in order to investigate the overall consistency among all of these results, examining the impact of the increase of various parameters from the core to the edge (like the safety factor, the logarithmic gradients of the kinetic profiles, the collisionality, and the shaping in realistic geometry). Recent discharges performed during the last campaign on ASDEX Upgrade will be used to this purpose, extending the computational effort also to other codes, in particular the gyrokinetic code GKW.

Discharge Simulation Package

In addition, a robust and accurate full tokamak discharge simulation package has been developed by coupling the transport code ASTRA with the equilibrium code SPIDER. The capabilities of this package presently allow free-boundary computations with coil currents evolution in feedback mode (mimicking the AUG controller for shape, position, and plasma current).

Turbulence Theory

Gyrokinetic and Gyrofluid Studies

The convergence properties of global particle-in-cell gyrokinetic simulations have been studied by means of a set of new 3D diagnostics recently implemented in the code ORB5, allowing for measurements of electromagnetic potentials and relevant fluid quantities (density, temperature, vorticity) as well as turbulence spectral analysis. For all the quantities considered, non-converged simulations show flatter spectra. However, not all the physically relevant quantities converge with the same rate: density fluctuation spectra can still show an unphysical flattening of the spectrum at small scales, even when electrostatic potential and heat fluxes appear to be converged. A remarkable result is that resolution in terms of number of markers, required to correctly describe the turbulence density fluctuations, is found to be size-dependent: larger systems (ITER like) require less numerical particles per active mode than smaller systems (figure 1).

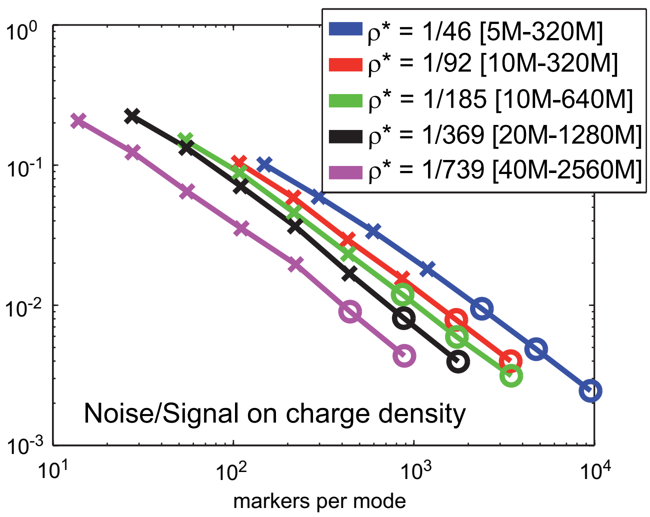

Figure 1: Turbulence simulations with ORB5. Noise/signal ratio for various system sizes, showing the earlier convergence in terms of markers/mode in larger systems.

The nonlinear drift-Alfvén gyrokinetic code Delta-FEFI was used to study the transition of the character of the turbulence between deep edge (normalised volume radius outside of 0.95) and deep core (inside 0.7). The edge cases show significant energetic interaction with long-wavelength Alfvénic responses, not MHD modes, but a weakly damped inductive component, which can maintain enough energy for self-sustainment of the MHD component, which actually provides much of the E×B transport in the saturated state. The trapped electron part of the response also does not represent instabilities but is important in dilution of the Alfvén response, allowing energy to reside more easily in the long-wavelength component. The resulting scaling qualitatively diverges from the linear growth rates. Transport scaling of the turbulence is determined more by saturation through the MHD component than the drive. The "edge" character extends further into the core than in the gyrofluid result, due to the effect of trapping on the Alfvén responses. Deep core results are found only for normalised radius inside of 0.7 as a result of these effects.

Toroidal momentum conservation was studied in both gyrofluid and gyrokinetic computations. A total-f set of gyrofluid equations was derived from the underlying gyrokinetic theory, and was shown to satisfy the same energy and toroidal momentum conservation laws. Indeed the conservation laws themselves represent moments of the kinetic equations. The mathematical structure of wave-wave transport components (e.g., Reynolds and Maxwell stresses) is the same even in the delta-f gyrokinetic and gyrofluid systems. The theory includes higher-order field effects resulting from the finite E×B Mach number. The resulting terms were measured in standard-case simulations of core and edge turbulence by the gyrofluid GEMR and gyrokinetic Delta-FEFI models, respectively, and found to be small in both mean and standard deviation when the PDFs of the various components was compared. Only the basic two-fluid effects represented by the finite-gyroradius are comparable to the basic MHD terms.

Study of the effect resonant magnetic perturbations (RMPs) on edge turbulence and ELMs, in collaboration with A Kendl and J Peer of the University of Innsbruck, continued and produced first results. The finding by earlier drift-wave turbulence studies that a time-dependent 3-D stationary state representing a perturbed equilibrium controls the transport results, which remain dominated by E×B pressure advection, was found to extend into the temperature-gradient dominated edge regime. Analysis of Poincaré plots and the Chirikov parameter of the perturbed magnetic structure shows effective screening of the RMP by the plasma response.

The total-f gyrokinetic code FEFI saw further development, producing saturated cases at realistic parameters for the first time in 2012. Collaboration with Lausanne CRPP/EPFL (T Vernay) produced a study and incorporation into ORB5 of Krommes's two-weight scheme for collisions, and scaling of dissipative trapped electron driven turbulence.

Collaboration with Princeton Plasma Physics Laboratory continues on two projects: Plasma Microturbulence (PI: W Tang), and Edge Plasma Simulation (CS Chang). The gyrofluid GEM has been applied to study of collisionless magnetic reconnection in collaboration with University of Nancy, France (D del Sarto). In addition to benchmarks with 2D models a systematic investigation of nonlinear growth acceleration in 3D Harris pinch equilibria in the regime of very small electron skin depth and ion sound Larmor radius was started.

Variational Integration Schemes

Following 2011 developments with our variational integrator methods, a version of it has been turned into a tractable numerical scheme, which has been applied to various test problems. One case is the Jeans instability problem, which is the same as a 1-D Vlasov-Poisson system with one species. It consists of a distribution function for particles as a function of space, velocity, and time, which satisfies a dissipation-free kinetic equation, and a Poisson equation for the field potential, which depends on space and time. The Hamiltonian for the system is simply the kinetic energy and the field energy in the potential (analogous to the E×B kinetic energy in a plasma). Until magnetic drifts are picked up in the extension to more space dimensions, there is no mathematical difference between this system and gyrokinetics, and indeed our aim is to create better schemes for gyrokinetic codes. Newer versions with more intensive implicitness in the scheme (the price of approaching the perfect variational scheme) are yielding better results but the resulting lack of dissipation forces insertion of conventional viscosity terms to maintain the runs in the nonlinear stages. Application of the scheme to ideal MHD problems is also finding early success.

EFDA Task Forces, Topical Groups, and other Activities

Integrated Tokamak Modelling (ITM)

IPP has provided a deputy Task Force Leader, the leaders of two physics projects (Core and Edge Transport, Turbulence), and one deputy project leader (Software Infrastructure) to the EFDA Task Force on Integrated Tokamak Modelling. The work in ISIP, the infrastructure project of the ITM, involved leading or supporting various development projects within the ITM, including the development of advanced visualization capabilities and a simulation data catalogue system. Significant physics contributions were also supplied to the ITM in the areas: edge transport physics, turbulence, heating and current drive, and ITER scenario modelling. With respect to the Core-Edge coupling, in a Fortran workflow the ETS and impurity core codes and the SOLPS5-B2 edge code have been coupled, and simulations for an AUG like shot performed.

Transport Topical Group (TTG)

During 2012, important scientific contributions have been provided in transport related areas within the ITER Physics EFDA Work Programme. In particular, in the physics of the pedestal and the H-mode: with studies on the inter-ELM pedestal profile development and particle transport, with Li-beam measurements of fluctuations across the edge transport barrier and with the design and construction of a new optical head and a new spectrometer to measure the edge current density via MSE polarimetry in ASDEX Upgrade. In the field of plasma rotation: with experiments on intrinsic rotation and torque modulation, and with coordination and studies on the impact of rotation on plasma confinement. Finally, in the area of electron heat transport: with the development, installation and exploitation of a new Doppler reflectometer front-end in ASDEX Upgrade for spectral measurements of density fluctuations at larger wave numbers.

ITPA Group on Energetic Particles

Studies on the linear threshold for global TAEs at JET and ITER have been carried out. Re-analysing the afterglow phase of JET-DT experiments using the linear gyro-kinetic spectral code LIGKA revealed that previously neglected diamagnetic effects influence substantially the alignment of the TAE gaps and therefore the overall damping of core localised TAE modes. The differences between the afterglow phase in JET and TFTR that were not understood so far could be explained by this more careful analysis. First studies on ITER scenarios have been carried out. In particular, NBI and alpha particle drive have been compared for different mode numbers and initial stability diagrams have been calculated.

Gateway Project

During 2012 EFDA launched a Call to host the successor to the Gateway computer that had been hosted by ENEA in Portici. The contract to provide the new Gateway was won by IPP. The 5 TFlop machine with 240 TB of data storage will be hosted by the RZG in Garching from 2013 through 2016. Preparation work has been done in 2012, in a collaborative effort by TOK and RZG.

MAPPER Project

IPP is one of the partners involved in the EU FP7 project MAPPER (Multiscale Applications on European e-infrastructures), started in 2010. This project aims at deploying a computational science environment for distributed multiscale computing across European e-infrastructures. In MAPPER terminology, a multiscale application is decomposed as a set of single scale codes or models, coupled together in an acyclic (loose-coupling) or cyclic way (tight-coupling). Even so MAPPER solutions are generic. The project is driven by seven applications from five user communities, fusion is one of those communities. IPP collaborates with Chalmers University (Gothenburg, SE) for providing two applications: a loosely-coupled MHD Equilibrium-Stability chain, and a tightly-coupled Transport-Equilibrium-Transport coefficients loop, using codes and common data structures developed within EFDA-ITM, as well as codes developed in their own institute.

Significant progress has been made in 2012 on adapting these applications to the MAPPER infrastructure. MAPPER high level web-based tools are used to build and execute an instance of the Equilibrium-Stability chain (HELENA and ILSA codes coupled through files) where each code can execute on a remote cluster. The tightly-coupled application is composed at this time of the ETS (transport), an equilibrium code (BDSEQ, HELENA, ...) and a code for updating the transport coefficients. This last component can be sequential (Bohm/gyro-Bohm) or parallel (flux tube GEM). The coupling is performed by the MUSCLE library (extended with a Fortran API) and distributed resources management is done via QCG-Broker.

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Stellarator Theory Division

Head: Prof. Dr. Per Helander

Global Gyrokinetic Simulations

Since it is unclear what influence electromagnetic effects may have on ITG modes in stellarators, global linear gyrokinetic particle-in-cell simulations of electromagnetic ITG modes in a sequence of Wendelstein 7-X equilibria were performed using the EUTERPE code. For comparison, ITG instabilities including only adiabatic or kinetic electrons were also simulated. The difference in the ITG growth rate for adiabatic and kinetic electrons is small while the inclusion of electromagnetic effects leads to a slight decrease. In the electromagnetic case two different regimes could be identified: Below $\beta \approx 2$ % the Fourier spectrum is highly extended and ballooning-like while for $\beta > 2$ % it is localised and shows a slab-like structure. Overall, β-effects lead to a decrease in the growth rate of only 30 %. In contrast to the tokamak case, where Alfvénic ITG or kinetic ballooning modes are the dominant instability for β larger than approximately 1 %, no such instability could be found in the simulations for Wendelstein 7-X.

A new fast solver for the gyrokinetic field equation (with adiabatic electrons) including flux-surface averaging has been developed and successfully tested. Nevertheless, it is necessary to make the gyrokinetic solver more effective, both with respect to time and memory consumption. In the standard scheme used in the EUTERPE code, the field equation is discretised using B-splines and, in order to reduce noise, the source term is Fourier decomposed and filtered. Development of a new solver has been started where the B-spline discretised field equation is fully projected into a Fourier subspace. This approach helps to further reduce memory consumption. Additionally, it may help to improve the numerical robustness of the overall PIC scheme. A first version of this new solver has been implemented and first tests have been performed successfully.

As part of an international benchmark effort, the destabilisation of TAE modes by fast particles (of energy 200-600 keV) in a realistic tokamak equilibrium was simulated using EUTERPE. The mode structure agrees very well with those obtained from ideal MHD, and the growth rate of the mode lies well within the range obtained from other codes participating in the benchmark.

Gyrokinetic simulations of tearing modes in slab geometry have been performed, and the saturated island width for single-mode simulations has been compared with analytic predictions. The influence of diamagnetic effects on the growth rate and island width has also been investigated.

Resilience of Quasi-isodynamic Stellarators to Trapped-particle Instabilities

It has been shown that so-called quasi-isodynamic stellarators are automatically immune to an important class of micro-instabilities. In a quasi-isodynamic magnetic field, all collisionless orbits are confined, and the contours of constant magnetic field strength are poloidally, but not toroidally, closed. Examples include W7-X at high plasma pressure and more recently found configurations that have been found in efforts to numerically construct highly optimised stellarator magnetic fields. It has been shown that in such magnetic configurations, where in an addition the parallel adiabatic invariant J decreases with increasing distance from the magnetic axis (so-called maximum-J configurations), most of the usual trapped-particle instabilities are linearly stable in the collisionless and electrostatic approximation in large parts of parameter space. The physical reason is that all trapped particles experience good average magnetic curvature. These analytical predictions have also been confirmed by gyrokinetic simulations in flux-tube geometry. Preliminary results show that the collisionless trapped electron mode (TEM) has a substantially higher growth rate in a circular tokamak than in a quasi-isodynamic stellarator, and that TEM stability improves further when the plasma pressure rises.

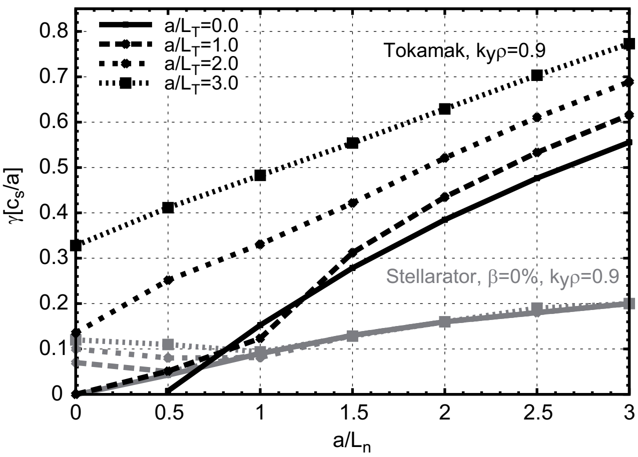


Figure 2: Growth rate of TEMs as function of the normalized density and temperature gradients (a/L_n and a/L_T, respectively) in a circular tokamak (upper curves) and in a stellarator (lower curves). The ion temperature gradient is set to zero, to avoid ITG modes, and the electron temperature gradient is seen to be destabilizing only in the tokamak case.

Full-surface Gyrokinetic Simulations

The gyrokinetic simulation code GENE was first constructed to do simulations in flux-tube geometry, but has now been extended to treat an entire stellarator flux surface, whilst still making a local approximation in the radial direction. The code has been used to perform ion-temperature-gradient (ITG) turbulence simulations (with adiabatic electrons) for the stellarators W7-X and NCSX. In the limit of small normalized gyroradius ρ^*, the results from the full-surface code approach (in terms of statistical turbulence levels) those from local flux tube simulations, see figure 3.

A number of qualitative differences in the behaviour of turbulence in axisymmetric and non-axisymmetric magnetic-field geometry have been identified. One striking feature has to do with the extent of the potential fluctuations along the magnetic field, which appears to be reduced in comparison with axisymmetric configurations.

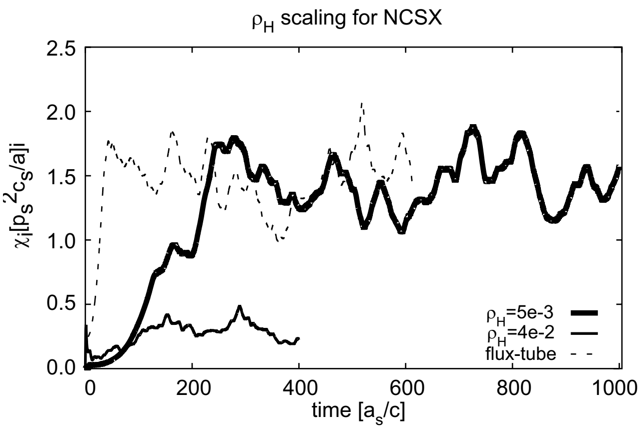


Figure 3: Gyrokinetic turbulence simulations of NCSX. The turbulent diffusivity is shown as function of time for two full-surface simulations as well as for a flux tube. In the limit of small normalized gyroradius, the former converge to the latter.

Visualization of Gyrokinetic Simulations

In order to support the newly developed full-surface nonlinear gyrokinetic GENE code, the cross-platform graphic-user-interface application GENEviewer was written in C++ (based on the MConf library). Main task of GENEviewer is the visualization (including movie generation) of GENE simulation results on the surface of a toroidal configuration. As an additional feature, GENEviewer is able to display important geometric quantities, such as the modulus of magnetic field, curvature, local shear etc. on a stellarator surface. These quantities are generated by the geometry interface GIST, which has now been extended to accommodate so-called PEST coordinates, which are natural to the VMEC equilibrium code, thus improving accuracy by skipping the interim transformation to Boozer coordinates used in previous versions.

Global Gyrokinetic Particle-in-cell Simulations of Internal Kink Instabilities

Internal kink modes have been studied in straight-tokamak geometry using the global gyrokinetic particle-in-cell code GYGLES. Both electron and ion gyro-centres were treated kinetically, but collisions were ignored. The simulations have shown that the kink mode properties depend strongly on the ratio between the ideal-MHD inertial-layer scale and the gyroradius. In the "MHD regime", the kink mode becomes more unstable if the rational flux surface is moved outward. In the "FLR regime", however, the kinetic-kink mode (the "collisionless m=1 tearing mode" with m the poloidal mode number) is more unstable for resonant magnetic surfaces located closer to the magnetic axis. Similarly, the scaling with respect to the ion temperature is also opposite: FLR-stabilization for the MHD-type kink mode is observed whereas the "collisionless m=1 tearing mode" is FLR-*destabilized*. It is thought that the most unstable m=1, n=1 instabilities (with n denoting the toroidal mode number) observed in tokamaks correspond to the "collisionless m=1 tearing" kinetic-kink) modes rather than the classical ideal-MHD internal kink modes, since at the marginal MHD-kink stability boundary the ion gyroradius exceeds the ideal inertial length.

Fast-particle Instabilities

Fast particles in ITER may originate from the fusion process itself or from external heating, such as Neutral Beam Injection (NBI). It is well known that these non-thermal populations of fast ions may destabilise otherwise stable Alfvén waves in the bulk plasma. This process takes place as a resonance phenomenon that requires a kinetic treatment of the fast particles, but not necessarily a kinetic treatment of the bulk plasma. The oscillating electromagnetic field in the plasma may lead to a loss of supra-thermal particles and damage to in-vessel components of the device. For over two decades, much effort has been invested in the development of theory and codes that can be used to describe and explain these phenomena. There has been no well-understood standard case that these models have been tested against quantitatively, but the first comprehensive quantitative code comparison for fast-particle instabilities has now been carried out by the

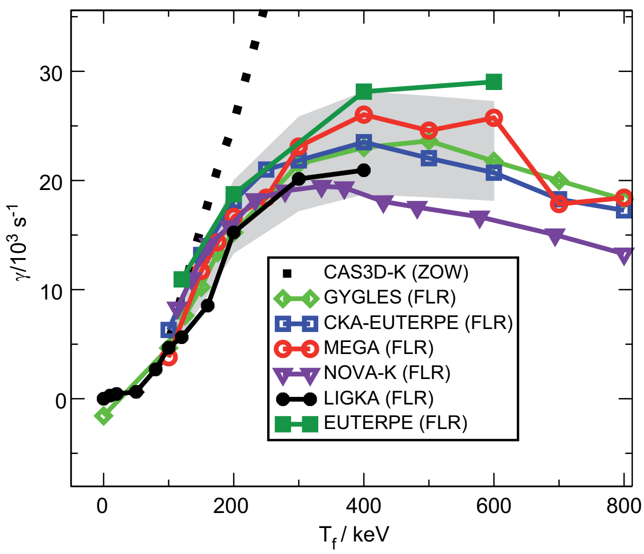
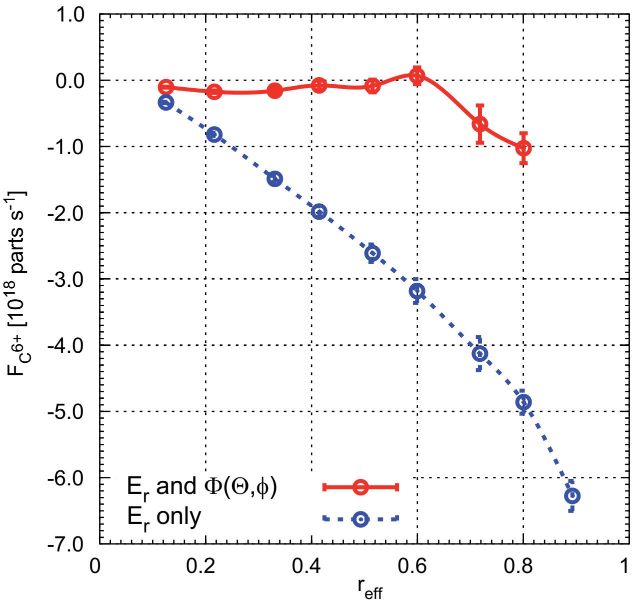


Figure 4: Growth rates from calculations with FLR effects for different temperatures T_f of fast particles. The dashed line from the CAS3D-K code is valid in the limit of zero orbit width (small energies) and is shown for comparison. The shaded grey area marks the ± 20 % margin around the mean value.

ITPA Energetic Particle Topical Group. A linear benchmark for the calculation of the growth rate of a toroidal Alfvén eigenmode has been performed by a number of codes (including five codes from IPP) using fully gyro-kinetic, kinetic MHD and gyro-fluid models. The importance of FLR effects has been illustrated and is in agreement with earlier research. The overall agreement of the codes is satisfactory for fast particle energies below 400 keV and lies within ± 20 % for the codes that include FLR effects. For higher energies, the orbits become large and numerical problems (lost particles, orbits outside the plasma boundary) become severe.

Neoclassical Impurity Transport

Standard neoclassical theory predicts highly charged impurities to accumulate in the plasma core when the electric field points radially inward. Only the radial component of electric field, $\boldsymbol{E}=-\nabla\Phi_0(r)$, is usually considered when solving the drift kinetic equation, and the electrostatic potential $\Phi_0(r)$ is taken to depend only on the flux surface label r. The variation of the electrostatic potential within the flux surface, $\Phi_1(\vartheta,\varphi)$, with ϑ and φ the poloidal and toroidal angular coordinates, is usually neglected. This practice has the benefit of reducing the number of phase space dimensions from four to three in the local limit (r nearly constant).



This treatment is not appropriate for impurities with moderate to large charge numbers, which makes it necessary to calculate Φ_1 to describe the impurity dynamics accurately in the resulting 4D phase space. This problem has recently been considered with the particle-in-cell Monte Carlo code EUTERPE. The calculation of Φ_1 was carried out by solving the gyro-kinetic quasi-neutrality equation for the bulk ions under the assumption of adiabatic electrons. Depending on plasma parameters, this part of the potential can either enhance or counteract the inward impurity particle transport. In figure 5 the calculated radial profile of particle flux for C^{+6} in the LHD stellarator is shown with and without taking the effect of $\Phi_1(\vartheta,\varphi)$ into account.

Ideal MHD

The concept of perturbed ideal MHD equilibria has been employed to study the influence of external error-fields and of small plasma-pressure changes on toroidal plasma equilibria. In tokamak and stellarator free-boundary calculations, benchmarks were successful of the perturbed-equilibrium version of the CAS3D stability code with the ideal MHD equilibrium code NEMEC. Furthermore, within an ITER task, three-dimensional distortions of the plasma boundary were studied. As a first step, free-boundary NEMEC calculations were performed for several ITER baseline cases (burn scenarios and an L-mode plasma), in the axisymmetric approximation for benchmarking various equilibrium codes, as well as with inclusion of discrete toroidal field coils for calculating the 3D plasma boundary.

MConf Package and MCviewer

The magnetic configuration software package MConf has been further developed. The initial goal of this library was to provide other codes with a tool for handling magnetic coordinates and performing coordinate transformations to/from real-space coordinates. During the past year the following additional features and components have been implemented: the ability to use magnetic equilibria in various representations such as EFIT, VMEC, Boozer and FP (a file resulting from Function Parameterization technique) files; a function to transform magnetic coordinates from VMEC to Boozer and PEST coordinate systems; a function for evaluating the effective ripple in stellarators; a function to calculate bounce-averaged ∇B drift velocity of trapped particles; a function to calculate the collisionless bootstrap current.

To improve performance, the CPU-time-intensive functions are parallelized by a multi-threading technique utilizing extra cores in modern processors; for example, VMEC to Boozer transformation of a typical W7-X equilibrium now requires 4 to 7 seconds on a typical notebook. The package was written in C++; interface routines for using MConf in FORTRAN or MATLAB environments are provided. The graphic-user-interface program MCviewer for displaying various properties of a magnetic configuration has been augmented by the new functions. The MConf package and MCviewer are used now in PPPL (Princeton, USA), at the University of Wisconsin (Madison, USA), and at Universidad Carlos III de Madrid (Spain).

On Transition from Low to High Density ECRH Scenario in W7-X

Wendelstein 7-X can be heated by electron cyclotron resonant heating (ECRH) using waves having either of two polarisations, X2 or O2. In order to find the relevant conditions for the X2→O2 transition, both X2 and O2 scenarios were simulated for the same initial parameters and for the different magnetic field values (B_0-scan). It was shown that the optimal B_0-ranges for X2 and O2 operation with the same density overlap, but do not coincide. In particular, the transition to the O2 scenario at moderate density can easily be performed in the first phase of W7-X operation with short pulse length, Δt<10 sec. However, long-time operation (Δt>10 min) with high-beta O2 scenarios and full power (10 MW) requires is more difficult since the B_0-range does not overlap with start-up range. As a possible solution, an optimized transition is proposed, by changing the magnetic field strength together with the polarization over a time-scale at about one minute.

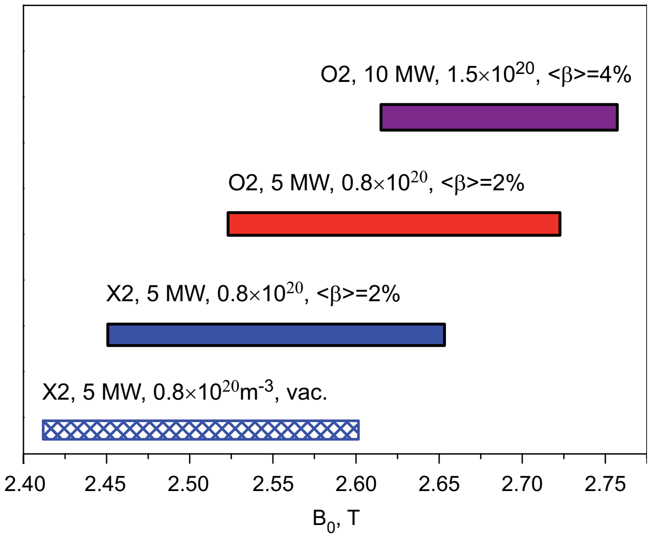


Figure 6: Ranges of magnetic field strength appropriate for different ECRH scenarios in W7-X.

Numerical tools for ECE Diagnostic

In collaboration with JET, a new version of the ray-tracing code TRAVIS has been prepared for calculating electron cyclotron emission. Preliminary calculations of the ECE spectrum from JET were successful.

ECRH/ECCD for Globus-M3

In collaboration with the Ioffe Institute (St. Petersburg, Russia), ECRH/ECCD scenarios for the Globus-M3 spherical tokamak have been analysed. It was found that the plasma parameters considered as optimal for this device are not consistent with any ECRH/ECCD scenario. However, for scenarios with reduced density and lower frequencies (90 GHz and 70 GHz instead 140 GHz), complete single-pass absorption and high ECCD efficiency can be reached.

Relativistic Effects in Electron Transport

In collaboration with Kharkov National University (Ukraine), relativistic effects on electron transport in hot plasmas have been investigated. It is found that these effects reduce the transport at low collisionality by up to 10 %. The collisional coupling of relativistic electrons and non-relativistic ions however exhibits qualitatively new behaviour. In non-relativistic plasmas, it was found that this coupling is stable as long as the electron temperature does not exceed three times the ion temperature, $T_e<3T_i$, but relativistic effects shift the upper T_e/T_i boundary of stability to higher values. For sufficiently high temperatures, $T_{e,i}$>75 keV, collisional decoupling between relativistic electrons and ions becomes impossible.

Stellarator Optimisation

A new code, called ROSE, for stellarator configuration optimisation has been constructed. The code uses VMEC to calculate the magnetic equilibrium and VM2MAG for converting the solution to Boozer coordinates. The equilibrium analysis is invoked by a variety of optimisation algorithms, including PRAXIS by Brent and several evolutionary algorithms. The optimisation criteria include common properties of the magnetic field like rotational transform, shear and magnetic well, but also quasisymmetry, effective ripple and related quantities. The code can also account for curvatures of the plasma boundary and properties of the coil set required to restrict the desired configuration. The code runs both on serial and massively parallel environments.

3D Edge Modelling and Divertor Physics

W7-X

In an effort to identify safe operation scenarios for W7-X, the power load on the first wall has been estimated using the EMC3-EIRENE code. Various magnetic configurations were compared, including the standard, inward-shifted, low- and high-iota cases, with and without island control coils. It was established that the standard divertor configuration with full control coil currents causes the largest heat flux to the first wall. For a 10 MW heating power the parallel heat flux density at the plasma-nearest wall position can exceed 6 MW/m^{-2}. This peak heat flux decreases faster than linearly with decreasing control coil current and drops almost by one order of magnitude after turning off the control coils.

Additional scraper elements are being designed for protecting the edge tiles on the target plates at the divertor gap against possible thermal overload during the configuration evolution phase. The resulting side effects on particle pumping are evaluated numerically, taking different evolution stages of the plasma current into account. First simulations using the EMC3-EIRENE code show sufficient thermal shielding effects of the scraper elements for the edge tiles, however, at price of considerable reduction of the divertor particle-

pumping efficiency. The pumping efficiency, which is considered to be already a critical issue of the W7-X island divertor, drops further by more than 20 %, even after the configuration has reached the desired end state.
Plasma detachment caused by line radiation of the intrinsic carbon impurity has also been examined, with the aim of finding favourable SOL plasma conditions for both power and particle exhaust without degradation of the overall divertor performance. A regime with near-target radiation just after the detachment transition is found to satisfy this requirement; more than 80 % of the SOL power is radiated by carbon and the neutral pressure in the divertor chamber increases by a factor of 3 from the maximum reached in attached states, while the islands still preserve the retention capability of intrinsic impurities.

Other Devices

LHD. The divertor closure being performed at LHD requires the inclusion of divertor legs in edge transport modelling, which are neglected in previous EMC3-EIRENE simulations due to technical difficulties in grid construction. These difficulties have recently been overcome by splitting the computation domain into a large number of sub-domains. The mesh surfaces in the regions accessible only to neutrals are achieved with help of solving Possion's equation. For this, the EMC3-EIRENE code has been modified significantly. Test runs of the new code version have provided very promising results.
HSX. EMC3-EIRENE has been implemented for the HSX geometry. The work was motivated by an island divertor program started on HSX recently.
AUG, EAST, TCV. In collaboration with AUG, EAST and Beihang University in Beijing, a grid generator has been developed for EMC3 applications to tokamaks, capable of both single- and double-null magnetic-field geometry, providing also basis grids for the TCV snowflake divertor and the advanced poloidal divertor with RMP fields. It optimizes the grid resolution according to physical requirements and minimizes spurious 3D effects on axisymmetric components induced by the intrinsically helical 3D mesh.
ITER. A contractual application of EMC3-EIRENE (in collaboration with FZ-Jülich) on the assessment of 3D heat and particle flows induced by the RMP fields in ITER has been completed successfully.

Magnetic Fields for Transport Simulations with EMC3

Transport simulations in the scrape-off layer (SOL) using field-aligned coordinates (as performed by the EMC3 code) depend sensitively on the quality of the underlying magnetic field – in particular the requirement $divB=0$. Up to now, most simulations done for W7-X have used vacuum fields. Some calculations exist studying finite-beta effects, which use fields, which combine the finite beta solution of the VMEC-code inside the plasma domain with the field outside (vacuum domain) combining the field provided by the vacuum field coils and the field generated by the plasma current densities, e.g. using the virtual casing principle implemented in the EXTENDER-code. Until recently, these fields constructed in this way were not divergence-free at the interface boundary, but using the same tools an alternative way have been found for constructing the full magnetic field satisfying $divB=0$ more accurately. The generation of the full field uses the virtual casing principle not only to construct the plasma-generated field in the vacuum region but also to construct the vacuum field in the plasma region. The latter field can then be used to extract the plasma part of the VMEC-solution. Thus the plasma contributions are available in- and outside the plasma domain and can be combined with the vacuum field in the full region. The resulting field is still not exactly divergence-free at the vacuum/plasma interface (VMEC-boundary), but accurately enough for use with the EMC3-code.

Scientific Staff

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Guests

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Computational Plasma Physics

Head: Prof. Dr. Eric Sonnendrücker

The division "Computational 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.

Creation of the Division

The division was created on 1st September 2012. The majority of staff was transferred at this date from existing divisions at IPP. Some others were hired in the last months of 2012 and further recruitment is scheduled for 2013.

General Orientation 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 for plasma physics" at the Mathematics Center of the Technical University of 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.

Kinetic and Gyrokinetic Codes

Collisions in delta f PIC

The delta f 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 delta f 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 delta f method, which is normally quite important in the collisionless case, not so interesting anymore. Putting the method in the framework of stochastic differential equations, we have started investigating how techniques developed in this field can help us to reduce the weight growth. Several ideas, like exact conservation of the weights and the use of a local Maxwellian have proven useful in preliminary simulations based on the Ornstein-Uhlenbeck process.

High Order Methods for the Vlasov Equation

We have been investigating the benefit of using very high order methods for the Vlasov equation and their optimization. This has been done for the 1D Vlasov-Poisson equations. The method used was a 1D split semi-Lagrangian method using high order spline or Lagrange interpolation. When they can be used, which is the case for the Vlasov-Poisson model, 1D split methods are very interesting for high dimensions, in our case, 4, 5 or 6 dimensional phase space. Indeed, by using only 1D methods, the algorithm scales linearly with the number of unknowns, independently of the dimensionality and thus avoids the curse of dimensionality and yields optimal algorithms. Optimizations performed in 1D will thus be used also in higher dimensions. In order to accommodate easily an arbitrary order of accuracy we implemented the method with periodic boundary conditions both in physical and velocity space. The latter can be done without problem if the velocity space is truncated at a high enough value. Then all the discretisations yield circulant matrices, on which all operations, including inversion, can be performed very fast using the Fast Fourier Transform. We also developed a simple delta f implementation where all computations are performed on the deviation from a Maxwellian rather than on the full distribution function. This proves very beneficial when using single precision arithmetics where round off errors become comparable to discretisation errors, but has negligible influence in double precision. Using the optimized CUDA FFT the code could also be ported on GPU with a minimal effort as the major part of the numerical work is the FFT, which was already well optimised for GPU. Test cases performed were Landau damping, bump on tail instabilities and KEEN waves, which consist in several nonlinearly interacting modes, which develop around the phase velocity of a driving wave and the simulation, of which requires very well resolved and accurate simulation methods.

Development of a Kinetic Library

The division is involved in the development of the SELALIB library for kinetic and gyrokinetic simulation. The library is written in object-oriented Fortran 2003. The project started two years ago at Inria and the University of Strasbourg in France. Its aim is to provide building blocks for physics codes as well as to provide a test bed for comparing different methods. It includes methods using a grid of phase space as well Particle-In-Cell (PIC) methods. It provides tools for curvilinear coordinate systems, has a large panel of interpolation methods, which are important in particular for the semi-Lagrangian method. These include optimized cubic splines, arbitrary degree spline and Lagrange interpolation, spectral interpolation and WENO. It also includes Finite Element and Discontinuous Galerkin methods and some specific algorithms have been ported on GPU using either CUDA or OPENCL.

Nonlinear MHD

We have started working on the reduced MHD code JOREK in collaboration with the Tokamak theory division. The nonlinear reduced MHD equation with resistive terms 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 non linear system of differential equations in time.

Instead of using an implicit discretisation of the linearized equations as was originally done, we propose to solve directly the nonlinear equation resulting from an implicit time discretisation of the system using a Newton method. This needs to be coupled with a Krylov solver, in our case GMRES for the linear system that needs to be solved at each Newton iteration. For a fast convergence of the method, the GMRES solver needs to be well preconditioned and the stopping criteria of the two embedded method adequately coupled.

Modelling of Anisotropic Diffusion

Diffusive transport in structured media is ubiquitous in plasma-material interaction and material sciences. For instance, the geometrical structure of polycrystalline metals determines the transport and permeation properties, bridging spatial scales from nanometer to millimeter range. Although diffusive transport can in principle be studied numerically, the complexity and multi-scale character prohibit direct numerical simulations. For that reason a multi-scale description based on molecular dynamics simulations is being developed. In this framework a coarser description of diffusive transport through a decomposition of the sample into a model resting on sample dependent connection matrices and transition probabilities can be established and has been applied to grain boundary structures in beryllium and tungsten. The fast numerical evaluation of this model allows to investigate diffusive transport at macroscopic time and length scales and to elucidate the main transport channels. Eventually the numerical results will be compared with permeation studies on suitable magnetron deposited tungsten layers.

Parallel Grad-Shafranov Solver

A fast numerical solver for the Grad-Shafranov equation was developed for future employment in real-time control of fusion experiments. Based on the long approved GEC solver utilized in the equilibrium code CLISTE we changed the numerical methods in the algorithm such that exploitation of the parallel capabilities of modern multi-core processors was possible. Our implementation termed GPEC (Garching Parallel Equilibrium Code) was integrated in an equilibrium reconstruction code called IDE for the offline analysis of ASDEX Upgrade data. In order to demonstrate the real-time capability of IDE further developments in the parallelization of the latter take place.

Workshop on Numerical Modelling for Fusion

The first event hosted by the new division was the Summer School on Numerical Modelling for Fusion sponsored by the French research organisation Inria. It was held on the IPP site in Garching from October 8-12, 2012. It involved around 50 mathematicians and physicists interested in numerical methods for different models occurring in magnetized plasmas, including kinetic and gyrokinetic, MHD and Wave plasma interactions. The lectures consisted of introductory courses as well as research talks.

Lectures

Sonnendrücker, E.: Numerical Methods for the Vlasov equations (WS 2012/21013. Vorlesung, Technische Universität München).

Sonnendrücker, E., Afeyan B.: KEEN waves, a challenging test case for Vlasov-Poisson, Algorithms and Models Verification and Validation Workshop, Michigan State University, November 12-15, 2012.

Toussaint, U. von: Bayesian Methods for Inverse Problems (WS 2012/2013, Vorlesung, Technische Universität Graz).

Toussaint, U. von: Numerische Übungen zu Bayesian Methods for Inverse Problems (WS 2012/2013, Technische Universität Graz).

Scientific Staff

A. Dodhy-Würsching, E. Franck, S. Gori, K. Hallatschek, A. Kammel, K. Kormann, O. Maj, L. Mendoza, R. Preuss, G. Strohmayer, U. v. Toussaint, A. Wacher.

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 following supercomputers: the High Performance Computer for Fusion (HPC-FF) located at the Forschungszentrum Jülich Supercomputing Centre (JSC), Jülich, Germany, and 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 five scientists. This year the HLST core team was involved in nine different projects submitted by scientists from all over Europe. As examples, we present here an overview of the work being done for three projects.

BLIGHTHO Project

The BLIGHTHO project is explicitly providing support for the European scientists who use the HELIOS machine at IFERC-CSC. At the beginning, the project went into operation by supporting selected European projects during the lighthouse phase. After the HELIOS machine went into production phase, starting in April 2012, the support activities have been extended to all approved European projects. The BLIGHTHO project gives support on different levels.

The 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 BLIGHTHO project investigates topics, which are of general interest such as checking and improving the documentation provided by CSC, testing the file transfer between Europe and CSC in Japan and assessing the hardware capabilities of HELIOS.

The HLST as a whole has submitted more than 90 tickets to the CSC tracker system. This gives a rough quantitative estimate of the contribution of the HLST at pointing out issues and helping to solve them. In the framework of this project, we also supported the Rechenzentrum Garching (RZG) at setting up the software environment for efficient file transfer between Europe and Japan. But the main contribution is 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. Some workarounds are proposed so that such ALL_TO_ALL operation can be performed now on the full system with 64k cores.

ITM-ADIOS Project

The initial ITM-ADIOS project's goal was to evaluate the usage of the "ADIOS" (ADaptive I/O System) parallel I/O library (a GPL licensed software) on the HPC-FF machine. It was subsequently decided to prolong the project in the perspective of extending the investigations to the HELIOS machine when it came into operation.

Motivation for the project came from the growing gap between computing and I/O capability of modern hardware. It leads to I/O being increasingly a bottleneck in Integrated Tokamak Modelling (ITM) simulations, when checkpoint functionality is used. To explore the capabilities of ADIOS, a special purpose parallel I/O throughput benchmark ("IAB", short for "ITM-ADIOS Benchmark") has been developed. In addition, an assessment of the maximum throughput achievable when writing from a serial program was performed. Using POSIX C I/O routines from a serial program, but tuning appropriately the (user side) LUSTRE file system "striping" parameters on HPC-FF, it was possible to obtain around 1 GB/s throughput in writing. For the general user, it is common to operate at a fraction (e.g. a quarter) of that, because of an inappropriate choice of I/O options and techniques.

In contrast, calling ADIOS from IAB and writing array data originating from 4096 MPI tasks to a subset of 64 files, with a good choice of striping parameters, allowed to obtain as much as 14 GB/s on HPC-FF. Easy to implement I/O choices, like using either one or all tasks, have been found to be not as successful as the aforementioned ones. The first choice suffers from node network bandwidth limitation, while the second incurs excessive network usage and I/O latency. The "optimum" observed with ADIOS on HPC-FF delivered about 75 % of the estimated machine hardware peak, this is approximately 20 times faster than a good serial I/O choice. These results are particularly interesting given the wide-spread practice of users operating their codes at the above cited extremes, therefore either under- or over-utilizing the machine, in both cases obtaining poor results. In contrast, we have been able to identify a set of parameters for optimal usage of ADIOS.

Our massive I/O experiments on HELIOS exposed several I/O system instabilities. We have been active in investigating these instabilities and communicating them to the CSC support team in Japan. Finally, most of the instabilities were solved so that it became possible to finish our benchmarking campaign with the following results: the maximal observed I/O throughput of HELIOS was circa 35 GB/s (roughly twice as on HPC-FF) and a significant gap of parallel to serial I/O, which can reach 70 times, was observed. This increased gap is due to both faster parallel and slower serial I/O throughput. The slower serial I/O has been identified as originating from an inefficiency in the LUSTRE version mounted on HELIOS; this problem is expected to be solved within future releases of LUSTRE.

To summarize, the major outcome of our investigation has been the characterization of the relations between LUSTRE striping parameters and general I/O quantities. By that we have been able to extrapolate rules of thumb for singling out poor performance cases and avoiding them in advance.

EMPHORB Project

NEMORB is a global nonlinear gyrokinetic particle-in-cell code that can be used for turbulence simulations in tokamak geometry. The aim of the EMPHORB project is to implement the phase factor transformation in the NEMORB code. Phase factor transformations can be used to decrease the spatial resolution for linear calculations and thereby lower the amount of computational resources needed for the simulation. The implementation of the phase factors involves small changes that extend throughout the whole NEMORB code. The code structure was analyzed and the phase factors were implemented for the main steps in the particle-in-cell (PIC) algorithm. This includes the matrix building routines, the field evaluation, the charge and current assignment. The equation of motion changes only for the weights, and the phase factors have been introduced for pushing the weights. When the phase factors are introduced, several variables need to be changed from real to complex. The call-graph for the code was investigated to check, which functions are influenced by the change of the variable types, and most of the necessary changes have been made. In the next step, the diagnostic methods will be updated accordingly. Once all the changes are done, an extensive testing will be necessary.

Scientific Staff

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EURYI Research Group "Zonal Flows"

Head: Priv.-Doz. Dr. Klaus Hallatschek

At the focus of the group are the properties of large scale flows, a critical agent controlling convective plasma turbulence. In toroidal systems, the mutual coupling of the flows and the pressure fluctuations results in (potentially multiple) oscillating geodesic acoustic modes (GAMs), and one stationary zonal flow (ZF) branch.

Geodesic Acoustic Modes: Nonlinear Frequency Selection

The problem of the large mismatch (>50 %) between experimental GAM frequencies and calculations based on Miller equilibria has been solved. Using a special algorithm we have calculated flux surface data close to the separatrix, which is sufficiently detailed at the X-point and doubly differentiable, as required by the turbulence codes. Comparing the linear GAM eigenmodes with NLET turbulence simulations for several experimental ASDEX Upgrade discharges, we have identified the unique branches chosen by the turbulence.

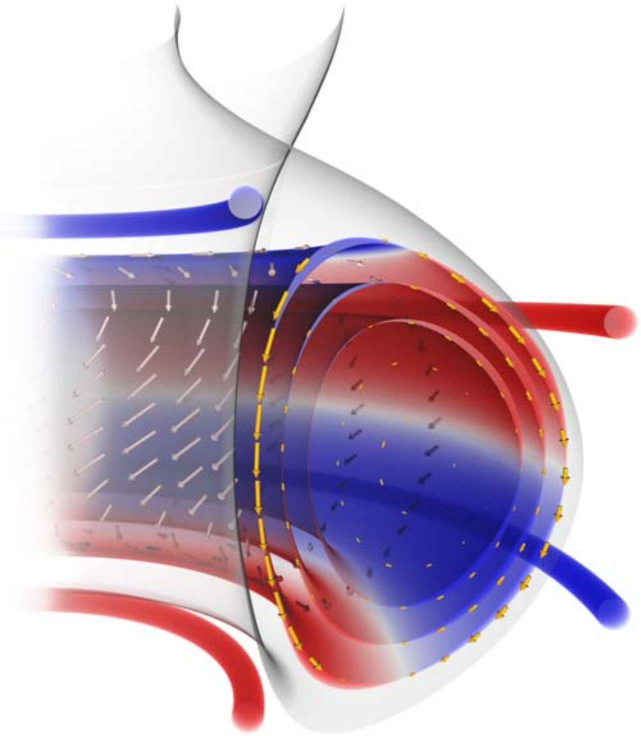

Figure 7: Equilibrium displacement for external GAM excitation in a DIII-D plasma. Gray: separatrix. Red/blue toroidal loops: position of positive/negative perturbation current. Red/blue shells: volume traversed by outward/inward displacement of flux surfaces. Yellow: poloidal displacement. White: displacement tangential to flux surfaces.

The obtained theoretical frequency agrees up to about 15 % with the experimental measurements indicating a quantitative understanding of the GAM frequencies up to the measurement uncertainties – a marked improvement lending credibility to our present picture of edge turbulence.

External Excitation of GAMs

It is appealing to excite GAMs in a tokamak, either for diagnostic purposes, since their frequency is dependent on the temperature, or, to artificially reduce the turbulent transport, since GAMs are expected to impact the transport. GAM excitation by external magnetic perturbation has been shown to be an effective possibility – in contrast to the injection of heat or momentum. Calculations of the induced amplitude by linear and nonlinear dynamic equilibrium code runs can be performed based on the interaction of the equilibrium perturbation with the GAMs by means of inertial forces. As seen in figure 7, the induced poloidal flows (and corresponding inertial forces) are amplified by nozzle effects for regions of close flux surface spacing and in the vicinity of magnetic nulls, which is why only surprisingly weak magnetic perturbations of a few mT are required.

Multistable Slab Zonal Flows

We have discovered multiple stable states for the ZF patterns in drift wave turbulence. Above the parameter threshold for ZF generation, a flow pattern of arbitrary wavelength larger than a certain minimum can in fact be initiated, and converges towards a stationary solution with piecewise constant shearing rate, which persists indefinitely (figure 8).

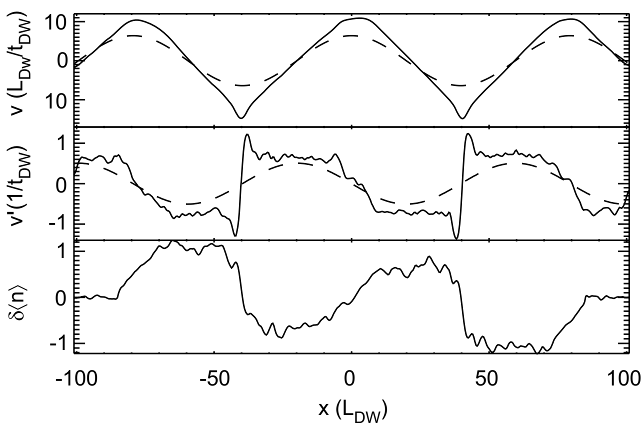

Figure 8: (Arbitrary) long wave length initial (dashed) and resulting final equilibrium (solid). Top: flow profile, middle: corresponding shearing rate, bottom: density corrugation.

Scientific Staff

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"Turbulence and Self-Organization 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 nuclear fusion devices as well as astrophysical applications. 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 described briefly. For more details, please see the papers cited below or visit the website http://www.ipp.mpg.de/~fsj.

Experiment-based Finite Size Effects Investigations with GENE

The turbulent transport scaling in magnetized fusion plasmas with the system size represents one of the key questions for the design of future fusion power plants. In 2012, supercomputing resources – e.g., within one of the Lighthouse Projects at the new Helios machine in Japan – have been employed to model actual TCV, AUG, and JET discharges. For this purpose, most of the features offered by the physically comprehensive gyrokinetic plasma turbulence code GENE (see http://gene.rzg.mpg.de) – e.g., kinetic electrons, electromagnetic fluctuations, and collisions – have been used to establish a high degree of realism. It could be shown that local transport modelling is sufficient for large devices without steep barriers while global models should be applied else [1,2]. In the former case, full profile prediction can be tackled by coupling to transport solvers, potentially gaining further efficiency by adapting Large-Eddy-Simulation techniques to gyrokinetics [3,4].

Small-Scale Reconnection and Magnetic Transport in Fusion Plasmas

The recent demonstration of linearly unstable microtearing modes (MTMs) – small-scale variants of MHD tearing modes – in standard tokamaks driven by electron temperature gradients has triggered on-going research and benchmarks [5]. As these modes intrinsically depend on magnetic fluctuations, they are typically found at large beta, i.e. large kinetic-to-magnetic pressure ratios. However, one of their signatures, magnetic stochasticity, can also be seen at very low beta values where ion temperature gradient (ITG) prevails. These contradictions could be resolved by demonstrating that the magnetic stochasticity and associated transport are not caused directly by the ITG mode. Rather, the salient mechanism is linearly stable microtearing modes, which are driven nonlinearly and operate at the same perpendicular scales as the ITG modes [6]. These results offer a paradigm for magnetic turbulent transport, which can be explored more extensively throughout parameter space in future studies.

Figure 9: Snapshots from global ab initio simulations of the ASDEX Upgrade (left) and JET (right) tokamaks with the comprehensive plasma turbulence code GENE.

Modelling of Dynamo and Magnetorotational Instability Experiments

While studying turbulent features of the Madison Dynamo system by means of direct numerical simulations and analytical investigations, it was observed that the dynamo effect can be suppressed in the presence of turbulence. Though the details are still not fully understood, new insights have been gained by applying analysis methods as the Singular Value Decomposition to large data sets produced with the DYNAMO code. In addition to the mean flow, a large-scale helical vortex with an unexpected temporal behaviour was found. This feature can explain the increase of the dynamo threshold when the fluid Reynolds number is increased [7]. In addition, first steps to simulate the Princeton Magneto Rotational Instability experiment have been undertaken, which shall help to better understand and identify this effect, which is thought to be particularly relevant in astrophysics as important part of the dynamics of accretion disks.

Scientific Staff

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Supercomputing and other Research Fields

Computer Center Garching

Head: Dipl.-Inf. Stefan Heinzel

The RZG supports optimization of complex applications from plasma physics, astrophysics, materials science and other disciplines for massively parallel high-performance computers and 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.

Introduction

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 supercomputer complex, since 2007 consisting of an IBM Power6 system with 6624 processors and an IBM Blue Gene/P system with 16 384 processor cores. As first part of a successor system, in October 2012 an Intel Sandy Bridge based Linux cluster with 9700 cores (named “Hydra”) has been put into operation. Furthermore, a series of different mid-range Linux clusters are operated for the IPP and further Max Planck Institutes.

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 systems of the supercomputers are accessible from the visualization nodes. The RZG also operates systems for developing and testing applications on GPU (Graphics Processing Unit) platforms based on the NVidia “Fermi” and “Kepler” product lines and on the competing “Many Integrated Core” (MIC) architecture (Xeon Phi preproduction hardware), which was recently introduced by Intel.

In the mass storage area, a new TSM server machine has been installed to accommodate for the fast data growth of backups from the Max Planck Institute for Biochemistry. The other TSM server machines for backups are getting closer to their end of life and will be replaced by new hardware in 2013. The method of mirroring archived data with the LRZ for safety reasons has been altered. From now on, a self-owned hardware will be used by the owners of the data. Therefore, a robot system of the LRZ has been set up in the cellar of the RZG, in return the RZG will in 2013 install its own tape-robot system in the rooms of the LRZ.

High-performance Computing

Support in the field of high-performance computing is a central task of the RZG. This comprises

1) optimization of codes, participation in visualization and graphical preparation of data, evaluation of new parallel programming techniques and models as e. g. for the use of accelerator coprocessors for numerically intensive application parts,
2) project-specific support, often in cooperation with several partners at various institutes.

In the following selected projects are presented in more detail.

GPEC Code

In order to achieve real-time control of fusion plasmas the flux distribution and derived quantities have to be calculated within the time of the machine control cycle, which in the case of ASDEX Upgrade (AUG) is of the order of 1 ms. To this end a new, highly optimized, yet fully portable numerical solver, GPEC, had been developed at the RZG in collaboration with the IPP (M. Rampp, R. Preuss et al., Fusion Science & Technology, 2012). GPEC tackles the two-dimensional Poisson problem posed by the Grad-Shafranov equation describing magnetohydrodynamic equilibrium in tokamaks like AUG. The new code has been validated with results from the equilibrium code CLISTE and is already routinely employed for offline data analysis at AUG (R. Fischer, IPP), thus demonstrating its numerical accuracy and robustness. In plasma equilibrium codes like CLISTE or IDE (R. Fischer), where a number of solutions of the Poisson equation are computed independently for a whole set of basis functions, the cores of multiple-CPU sockets can be used in parallel by mapping individual GPEC calls to different CPUs. In a prototype implementation based on a hybrid OpenMP/MPI parallelization of the GPEC/IDE equilibrium code, recently runtimes of below 0.2 ms per iteration have been achieved for a grid size of 32×64 employing 7 basis functions and about 80 diagnostic probes and running on commodity hardware (four Intel Xeon E5-2670 CPUs mounted in two server nodes). Accordingly, the new code can complete at least 5 iterations within the AUG machine control cycle, which is generally considered as sufficient for obtaining a converged solution of the Grad-Shafranov equation. This, together with our ongoing optimization work on the post-processing routines is expected to pave the way towards real-time applications in an environment such as AUG, either as a real-time diagnostic or, ultimately, fully incorporated into the control system, thus significantly enhancing the operational regime for real-time plasma control.

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 respect to the extension to new physics and to include more efficient numerical algorithms, and also to improve the computational performance. During the year 2012 major efforts at the RZG were dedicated to porting GENE to GPUs and to the MIC architecture for evaluation purposes (see below). Specifically, the so-called nonlinearity of the Vlasov equation, which is computationally the most expensive part of the algorithm, was ported and optimized for computation on GPU accelerator cards and Intel MIC coprocessors.
In order to improve the handling of different implementations (e. g. for specific hardware architectures such as GPU or MIC) and of algorithmic variants, a restructuring of the code in an object-oriented manner has been started. A new design and inheritance strategy was developed in order to unify different implementations of the right-hand-side terms of the Vlasov equation, and especially of the nonlinear term. It has been found that in addition to improving the code quality also the computational performance increased for some cases as a result of this restructuring.

JOREK Code

The MHD code JOREK is used to investigate the physics of edge-localized modes (ELMs) in tokamaks. It solves the three-dimensional nonlinear MHD equations in toroidal geometry. JOREK uses a finite-element method in the poloidal plane and Fourier harmonics in toroidal direction. A fully implicit time stepping scheme requires solving large matrix systems at each time step. At the RZG the code was extended with a new module enabling usage of the Watson Sparse Matrix Package (WSMP). The WSMP library is actively developed by IBM and offers high-performance direct and iterative matrix solvers, which are parallelized by means of MPI. The library is available on all HPC machines at the RZG, in particular on the new Hydra supercomputer. The WSMP solver can now be used by JOREK simulation runs serving as an alternative to the default solver and offering potential performance benefits depending on the machine and the input parameters.

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. Depending on the scientific problem, matrices of quite different sizes and kinds are used. So far, performance measurements of the solvers had been carried out only for particular matrices and on hardware, which is not at the very latest. Therefore, a systematic ELPA performance study has been performed for a series of matrix sizes, ranging from 2500 to 100 000, both for double real and for double complex cases, and for different fractions of eigenvectors calculated, ranging from 100 % down to 10 %. This study was carried out on an Intel Sandy Bridge based compute cluster at the RZG for different numbers of parallel processors ranging from 1 node (16 cores) to 128 nodes (2048 cores). The ELPA solvers showed good scalacability and outmatched the corresponding routines from Intel's MKL library. The comprehensive study was presented as a poster at the Supercomputing Conference 2012 in Salt Lake City and gained international interest.

Assessment of 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 (HPC) landscape. In fact, an ever increasing number of major HPC centres in the US, Asia, and Europe are already operating systems with such types of so-called "accelerators" (GPU) or "coprocessors" (MIC). Both architectures are characterized by a large number of processor cores with comparably low clock frequencies, and are thus able to combine significant compute performance (in the order of 1 TFlop/s per card for double-precision floating-point arithmetic) with high energy efficiency (in the order of 5 GFlop/s/Watt). In order to assess the suitability of these technologies for developing and operating actual scientific applications in the Max Planck Society, the RZG has ported three major codes to the NVidia GPU and Intel MIC platforms and has evaluated a number of community codes (mostly classical molecular dynamics, MD), which have already been ported to the GPU (no MIC variants available yet) by the community. For the codes VERTEX (radiation hydrodynamics for core-collapse supernova simulations, MPI for Astrophysics), GENE (gyrokinetic plasma turbulence simulations, IPP) and ELPA (scalable direct Eigenvalue solver library, see above) speedups of up to a factor of two were achieved when comparing runs on a compute cluster equipped with nodes comprising two NVidia GPUs and two Intel CPUs with runs on a pure CPU cluster of the same type. For the MD codes it turns out that the latest versions of GROMACS (4.6), LAMMPS and AMBER are able to deliver speedups of up to a factor of 8 on actual application setups, which consume major computing time budgets on the HPC systems of the MPG. The detailed findings of the assessment together with specific recommendations for the adoption of GPU and MIC computing in the MPG were compiled into a comprehensive report, which was submitted to the advisory board of the RZG at the end of 2012.

Scientific Visualization

A special Linux cluster is operated at the RZG, which is dedicated to quantitative analysis and visualization of simulation data. It comprises a large file system and several visualization nodes equipped with large main memory and two powerful graphics processing units (GPUs) each. The cluster enables scientists to efficiently perform remote visualization of large data sets, in particular without the need to transfer the data to local workstations. On the cluster, state-of-the-art visualization tools for various purposes are available.
In addition to providing a hardware and software platform, the RZG offers support for the selection and the usage of visualization and data analysis tools and for the instrumentation of simulation codes. The RZG has supported and – in some cases – taken over a number of particularly challenging visualization projects. In these cases, either the complexity or size of the simulation data, or specific visualization goals required expert knowledge of existing visualization methods or sometimes the development of tailored software solutions. Recent examples include projects from astrophysics (MPA, MPE), plasma physics (IPP) and materials research (FHI), among others.

Figure: Frame from an animation, which illustrates the migration route of a bird in correlation with wind and topography data. (Data: Max Planck Institute for Ornithology; Visualization: RZG)

Recently, a visualization project in cooperation with the Max Planck Institute for Ornithology was carried out. The Department of Migration and Immuno-ecology (Prof. Dr. Wikelski) studies the migration and the survival strategies of animals. Individuals are equipped with GPS loggers to record their migration routes. The data is then correlated with geodata. At the RZG, an animation was created to illustrate the methodology. First, a number of points is shown in 3D space, which represent the individual data points collected by the bird's GPS logger. These points are then connected to point out the route of the animal. After that, a terrestrial globe is faded in together with colour-coded 3D topography data, followed by arrows representing the wind field. The second part of the animation shows these elements in a fully time-dependent way. It becomes clear to the viewer that the migration route of the bird is highly influenced by the wind situation and by the topography.

Data Services

The *Data Service Group* established last year has started its work in supporting and optimizing the handling of data, covering the whole range of services related with the different types of data, from the hardware-near *bit-stream services* over the logical *metadata services* up to the support of *project-specific data services*. Selected examples of the activities of this group are presented.

High Performance Storage System (HPSS)

In 2012 the HPSS tape storage has become the only production HSM (Hierarchical Storage Management) system for archiving at the RZG. All data located still in the old TSM (Tivoli Storage Manager) controlled HSM file system is and will be transferred to the new technology transparently for the user. Copying of the data – including those from the migrating AFS (Andrew File System) – is still ongoing, but is very likely to be finished in 2013.
The new HPC system with a migrating GPFS (General Parallel File System) is a prominent user of HPSS via GHI (GPFS-HPSS-Interface). HPSS is also used as back-end storage in several data-oriented projects, like EUDAT, where apart from GHI some of the other HPSS interfaces available are employed. Last but not least, a test installation of a GPFS for data produced in the Wendelstein 7-X experiment has been set up. It is planned to connect this file system via GHI to the HPSS thus providing HSM functionality, too. For 2013 it is planned to add further dedicated GHI-controlled file systems storing data for sufficiently large data projects.

Oracle Databases

The Oracle databases provided in Garching support both MPE and ASDEX. They are running on real Linux machines with dedicated storage directly attached to them. Maintenance and backup procedures have been fully established. In Greifswald the migration of the Wendelstein 7-X Oracle database from a dedicated Sun-SPARC-Solaris machine onto a virtualized Linux system, where also the storage provided is completely virtualized, has been completed in 2012. For 2013 it is planned to provide an Oracle Application Server for ASDEX to enable a modernized web-based access to the database.

Project-specific Data Services

Some of the collaborative data projects cover support and development of technologies to handle data in a world-wide context. In the Galformod project the RZG together with the MPA provides web access to work flows acting on the simulation data of the Galaxy-formation computations. The management of the linguistic data in the Replix project, together

with the MPI for Psycholinguistics, Nijmegen, is based on iRODS (integrated Rule-Oriented Data System).
Other collaborations are concentrating on the replication of data in the tape storage system at the RZG, like the data for the MPI for Ornithology in Seewiesen. Together with this institute in addition a database and web interface for a better organization of the metadata associated with the raw data just mentioned is developed and implemented.
For plasma physics or fusion research, respectively, the RZG acts as a central European data hosting site for the simulation data of the European science community, which conducts 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.

Collaborative Projects

Apart from the already mentioned data management projects the RZG participates in further IT projects, which require e.g. acquisition and deployment of novel software techniques or bringing into service of comprehensive tools and which often aim on infrastructure extending across cooperating sites. For instance, in collaboration with the MPI for Physics, LRZ and LMU the RZG has deployed, and now maintains, a federated Tier-2 grid centre for the WLCG (Worldwide LHC Computing Grid). In this project common computing power is provided for the CERN particle physics experiments as well as the necessary infrastructure for accessing the common data, which are used by many institutes and thousands of scientists all over the world. In the EU project PRACE-2IP (Partnership for Advanced Computing in Europe), which started in September 2011 with participation of the RZG, the European Tier-1 HPC infrastructure on the basis of national HPC systems established in former EU DEISA projects (also with participation of the RZG) is maintained in addition to new, dedicated Tier-0 systems. MPG scientists are already lively engaged in projects for using the Tier-0 and Tier-1 resources of PRACE. Moreover, the RZG participates in two MPG projects: in maxNet, the internal social network of the MPG, and in MPG-AAI, which is to establish an MPG-wide corporate and federal infrastructure for authentication and authorization for the purpose of managing the access to protected web resources. Especially for bioinformatics applications the RZG maintains a dedicated hardware and software infrastructure for computational biology applications and offers high-level application support for all kinds of bioinformatics projects of the Max Planck Society.

Data Network

The data network has been further optimized. The "collapsed backbone" concept consists of high-level switches at a few central locations, which directly connect to all endpoints via links based on copper or fibre – eliminating the need of aggregating and limiting switches at workgroup or storey level. This structure greatly enhances overall network performance. Several active network components on the IPP campus as well as at the RZG were replaced, since they were approaching their end of life. By choosing devices from the same model line the number of spare parts to be kept on stock could be minimized. Wireless Network infrastructure supporting the standards 802.11b/g/n was established in D2/D2a as a reference installation for other buildings. The data connection to the Supercomputer of the International Fusion Energy Research Centre / Computational Simulation Centre (IFERC-CSC) in Rokkasho, Japan was tested; a front end with optimized parameters was set up for data transfers to and from the European fusion community.

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. A new software framework ArcAccess has been designed and implemented, which will handle the storage, migration, archival and retrieval of the measurement data of W7-X. The mass data are stored in plain files, while associated metadata are stored in a database. The functionality of this software package has been successfully tested with mock-up data within the GPFS and HPSS infrastructure of the RZG. The W7-X object editor ConfiX has been extended with options for error/status logging and additional search possibilities of objects and their references. Furthermore, the DB interface has been re-implemented to eliminate database dependencies from the ConfiX. For the TDC (Time to Digital Converter) new hardware device drivers have been developed to support the Microsoft Windows 7 and Windows Server 2008 operating systems, both in 32-bit and 64-bit versions. A first high-channel (64) data acquisition system based on ATCA standard has been installed and successfully integrated into the W7-X CODAC environment. Final performance tests are expected to be finished in early 2013.

Scientific Staff

A. Altbauer, D. Beckert, V. Bludov, G. Bronold, T. Dannert, K. Desinger, R. Dohmen, E. Erastova, C. Falls-Rodriguez, K. Gross, C. Guggenberger, A. Hackl, C. Hanke, S. Heinzel, F. Heiss, F. Hinterland, F. Kaiser, J. Kennedy, T. Khan, M. Kölbl, H. Lederer, K. Lehnberger, A. Marek, W. Nagel, M. Panea-Doblado, F. Paulus, A. Porter-Sborowski, M. Rampp, J. Reetz, H. Reuter, K. Reuter, K. Ritter, B. Sanchez, A. Schmidt, A. Schott, J. Schuster, S. Wangnett, I. Weidl, K. Zilker.
XDV Data Acquisition Group: P. Heimann, J. Maier, M. Zilker.

Energy and System Studies

Diverse trends characterize the energy situation in 2012. The US is developing unconventional fossil fuels hoping to become energy independent. China continues to develop the whole portfolio of energy technologies. Even Japan reconsiders the use of nuclear. Germany builds up rapidly renewable energies: 21 GW of PV were added in the last three years. Energy research with all options including fusion is necessary to be prepared for future imponderabilities.

Energy Models

EFDA-TIMES Global Energy Model

Since 2004, the group for energy system studies participates in the development of the global energy system model EFDA-TIMES, concentrating on the evaluation of future pathways for the integration of fusion power in the electricity market. In 2012, the work focused mainly on the scientific dissemination of model results representing fusion as a future energy option in the long-term global scientific energy debate. In cooperation with the involved associations, several scientific publications have been prepared investigating the effects of demand variations, the development of renewable energies and the increase of cogeneration on fusion market penetration. Furthermore, the setup of a TIMES-based fusion module allowing for the integration of fusion technologies into various long-term energy system models was prepared and will be maintained continuously. In parallel, a new modeling software framework has been developed allowing for a higher spatial and temporal resolution of TIMES based energy models.

Analyzing the Variance of Measured Heat Consumption

In previous years a geo-database for various parameters of about 40.000 buildings in Oldenburg in Niedersachsen, was designed and filled with data from municipal and administrative sources. Based on this information, the variance of measured heat consumption can be compared to previous gained building parameters. This shows that user behavior, the volume of a building and its year of construction are the most dominant effects on measured heat consumption. Using these results it is possible to estimate heat consumption and the margin of error of these estimations for areas with no measured data available. It can be shown that the geographical scale of a heat consumption estimation is crucial to its margin of error.

Dual Use in Fusion and Industry

The investigation of synergies between results from fusion science and industrial applications was the scope of a project together with the Siemens AG. By a systematic approach several technologies and research topics with potential synergies have been identified. On the basis of fusion research results one technology has been investigated in detail and adapted by further developments to the needs of industrial applications. The project demonstrates how fusion science could be beneficial to industrial applications nowadays by a systematic cooperation between industry and research.

Fusion Power Plant Model

Systems Code Studies

The development of the systems code TREND was continued this year. It includes now comprehensive modules for the plasma geometry and the core physics. In addition, simple modules for the divertor, the power flow and the costs were implemented. The benchmarks of TREND with PROCESS (CCFE), HELIOS (CEA) and TPC (JAEA) were finished. This activity helped to identify few weaknesses of all involved systems codes and led to suggestions for reasonable updates. Furthermore, first parameter studies were conducted with TREND (figure 1). Within this framework, the implications of physics assumptions for several key-parameters on the design of DEMO were evaluated. This activity is continued in 2013 in order to refine the conceptual designs for DEMO.

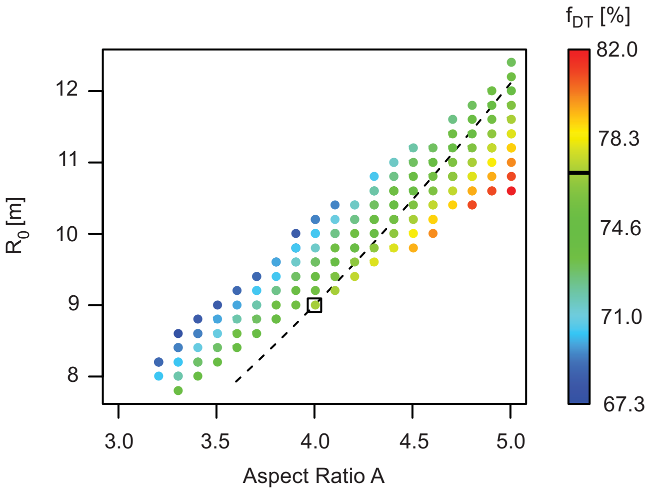

Figure 1: Comparison of the results of TREND with analytical calculations for the dependency of the aspect ratio and the major radius for constant fusion power (2 GW) based on a reference configuration for DEMO. The black square in the plot and the solid black line on the colour legend marks the DEMO reference design point. The dashed black line corresponds to analytical calculations. The operation points obtained by TREND are coloured with respect to the individual fuel concentration. The variation of the latter is the main reason for the observed difference between the results of the analytical calculations and those of TREND due to a higher level of self-consistency.

Scientific Staff

P. Böhme, T. Eder, Th. Hamacher, T. Hartmann, M. Sommerer.

Communication Studies

What effect did the reactor accident in Fukushima have on the media coverage of fusion research and fusion energy? This question is at the centre of an international comparative study within the EFDA SERF Work Programme, and within this framework the IPP Public Relations Department and the University of Mainz examined the German situation.

Unlike the British and French media, the German media gave extremely intensive and negative coverage of the reactor catastrophe in Japan, portraying it as typical of the hazards presented by nuclear energy.* Presumably also as a consequence of the extreme coverage, the German Government set up a moratorium and then decided to abandon nuclear energy. Whether this development had an effect on the coverage of fusion was examined by both the University of Mainz and the IPP Public Relations Department in a content analysis. The following findings refer to the study by the University of Mainz with a larger SPSS database. Unlike the IPP analysis, which was restricted to quality national newspapers and magazines, Kepplinger & Lemke and their 18 well-trained coders analysed all newspaper and magazine articles that appeared in Germany between December 2009 and February 2012.

Out of a total of 830 articles, 570 dealt exclusively with fusion energy and a further 260 with nuclear energy as well. After the reactor disaster (11 March 2011) almost exactly the same number of articles about fusion energy appeared as beforehand (405 vs. 416). There was a sudden rise in the number of articles about fusion immediately after the Fukushima reactor accident but this then fell back to the original level or below.
Overall the coverage of fusion energy was positive. On a scale of +2 (= pro fusion energy) to -2 (= con fusion energy) this positive tendency was more marked in articles about fusion energy that also addressed nuclear energy (.47), than in articles that did not mention nuclear energy (.25). In this respect the image of fusion energy benefited from the image of nuclear energy.
Most articles appeared in regional subscription newspapers, followed by national subscription newspapers. Contrary to all other types of media (except for a few online offerings, which can be ignored), the national daily papers portrayed fusion energy in a slightly negative light (-.04). This overall slightly negative tendency was a consequence of the much more negative tendency of the articles that only dealt with fusion energy (-.15). On the other hand, these same publications portrayed fusion energy in a slightly positive light (.20) in articles that also dealt with nuclear energy.

Unlike all the other types of media, the printed editions of the specialist journals (.71), popular scientific journals (.71) and online editions of scientific journals and organisations (.86) portrayed fusion research as distinctly positive – by and large irrespective of whether these articles also dealt with nuclear energy or not.
The media that were analysed portrayed nearly all fusion topics predominantly positively. The consistently negative portrayal of one topic – the financing of fusion research – is therefore all the more notable. It was generally characterised as negative by media of all three types, i.e. the costs were portrayed as being too high, the investment required unaffordable.
The overall tendency of coverage after the Fukushima accident was not significantly different from the overall tendency beforehand (.33 vs. .30). This is still the case if articles with and without reference to nuclear energy are considered separately.

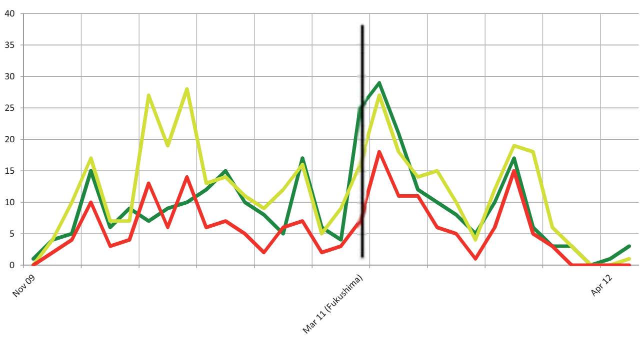

Figure: Evolution of the tendency. Dark green: positive articles, light green: neutral/ambivalent articles, red: negative articles.

From these and further results can be concluded: The extremely negative coverage of nuclear energy in the German media following the Fukushima reactor disaster did not have any notable impact upon the tendency of reporting about fusion energy/fusion research. If there were any consequences, they resulted in fusion being portrayed more positively rather than more negatively.
The positive and negative image of individual aspects of fusion was largely independent of the disaster in Japan and its portrayal in the German media. This suggests that judgements andassessments were determined by the respective aspects/topics rather than by current events.

* *Hans Mathias Kepplinger, Richard Lemke: Die Reaktorkatastrophe bei Fukushima in Presse und Fernsehen in Deutschland, Schweiz, Frankreich und England. Lecture at the Annual Meeting of the German Commission on Radiological Protection, Hamburg, 15 March 2012.*

Scientific Staff

University of Mainz and IPP: H. M. Kepplinger, R. Lemke, I. Milch, J. Sieber.

1

Astrophysics and Laboratory Plasma Studies (ALPS)

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

The group was active starting September 2009 and closed in December 2012. The vision was to create a link between X-ray studies of plasma in astrophysics and in the laboratory. With time the group acquired more and more members, some for a short time, in both fields of interest. For the final annual report of our group we would like to stress the very recent laboratory results obtained by J. Belapure, Dr. O. Maj and B. Huber.

Supra-thermal Electron Tails during Strong ECRH

The main goal of our group was to obtain information about the ASDEX Upgrade plasma in the hard X-ray regime (20-500 keV), to look into the electron cyclotron resonance heating (ECRH) physics processes. The compact CsI(Tl)+SDD based advanced detector has been employed, recording photons between 20-500 keV, with an energy resolution of about 3 % at 100 keV, and a time resolution of tens of milliseconds.

From the beginning of the project in Fall 2009, the HXR diagnostics on port 16Bo underwent a major upgrade before the 2012 campaign. Finally, with the appropriate steps of an improved grounding scheme, proper optical light shield, and the neutron/Gamma-ray shielding surrounding the detector, the noise in the spectral recordings was impressively suppressed.

The genuine hard X-ray emission has been constantly monitored during various ASDEX Upgrade plasma scenarios, with our main focus being on the strong ERCH discharges. In order to facilitate accurate spectral analysis, the detector Response Function Matrix was not only simulated but also tested in the laboratory. Efforts were also taken in developing necessary python based analysis modules as well as a GUI, which allows a complete visualization of the data and control of the analysis.

Ultimately, one of the spectacular hard X-ray spectrum recorded during shot #27698, with ECRH heating power of 2.1 MW and electron density n_e =1.69, is shown in figure 1, where the supra-thermal tail is clearly detected up to 120 keV. The supra-thermal tail is also recorded in plasmas with P(ECRH) as low as 0.6 MW at the same electron density.

In addition, very recently we also made a remarkable observation of oscillations of the HX signal correlating with SX saw-tooth crashes (figure 2). This once more underlines the potential of the diagnostics that set up, are ready to be used as a routine diagnostic for AUG.

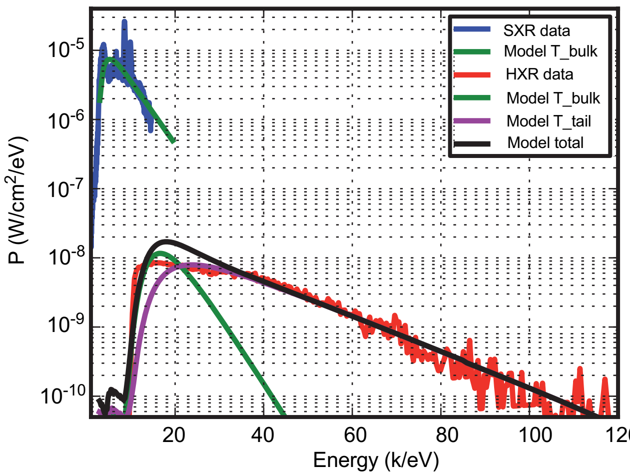

Figure 1: Hard X-ray spectrum (in red) of the shot #27698. It shows the supra-thermal tail extending up to 120 keV, characterized by a slope of 20 keV. The soft X-ray spectrum (in blue) measured by the PHA system (Dr. Weller) is plotted in the same plane and shows the thermal emission. The green curve shows the expected thermal emission spectrum predicted for the SX and HX diagnostics cases, respectively.

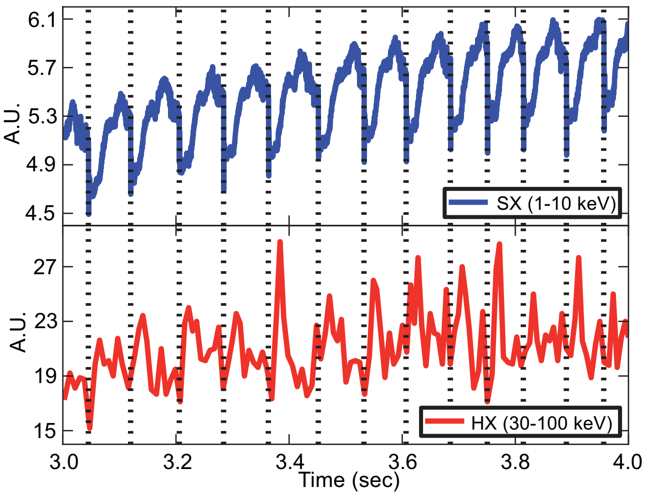

Figure 2: During the saw-tooth oscillations in discharge #27761, we observed the spiky HX burst appearing just after the collapse of the SX signal during magnetic rearrangement.

Fokker-Planck Modeling

In presence of electron cyclotron resonance heating (ECRH), the X-ray spectrum emitted by the plasma via electron bremsstrahlung provides important information on how the high-energy tail of the electron distribution function is shaped by the balance of the effect of collisions against the combined effect of the Ohmic electric field and the electron cyclotron wave. From the comparison of observations with theoretical predictions, one could obtain important insights on energetic electrons, particularly, in presence of high power ECRH.

With this aim, the numerical modeling of the electron distribution function for AUG discharges has been attempted by coupling the beam tracing code TORBEAM, for the propagation of the electron cyclotron wave, to the bounce-averaged quasi-linear relativistic Fokker-Planck solver RELAX for the description of the effects of collisions, Ohmic electric field and quasi-linear wave-particle interaction.

A novel module has been added to the code TORBEAM for the calculation of the bundle of extended rays (O. Maj, E. Poli, and E. Westerhof, 2012). Such ray-based description of the beam is equivalent to the standard beam tracing description, but it has the advantage of being "ray-based": since RELAX is a optimized for a "ray-based" description of the beam, the new module allows us to interface the two codes in a relatively straightforward way.

For the ASDEX shot #27764, the distribution function at the position of maximum power deposition is shown in figure 3. One can observe the formation of a quasi-linear plateau predicted by the theory. Such severe deformation of the electron distribution function is made possible by the low plasma density achieved in the discharge under consideration. In figure 4 we show that our prediction is in good agreement with the observed spectrum of the same shot.

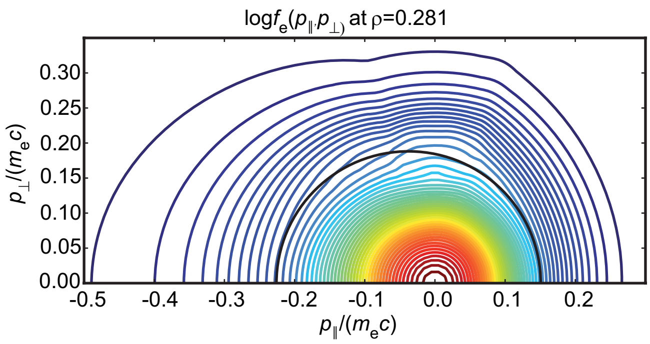

Figure 3: Contour plot of the (normalized) electron distribution function at the position of maximum electron cyclotron power deposition for the discharge #27764. The effect of wave-particle interactions can be appreciated as a deformation of the contours from the perfectly circular shape, which corresponds to the Maxwellian equilibrium. The black curve indicates the locus of resonant electrons. This calculation does not account for the Ohmic electric field.

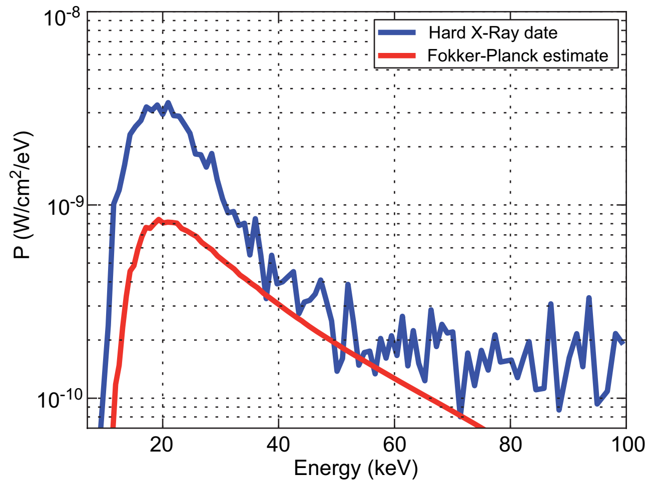

Figure 4: The hard X-ray emission measured (blue) during discharge #27764 is compared for the first time with the Fokker-Planck calculated suprathermal tail, then translated into a photon spectrum (red).

Imaging in Hard X-rays

A novel pinhole-camera type 7-cell SDD+CsI(Tl) based hard X-ray detector has been developed and demonstrated to be excellent not only for its spectral and timing properties but also for its image reconstruction capability. The performance of the 7-cell detector is similar to the single cell detector, but added imaging ability. Using the signals from 7-cells in real time, the energy of the incident single photon and its 3-dimensional direction is reconstructed. For this purpose, based on the Principle Component Analysis technique, a rigorous python code was developed and tested with Monte-Carlo simulations creating artificial photons interacting within the detector. The actual laboratory testing was carried out only at the end of December, after all the mechanical pieces and the multi-channel Data Acquisition System (DAS) was constructed and tested.

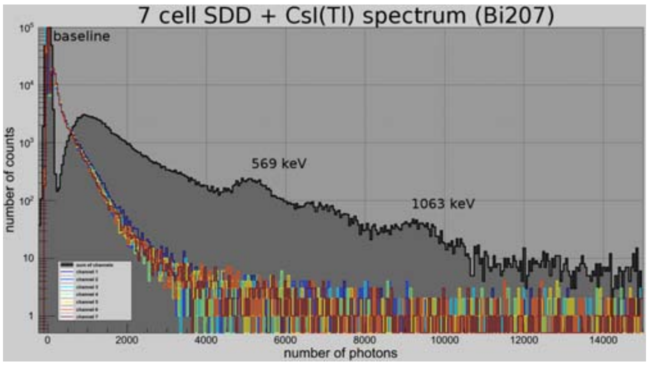

Figure 5: The spectrum recorded by the 7-cell hard X-ray imaging detector complete of scintillator and pin-hole. Due to lack of time statistics is a little poor, but lines are clearly visible.

A GUI is also developed to ease controlling of the 7-cell detector and assembly and the DAS. The detector has already seen the first X-ray light, as shown in figure 5. The only missing part is now the direct use of the camera at AUG.

References

TORBEAM: E. Poli, A. G. Peeters and G. V. Pereverzev, 2001.

RELAX: E. Westerhof, A. G. Peeters and W. L. Schippers, 1992.

Scientific Staff

M. Salvato, J. Belapure, V. Allevato, S. Fotopoulou, O. Maj, G. Lanzuisi, A. Weller, U.

Max Planck Princeton Cooperation

Max Planck Princeton Research Center for Plasma Physics

Head: Prof. Dr. Sibylle Günter

A new Max-Planck Center has been established to provide a framework for collaborative plasma physics research between IPP, the Max Planck Institutes for Astrophysics (Garching) and Solar System Research (Katlenburg-Lindau), Princeton Plasma Physics Laboratory (PPPL) and the Department of Astrophysical Sciences at Princeton University.

Introduction

The Center was inaugurated in Princeton in March 2012 by the presidents of the Max Planck Society and Princeton University, and a scientific kick-off meeting also took place. The hiring of post-docs for the Center commenced in the autumn, and most positions have now been filled. The scientific projects to be explored within the framework of the Center fall under four broad topics described below.

The emphasis lies on fundamental aspects of plasma physics, and an important aim is to strengthen the links between astrophysics and fusion plasma physics. Collaborative work will be carried out using experimental facilities at IPP and PPPL, as well as numerical codes available at all the five participating institutes. It is envisaged that scientists involved in the work will spend extended periods on the other side of the Atlantic, scientific workshops will be held approximately every nine months, and the Center will reach out to other institutions involved in the relevant areas of plasma physics.

Magnetic Reconnection

For investigations of driven magnetic reconnection, the new linear experimental device VINETA II has been conceptionally designed and constructed at IPP Greifswald. The device is homogeneously magnetized by an arrangement of azimuthal magnetic field coils providing a guide field B_g. The superimposed reconnection magnetic field B_{rec} is realized by three axial electrical conductors, which generate a magnetic field of $B_{rec}/B_g = 1$ and allow for characteristic frequencies of the reconnection drive in the range of $f_{drive} = 50$-100 kHz. Due to the flexible rf plasma generation by either capacitive, inductive, or helicon wave sustained mode, the plasma density can be varied over three orders of magnitude, which renders a controlled transition scenario between collisional and collisionless reconnection possible. A plasma gun has been developed providing the electron current necessary to flow during the magnetic reconnection process. All individual parts of the experimental setup and diagnostics (spatiotemporal reconstruction of fields, diagnostics for plasma dynamics, and kinetics) have been completed and are integrated. The primary research objectives of the reconnection studies are (*i*) guide field dependence of reconnection, (*ii*) plasma dynamics and kinetics within the current sheet, and (*iii*) role of local and global boundary conditions. Those objectives are tackled together with accompanying numerical simulations, which are performed in close collaboration with the Ernst-Moritz-Arndt University, Greifswald, and are envisaged to incorporate closely the experiment geometry, drive setup, and boundary conditions. First experimental results on the guide field dependence of magnetic reconnections, especially on the evolution of the reconnection current sheet topology, have been obtained. They indicate that for large ratios of B_{rec}/B_g, the current sheet is predominantly determined by predefined geometrical parameters as, e.g., the plasma gun aperture. For smaller guide fields of $B_{rec}/B_g \approx 1$, an elongated current sheet forms in response to the reconnection process with wing-like current structures along the separatrices, possibly already representing signatures of two-fluid effects. These studies will be pursued with special emphasis on the corresponding electron and ion kinetics. Reconnection is also a key aspect of large scale instabilities in tokamaks (like sawtooth collapse and disruptions), of the interaction of modes at different radial positions, and of the effects of externally applied 3-d perturbation fields. Open questions of NTM triggering, field penetration and sawtooth crashes will be addressed in the frame of the centre. Recent results show that a sawtooth crash apparently triggers an ideal MHD perturbation at the NTM rational surface, which transforms into an island only on a longer time scale. New power supplies for the internal coils with a faster current ramp-up will be a unique tool for investigation of the field penetration. The Centre also offers good opportunities for cross comparisons between ASDEX Upgrade and NSTX Upgrade. The modelling of reconnection phenomena in fusion plasmas within the Centre will concentrate on the application of 2-fluid MHD codes. A first aim of our studies is the penetration of error fields into a rotating plasma. Following extensive calculations in the cylindrical plasma approximation, we presently address this issue with the 3-d XTOR code. The best diagnosed spontaneous reconnection event is, however, the sawtooth collapse, which can exhibit quite differing phenomenology. Simulation of typical events with the M3D-C1 code, developed at PPPL, will be subject of a PhD thesis within this Centre.

Energetic Particles

In the area of energetic particles in fusion and astrophysical plasmas, one important part of the collaboration between IPP and PPPL is the understanding of fast ion transport in present-day tokamaks and future fusion devices. Within the MPPC, new aspects of this subject such as the interaction of fast-particle-driven instabilities with the background turbulence and the quantitative modeling of unexplained experimental data are addressed. As a first step, after identifying the codes involved (LIGKA, HAGIS, NEMORB on the IPP side, and NOVA-K, M3D-K, GTS, GKM on the PPPL side) two benchmarks are set up that allow all codes to contribute. One case is based on the very recently measured n=0 mode driven by off-axis neutral beams at ASDEX Upgrade. Both the linear onset and the non-linear

behaviour such as frequency chirping and the turbulence interaction can be addressed. The second case is a reversed shear Alfvén eigenmode that changes into a toroidal Alfvén eigenmode. Excellent two-dimensional ECE imaging mode structures allow for a detailed code validation with the experiment.
Another research project within the MPPC deals with the possibility to use a passive runaway electron suppression technique in tokamak disruptions. The idea is to let the conductivity of the plasma vessel be such that the large electric field generated in the disruption drives a helical current in the vessel. This breaks up the nested flux surfaces of the plasma, leading to enhanced runaway losses, which could potentially balance the gain from the avalanche mechanism. One major advantage with this type of technique is that it is not needed to perform the difficult task of detecting that a disruption is going to happen, because the necessary currents would be driven by the electric fields generated by the disruption itself.

Plasma Turbulence

Within the MPPC, there are presently five projects directly dedicated to plasma turbulence, while many other projects in the areas of magnetic reconnection, energetic particles, and magneto-rotational instability are also linked to and will benefit from a deeper understanding of this phenomenon. One goal is to extend the gyrokinetic turbulence code GENE to non-axisymmetric toroidal configurations like stellarators or tokamaks with symmetry breaking magnetic perturbations (e.g., to control Edge Localized Modes). In a first step, a flux-surface global version of GENE has been developed and is currently being applied to various stellarator and tokamak configurations. Work towards a full-torus extension is underway. A second goal is to develop a novel gyrokinetic edge turbulence code on the basis of Discontinuous Galerkin methods, which hold the promise of a robust, flexible, and highly parallelizable implementation. Preliminary tests of a low-dimensional version of this code have been successful. A third goal is to apply GENE to various astrophysical problems including turbulent heating in collisionless accretion disks and the solar wind as well as magnetic reconnection in a strong guide field. Two-dimensional gyrokinetic studies of turbulent reconnection exhibiting the formation and merging of plasmoids are presently being analyzed.
The remaining two projects complement the ones based on gyrokinetics. The fourth goal is the (further) development of hybrid and fully kinetic codes, which can test and extend the gyrokinetic studies of both laboratory and astrophysical plasmas. This includes, in particular, the edge region of fusion devices as well as the physics at the tail of the MHD turbulence cascade and magnetic reconnection in weak or no guide fields. This should be viewed as a longer-term effort involving extreme computing. The fifth and final goal is to better understand and model the propagation of energetic particles in turbulent magnetic fields. This question is of importance to both fusion devices (e.g., the dynamics of runaway electrons during tokamak disruptions) and cosmic ray physics. Regarding the latter case, analytic theories and test particle simulations are currently being applied to cosmic ray propagation in the solar wind and the interstellar medium. All of these projects are being pursued in close collaborations between groups at PPPL, Princeton University, MPA, MPS, and IPP.

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. The actual infall can only be accomplished by transporting angular momentum radially outward within the accretion disk surrounding the object. As standard molecular viscosities are orders of magnitude too small to explain astronomical observations, only turbulence excited by the MRI is regarded as a viable candidate for this task. Since the MRI has only rather recently been re-discovered for the destabilization of accreting flows in an astrophysical context, many aspects of MRI turbulence still need to be investigated and understood.
To this end, a liquid-metal MRI experiment is hosted at PPPL. In close collaboration with scientists at PPPL and Princeton University, direct numerical magnetohydrodynamic (MHD) simulations are performed at IPP Garching with the main task of helping 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. Following a phase of in-depth code-code comparisons, these tools are currently being applied to interpret recent experimental data obtained at PPPL.
A second line of research is concerned with MRI turbulence, and is pursued by groups at the Technical University of Berlin and at Princeton University. By means of direct numerical simulations with the self-developed compressible MHD code KT-MHD, investigations of fundamental statistical and structural properties of MRI-driven turbulence are envisaged. This includes investigations regarding the spatial structure and possible anisotropy imprinted by the MRI on the turbulence, the influence of the MRI on the spectral flux of energy, and the effect of the roughness of the velocity and magnetic fields on the MRI's saturation amplitude. Additionally, the dynamo effect in MRI turbulence will be studied theoretically and numerically using the Cho-Vishniac dynamo model as a starting point.

Scientific Staff

S. Günter, P. Helander, K. Lackner, V. Igochine, P. Lauber, F. Jenko, W.-C. Müller, O. Grulke, J. Clementson, G. Plunk, H. Smith, P. Singh Verma, B. Teaca.

University Contributions to IPP Programme

Cooperation with Universities

Author: Gregor Neu

Teaching and Mentoring

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.

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 2012, 22 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.

University	Members of IPP staff
University of Greifswald	Dr. Hans-Stephan Bosch Dr. Andreas Dinklage Prof. Per Helander Prof. Thomas Klinger Prof. Thomas Sunn Pedersen
Technical University of Berlin	Prof. Wolf-Christian Müller-Nutzinger Prof. Robert Wolf
Technical University of Munich	Prof. Sibylle Günter Dr. Klaus Hallatschek Dr. Philipp Lauber Prof. Eric Sonnendrücker Prof. Ulrich Stroth
University of Munich	Dr. Thomas Pütterich Prof. Hartmut Zohm Dr. Jörg Stober
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

Table: IPP staff who taught courses at universities in 2012.

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.

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 2012 for the 27^{th} time in Garching. Most of the about 70 participants were from Europe but the number of attendees from abroad is steadily increasing. Some of them are taking part in the "European Doctorate in Fusion" programme. A "European Doctorate" title is awarded to PhD students in parallel to a conventional one. This requires spending a significant part of the work on their subject at another European university or research centre. The European Doctorate in Fusion was initiated five years ago. At present institutions in Germany, Italy (EURATOM Association Consorzio RFX Padova and the University of Padua), and Portugal (EURATOM Association IST) are supporting this programme.

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 2012 a total of 53 postgraduates were supervised, 15 of them successfully completing their theses.

Joint Appointments, Grown and Growing Cooperation

IPP cooperates closely with several universities in the form of joint appointments. In 2012 there were two W3 appointments at the Technical University of Munich – that of Prof. Stroth in the field of plasma edge and divertor physics and that of Prof. Sonnendrücker for numerical methods in plasma physics. A third joint W2 appointment for plasma-wall interaction is well under way.

The cooperation with the Technical University of Berlin in the field of plasma astrophysics resulted in the W2 appointment of Prof. Müller in 2012.

Further examples of close cooperations with universities are those with the University of Stuttgart, the Technical University of Munich, the École Polytechnique, Palaiseau (F), and the École Polytechnique Fédérale de Lausanne (CH) in the Helmholtz Virtual Institute "Plasma Dynamical Processes and Turbulence Studies using Advanced Microwave Diagnostics" and with the University of Augsburg for the development of a negative-ion source for the neutral-beam injection which was selected as the reference source for ITER. A highlight of the latter cooperation was the inauguration of the test stand ELISE in November 2012.

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” has been awarded to Dr. Rachael McDermott. The award comes with a financial support of 250 k€ for a duration of five years. The University partner is the University of Augsburg.
- The European Research Council (ERC) Starting Grant on “Plasma Turbulence in Laboratory and Astrophysical Plasmas” headed by Professor Dr. Frank Jenko at the Max Planck Institute of Plasma Physics (IPP) in Garching,
- European Young Investigator Award Group, “Zonal Flows”, headed by Dr. Klaus Hallatschek (until autumn 2012),
- Helmholtz Russia Joint Research Group, “Hydrogen Behaviour in Advanced and Radiation damaged materials for fusion applications”, headed by Dr. Matej Mayer as Helmholtz Principle Investigator and Dr. Alexander V. Spitsyn, RSC Kurtschatov Institute.

Research partnerships:
- Participation in the DFG Collaborative Research Centre Transregio 24, “Fundamentals of Complex Plasmas”, together with Greifswald University, Kiel University and Leibniz Institute for Plasma Science and Technology, Greifswald.

Participation in Clusters of Excellence in the context of the German government’s Excellence Initiative in cooperation with Ludwig Maximilian’s University and Technical University Munich:
- “Origin and Structure of the Universe”, together with Max Planck Institute for Astrophysics, Max Planck Institute for Extraterrestrial Physics, Semiconductor Laboratory and Max Planck Institute for Physics and the European Southern Observatory.

A few years after its formation, IPP joined the European Fusion Development Agreement as a EURATOM Association. When the decision was made to build ITER, it became clear that training of young scientists and engineers had to be intensified. A European Fusion Education Network (FUSENET) was therefore formed in FP7. FUSENET consists of 14 EURATOM associations – one of them IPP – and 19 universities from 18 European countries.
IPP is also one of the eight partners of the newly formed International Doctoral College in Fusion Science and Engineering, which has been approved under the auspices of Erasmus Mundus, the European programme to promote training schemes. The doctoral college which has started in October 2011 is being supported with about five million euros and provides 40 doctoral scholarships for work in the field of fusion research.

University of Augsburg
AG Experimentelle Plasmaphysik

Head: Prof. Dr.-Ing. Ursel Fantz

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

Developments for Negative Hydrogen Ion Sources

As low pressure operation of negative hydrogen ion sources for the neutral beam injection systems of ITER and DEMO reduces the stripping losses of negative ions in the accelerator, helicon discharges are investigated as an alternative to the purely inductive RF-coupling used in the IPP prototype ion source. Beside the gain in the negative ion current, this concept promises higher RF-power efficiency as well as a higher degree of ionization and dissociation. The present helicon setup (see Annual Report 2011) has been reconstructed to achieve pressures of 0.3 Pa or even below. Stable operation in hydrogen and deuterium is demonstrated. The typical density ratio of atoms to molecules is about 20 % as in the IPP source. Parameters for optimization are power and magnetic field strength. The diagnostic setup has been completed to allow for a full characterization of the plasma.

Alternative concepts to the magnetic filter field for electron cooling are investigated as well, since the magnetic field causes plasma drifts resulting in non-uniform plasma illumination of the extraction area. Thus, an electrostatic concept, the meshed grid method, has been successfully tested in an ECR discharge. This HOMER experiment is also used for investigations on Cs-free ion sources as present sources require caesium to produce sufficient negative ions with the drawback that the source performance is determined by the caesium dynamics. The activities for ion sources for ITER and DEMO are extended by exploring the laser neutralizer concept with proof-of-principle experiments in laboratory scale.

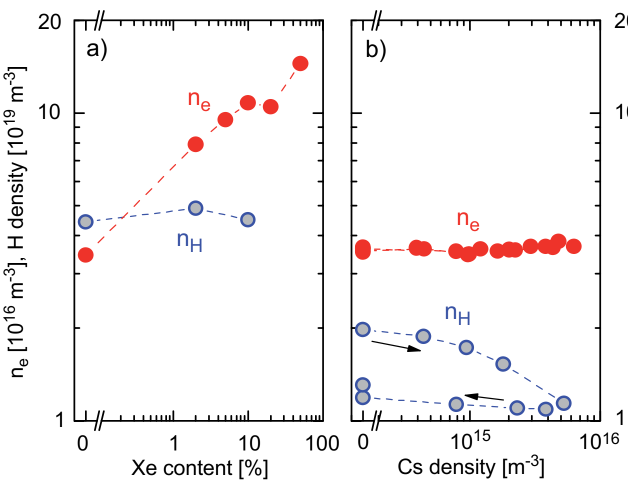

Figure 1: Electron and atomic hydrogen density in H_2 discharges at a pressure of 10 Pa and 250 W RF power. Left: variation of the xenon content; right: variation of the caesium density by caesium evaporation.

Consequently a pulsed cavity ring-down system for laser detachments is in preparation followed by a cw laser setup.

In order to understand the caesium dynamics in vacuum and in hydrogen low temperature plasmas, basic investigations in a laboratory experiment with comparable plasma parameters to the IPP prototype source are performed. The planar ICP is equipped with multiple diagnostics, which can be applied simultaneously to get an insight into the complex caesium dynamics. This setup is also used to develop caesium supply systems and diagnostics, which are subsequently transferred to the IPP sources. Recently a new type of ceasium oven was developed to improve the reliability of caesium evaporation in a wide range of evaporation rates. The full-metal system comprises an alloy dispenser as caesium source, a valve and a surface ionization detector at the oven nozzle to measure the evaporation rate in-situ. This oven has proved reliable and controllable operation in vacuum, gas, and plasma environment and is now the prototype oven for the ELISE test bed at the IPP.

With this controlled evaporation, the influence of caesium on the plasma parameters of hydrogen discharges has been investigated. In order to obtain the exclusive effect of adding a gas with a higher atomic mass and lower ionization energy than hydrogen, xenon admixtures have been tested as well. Figure 1 shows the change of electron density and atomic hydrogen density by adding xenon or caesium to the hydrogen discharge. The caesium density is measured by absorption spectroscopy, the atomic hydrogen density is determined via emission spectroscopy and the electron density is measured by a Langmuir probe system. As expected, the admixture of xenon results in a decrease of the electron temperature (not shown) and increases the electron density whereas the atomic density is almost unaffected. Caesium, with even higher mass and lower ionization energy, however, shows no influence on the electron temperature or density. On the other hand, the atomic hydrogen density decreases with increasing caesium showing a hysteresis. This can be attributed to the getter effect of hydrogen at the caesium coated vessel walls. The effect of a caesium coated surface on the electron density close to the surface is measured in different distances from the surface. With decreasing distance the electron density decreases as shown in figure 2. Without caesium evaporation stable values are obtained while a decrease over time is observed with evaporation. The decline, which is more pronounced closer to the surface, is attributed to enhanced negative ion production on the fresh caesium surface, which in turn pushes the electrons away to keep quasineutrality. As with increasing distance the negative ions are destroyed by collisions with plasma particles, a weaker effect is observed with increasing distance.

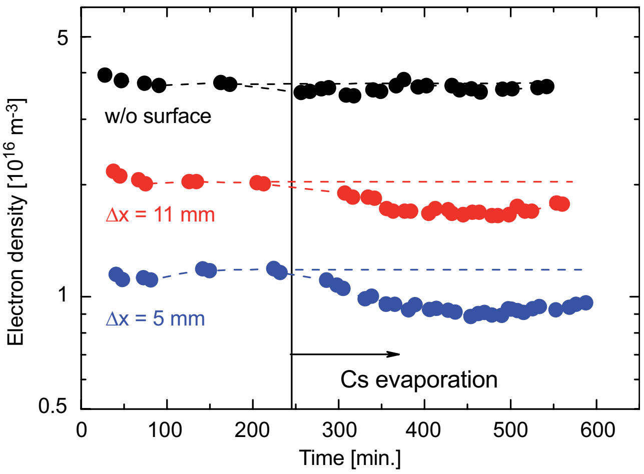

Figure 2: Electron density in a H_2 discharge at 10 Pa and 250 W RF power at different distances from a sample surface for different distances Δx of the probe tip to the surface. As indicated caesium evaporation starts after $\approx$ 240 minutes. A caesium density of about 5×10^{15} m^{-3} is obtained in each case.

Low Temperature Plasmas

A substantial part of the research activity is the development, steady improvement and benchmark of collisional radiative (CR) models. In order to gain access to population densities of resonant levels in hydrogen, i.e. n=2 populations, a scanning VUV monochromator has been recomissioned providing a good spectral resolution (FWHM of about 40 pm) in the wavelength range from 105 nm to 300 nm. Typical spectra of hydrogen and deuterium measured with an axial line of sight in the helicon discharge are shown in figure 3. Besides the resonant Lyman alpha line of atomic hydrogen, molecular bands, the Lyman and the Werner band as well as the continuum radiation are detected. In a next step, a calibration of the intensity will be carried out allowing for the determination of absolute population densities. Further studies will focus on reabsorption, i.e. opacity effects, utilizing the Lyman alpha radiation in combination with the Balmer line emission.

For the purpose of improving and benchmarking an established CR model for nitrogen coupled with argon, a low pressure (0.1 mbar – 10 mbar) N_2-Ar arc discharge experiment has been modified for the application of extended diagnostics. The new discharge vessel allows for direct measurements of the population of metastable particles of argon by means of absorption spectroscopy and the determination of electron density and temperature via a double probe system. As reported last year, these parameters are critical input parameters for the CR modelling of the emission of the 1st ($B^3\Pi_g \rightarrow A^3\Sigma_u^+$) and 2nd ($C^3\Pi_u \rightarrow B^3\Pi_g$) positive system of nitrogen.

The rare gas investigations in a planar ICP have been continued, focussing now on non-Maxwellian EEDFs, the increased influence of opacity on emission lines from heavier gases like krypton, and on metastable particles. This will enable further identification of suitable emission lines for different diagnostic purposes, e.g. electron temperatures as reported last year, but also a two temperature distribution and the metastable density. Atmospheric plasmas generated by a water discharge – an IPP experiment – have been investigated in the framework of Bachelor and Master Theses. The influence of the discharge parameters, and thus the energy, on the autonomous phase has been studied as well as the temporal and spatial evolution of the plasmoid by a fast camera and by emission spectroscopy.

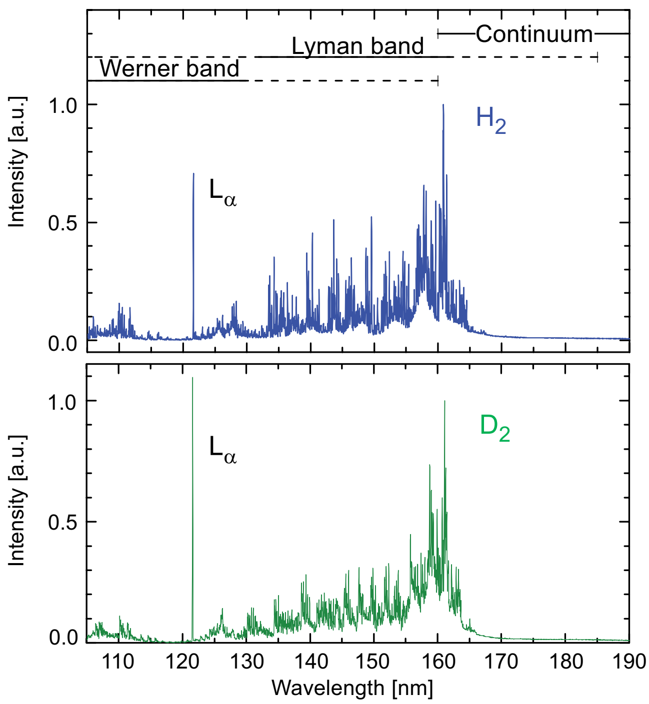

Figure 3: VUV spectra of a helicon discharge in hydrogen and deuterium (p=0.3 Pa, P=400 W, external magnetic field 14 mT). The wavelength range of the molecular emission from the Lyman band $B^1\Sigma^+_u \rightarrow X^1\Sigma^+_g$, the Werner band $C^1\Pi_u \rightarrow X^1\Sigma^+_g$ and the continuum $a^3\Sigma^+_g \rightarrow b^3\Sigma^+_u$ is indicated using a solid line for the most prominent emission.

Theses

U. Kurutz: Identifizierung geeigneter Emissionslinien von Edelgasen zur Elektronentemperaturbestimmung in Niederdruckplasmen. (Diploma Thesis)

S. Kalafat: Influence of discharge parameters on the physical properties of atmospheric plasmoids. (Master Thesis)

P. Hannawald: Messung der zeitabhängigen Emission eines atmosphärischen Plasmoids mittels Photodioden. (Bachelor Thesis)

Scientific Staff

U. Fantz, S. Briefi, J. Doerfler, D. Ertle, R. Friedl, P. Gutmann, P. Hannawald, S. Kalafat, U. Kurutz, D. Rauner, F. Vogel.

University of Bayreuth
Lehrstuhl für Theoretische Physik V

Head: Prof. Dr. Arthur G. Peeters

Through the Chair for theoretical plasma physics, the University of Bayreuth and the IPP continue and strengthen their long term collaboration, which focuses amongst others on the effect of the centrifugal force on impurity transport, the physics of tearing modes and in particular the coupling of such modes with turbulent dynamics, the physics of toroidal rotation, and the physics of ITG modes that are not localized at the low field side of the tokamak.

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. Both these areas are central in the research at the IPP and the close collaboration will also give input to the research conducted in Bayreuth. 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. In 2012 these projects resulted in six publications with shared co-authorship. Below we discuss briefly only two topics: the study of the tearing mode and the further development and benchmarking of the nonlinear gyro-kinetic code GKW, which is used in many of the projects.

Previous work investigating the interaction of magnetic islands with micro-turbulence has uncovered the observation of large scale vortex modes forming within magnetic island structures. These electrostatic vortices are found to be the size of the island and are oscillatory. It is this oscillatory behaviour and the presence of turbulence that lead us to believe that the dynamics are related to the geodesic acoustic mode (GAM). In 2012 we derived an equation for the GAM in the MHD limit, in the presence of a magnetic island modified three-dimensional axisymmetric geometry. The eigenvalues and eigenfunctions were calculated numerically and then utilised to analyse the dynamics of oscillatory large-scale electrostatic potential structures seen in both linear and non-linear gyro-kinetic simulations. It is found that frequency and damping rate are consistent with the observations on the oscillating vortex mode.

The highlight of 2012 in the collaboration between Bayreuth and IPP is the further development of the nonlinear gyro-kinetic code GKW. The physics model has been extended to include the radial dependence oft he geometry and profiles of the equilibrium quantities (global versus flux tube version). Furthermore, the parallelization of the code has been extended.

The study of turbulent transport is a major topic in the theory division of IPP. Several state of the art tools are available, which allow for a detailed benchmarking of the extended GKW model. The global version has been benchmarked with the particle in cell code NEMORB. The figure shows the growth rate of the global ITG as a function of the toroidal mode number for two values of the normalized Larmor radius. The latter is chosen to be large in order to enhance the non-local effects, and comparing the curves it is indeed clear that non-local effects are non-negligible in this case. It can be seen that the agreement between the two codes is excellent. Also the non-linear fluxes have been benchmarked. Again agreement is good. Further efforts have been dedicated to testing, debugging and benchmarking the non-spectral flux tube version of the code including the adiabatic electron zonal correction, the Rosenbluth-Hinton test, the shifted metric and nonlinear electromagnetic simulations.

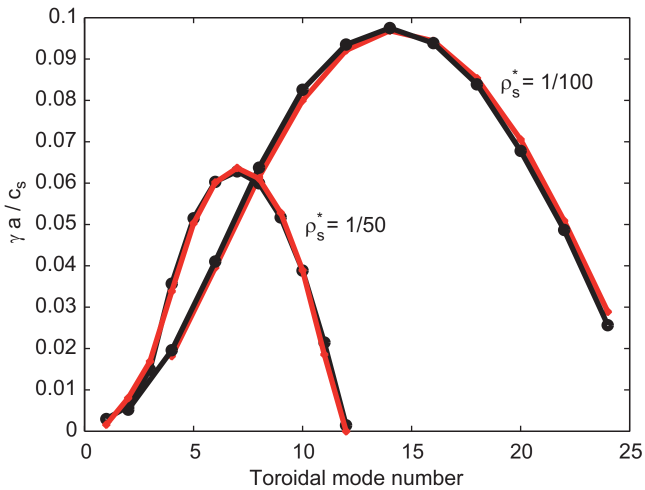

Figure: Benchmark of the global version of GKW against NEMORB. Shown is the growth rate of the ITG with adiabatic electron approximation for two values of the normalized Larmor radius as a function of the toroidal mode number.

An important contribution to GKW has been the implementation of the radial parallelism, which is expected to allow for numerical simulations using well up to 100,000 cores (demonstrated so far up to 16384 cores). Moreover, shear-periodic boundary condition have been implemented to study the effects of E×B shear. Finally, the newly implemented local Miller geometry has been benchmarked against GS2, demonstrating good agreement between GKW and GS2.

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, T. Sung, W. Suttrop, G. Tardini, C. Veth.

Ernst-Moritz-Arndt University of Greifswald

The "International Helmholtz Graduate School for Plasma Physics" is now well 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.

Electron Beam Ion Trap

Head: Prof. Dr. Lutz Schweikhard

The former Berlin EBIT operated by IPP at the plasmaphysics group of the Humboldt-University of Berlin has been reassembled and successfully put into operation in the laboratory of the atomic and molecular physics group at the EMAU. Experiments continued with the further investigation of the sawtooth phenomenon of ensembles of mixed highly charged ion species. The observation of the x-ray intensity evolution emitted by argon and xenon ions trapped and excited in EBIT by the electron beam demonstrate the dynamic interaction of a complex two-component plasma of confined light and heavy ion species exchanging energy by Coulomb collisions.

The main aim at EMAU is the study of interaction of highly charged ions with atomic clusters observing charge-exchange and dissociation. Highly charged ions have been produced and extracted from EBIT and guided by in a beam line with benders and lenses through a Wien Filter for charge-state selection and a deceleration unit to slow the highly charged projectiles down to the interaction velocity. In first experiments the ions will cross a beam of atoms in the reaction chamber, where target products are analyzed in a Time-of-Flight extraction system while projectiles are detected straight ahead.

Scientific Staff

C. Biedermann, S. Gierke, G. Marx, R. Radtke, 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 now 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, which 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. The lectures and courses find a large resonance among the participants of the HEPP and are still increasing in number. A regular seminar has already been established at the starting of the HEPP in 2011. Besides its main purpose, serving as a means for regular exchange on the progress of the individual Ph. D. Projects, it became 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. Especially the last point shows the high level of acceptance, the HEPP has gained in only one year. The yearly HEPP graduate colloquium has taken place in Greifswald in September. Organized as a workshop with roughly 70 participants, it provided a platform for the students close to finishing their Ph. D. work to present their latest results, complemented by poster presentations of the first and second year students and invited general and topical lectures. By the end of 2012 60 students were members of the HEPP.

Modelling of Magnetic Reconnection

Head: Prof. Dr. Ralf Schneider

Magnetic reconnection is a process in plasmas where magnetic field lines break, tear apart and are rearranged topologically. This way plasmas former distant to each other get connected. 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.

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

Since research on magnetic reconnection is mainly motivated by astrophysical phenomena, the modelling is often based on a MHD description of an infinite system. The magnetic field lines are assumed to have a closed configuration in order to have well defined (periodic) boundary conditions. This is not the case for all natural and laboratory environments, e.g. many magnetic field lines in the solar atmosphere are bounded by the conducting surface of the sun. One goal is to investigate the influence of various boundary conditions on magnetic reconnection.

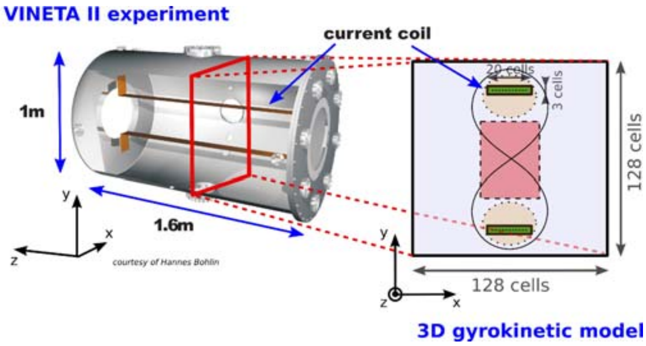

Figure 1: Schematic of the VINETA device (left side) and its corresponding representation in the simulation (right side). The reconnection event is driven by applying a sinusoidal current to axial drive coils and thereby generating an antiparallel field configuration.

A three-dimensional gyrokinetic Particle-in-cell (PIC) code from Richard Sydora is specifically adapted to the bounded field configuration of the linear VINETA device. In addition, Abha Rai, a postdoc from IPP, is applying the GENE code to the very same system.

This allows direct comparison of the results of both, PIC and Vlasov solver, and validation of the calculations with measurements.

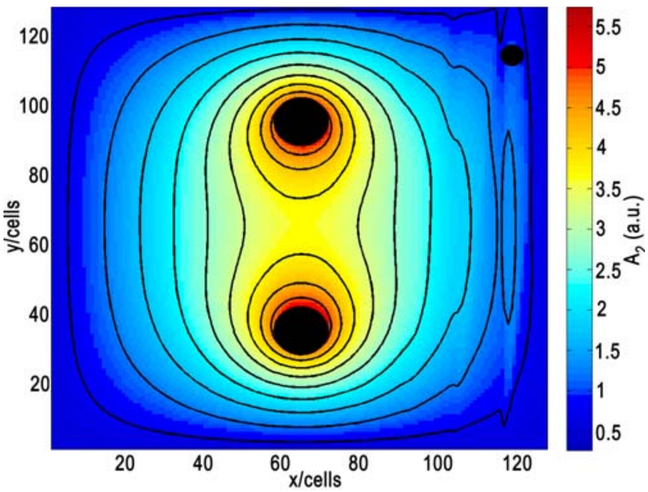

Figure 2: The simulated z-component of the vector potential A_z is shown in colors. The black contour lines correspond to the magnetic field lines. The solid black circles indicate the axial, out-of-plane field coils, which produce the in-plane magnetic field. A steady current of 2 kA in the two larger coils generate a magnetic field, which is superimposed by the field of the oscillating coil in the upper right corner.

The simulation is setup to closely mimic the driven reconnection process in VINETA. The in-plane quadratic domain seen in figure 2 has dimensions similar to the actual experiment 50 cm × 50 cm. It is bounded by conducting walls for the electric and magnetic fields while particles are reflected. The third and axial dimension has periodic boundary conditions for particles and fields, but it is planned to include a plasma sheath model.

In the VINETA experiment three field coils (two with steady current, one driven) produce a time-varying in-plane magnetic field, which generates an antiparallel field configuration at the center of the device. In time magnetic field lines are pushed and pulled to and from the central region, where the pileup of magnetic flux can then be reconnected.

In ideal MHD magnetic reconnection is forbidden due to the good conductivity of the plasma. 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.

Technical University of Munich
Lehrstuhl für Messsystem- und Sensortechnik

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

There has been a continuous cooperation of IPP and Technische Universität München in the past. Next to thermography measurement techniques, thin film and speckle interferometry has been a field of research. For two years now, the focus has been on the collaboration with the ITER Bolometry Group. The objective of this cooperation is the development of an automated method to measure the geometric function of the lines of sight of diagnostics.

Introduction

The verification and measurement of the lines of sight (LOS) of bolometry is an important issue for a reliable operation of the tomographic reconstruction algorithms. Therefore, the ITER Bolometer Robot Test Facility (IBOROB) was developed as a diagnostic tool in order to analyze LOS geometry and assess the performance of different collimator prototypes. It is crucial to know accurately the alignment, characteristics and geometric properties of the various components of the corresponding sensors and detectors. Comparison of theoretical values to the measured values allows to assess the impact of stray light and detect internal reflections. A set of about 100 different collimator configurations was examined. They were manufactured as part of the development for the ITER bolometer diagnostic (see chapter 'ITER'). The results achieved have helped to evaluate the different design versions and optimize the means for stray light reduction. Theoretical analysis has already indicated that the number of apertures inside the collimator influences the stray light from neighboring channels. The wall design, especially the surface (material, shape and finishing) has a major influence on the LOS by reducing or allowing for reflections.

Experimental Set-up

The method used for the assessment of the LOS characteristic of the ITER bolometer diagnostic components is based on previous work performed at JET. It is currently under development for the utilization as a LOS calibration device in ASDEX Upgrade, the viability of the proposed method was shown last year. The laboratory assembly IBOROB consists of a lightweight robot from KUKA Robotics, which is used to efficiently position a laser on many points, covering the complete viewing cone of each LOS and to direct the beam precisely into the entrance aperture of the bolometer.

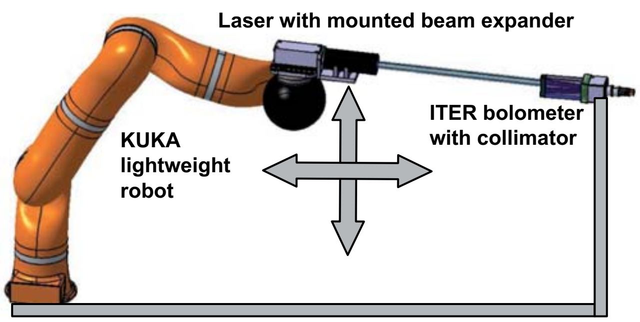

Figure 1: Schematic CAD drawing of laboratory assembly for the line of sight calibration.

Measuring the response of the bolometer and simultaneously the position of the robot allows for the calculation of the transmission function, the angular étendue and finally the geometric function in reconstruction space. A schematic drawing of the experiment is shown in figure 1. A CAD drawing of the basic bolometer prototype design used for the measurement of the LOS can be seen in figure 2. It also shows different top plate and aperture designs, which can be mounted on the bolometer.

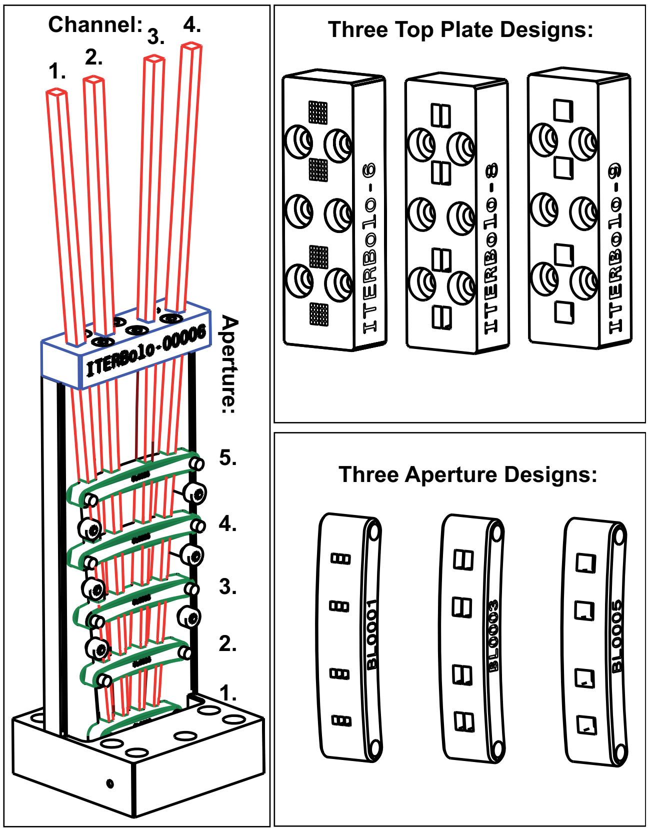

Figure 2: CAD drawing of the collimator prototype used for the measurement of the LOS on the left. Three top plate and aperture designs are shown on the right. For proper identification, the four channels and five apertures are numbered sequentially.

Measurements with Different Collimator Configurations

The main purpose was to evaluate the various collimator configurations and design versions shown in figure 2 in order to approach the target specifications. The LOS are influenced by the characteristics of the channels, apertures, walls and reflections, the used materials, and by the manufacturing process.

Options such as using multiple aperture configurations with and without top plates, are compared to each other, in order to understand the signal characteristics. In parallel, a big database was established, which helped to see common features of the various designs and discover future risks. Figure 3 shows the normalized transmission functions of one single channel in the poloidal plane, i.e., representing a vertical movement of the light source from top to down: the behavior of the different prototypes for a small viewing cone (FWHM~1°) as a function of number of apertures. In comparison with the ideal signal, strong stray light ([-0.5°,-1°]&[0.5°,1°]) is evident, which broadens the signal.

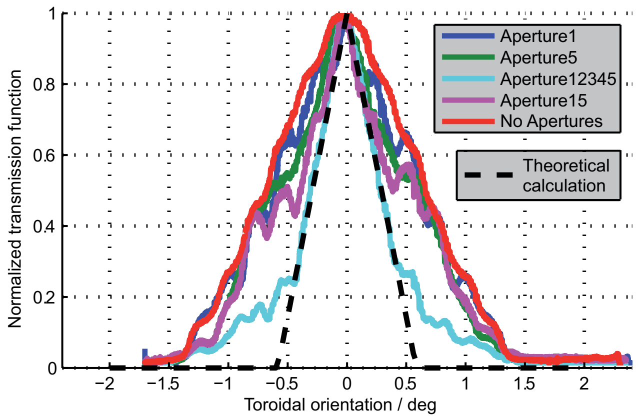

Figure 3: Comparison of five different aperture configurations. A set of all apertures (Apertures12345), the first (Apertures1), the last (Apertures5), a combination (Apertures15) and without apertures (No Apertures) at all.

These measurements, here in the toroidal orientation, effectively determine the minimum number of apertures that are necessary for a given channel width. Another example analysis was to identify separately the influence of the microwave filtering top plate, as shown in figure 4.

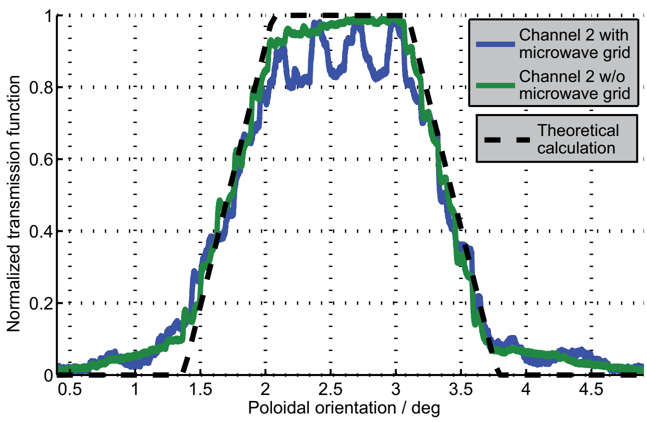

Figure 4: Comparison of two different top plate designs: with and without microwave filtering aperture.

It shows the transmission function in poloidal orientation of measurements with (figure 2: ITERBolo-6) and without (figure 2: ITERBolo-9) the microwave filtering grid. The collimator version with a wide viewing cone shows signal disturbances in the center. This is due to the microwave filtering grid (respectively top plate) thickness of 5 mm.

3D Measurement of the Viewing Cone

Applying data fusion, the performance of the system can be increased: IBOROB now allows the measurement of the complete 3D viewing cone. Figure 5 shows the reconstruction of a single channel 4 in a mesh grid: 5.15° toroidal deflection versus the horizontal plane. 60×60 samples were measured with a robot step size of 0.1°.

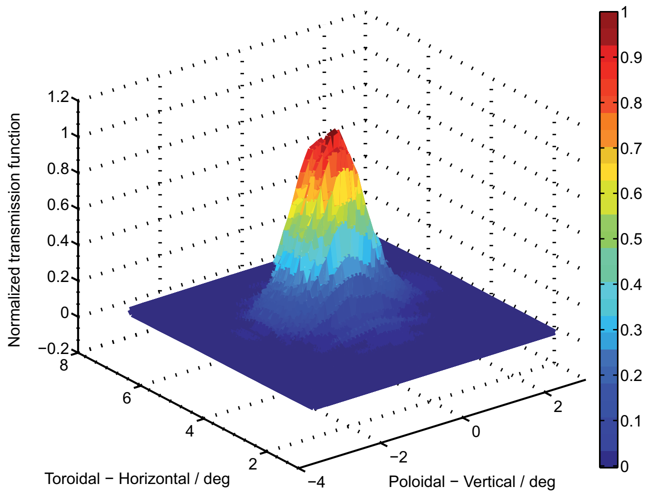

Figure 5: Three-Dimensional reconstruction of the signal response in amplitude and angle.

Outlook

The assessment of the LOS characteristic of ITER Bolometer prototype collimators has demonstrated its usefulness by identifying different construction problems. Different characteristics like reflections on the side walls and the microwave grid diffraction could be identified. IBOROB showed that it can help the evolutionary prototyping process of the ITER bolometers. It provides enough information so that the collimators can be continually improved.
The collimator design can be guided by combining and varying results of different measurement series. The final design will presumably be a combination of multiple design versions. All characteristics in the measured transmission functions could not be identified, but the research in this area continues.

Scientific Staff

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

ECRH in Over-dense Plasmas

If the plasma density exceeds the corresponding cutoff density of an injected microwave it becomes inaccessible to convectional O- or X-mode heating. This problem can be overcome by using electron Bernstein waves (EBWs), for which no high-density cutoff exists. These waves are very well absorbed at the electron cyclotron resonance frequency (ECRF) and its harmonics in high- and low-temperature plasmas. EBWs are, however, of electrostatic nature and need to be coupled to injected electromagnetic waves. At the stellarator TJ-K, the beam of the 8 GHz microwave heating system has been shaped to achieve high coupling efficiencies. This allows to routinely generate EBW-heated plasmas. EBW heating at high harmonics can also be investigated at TJ-K. To this end, plasma is generated at a magnetic field strength, where the fundamental ECRF is located inside the confinement region. If the plasma density is high enough, mode conversion of the injected microwave into the EBW sets in and the magnetic field can be ramped down as illustrated in figure 1. Harmonic numbers as high as 8 can be achieved. The injected microwave power can now be reduced by approximately 40 % as compared to the value that was necessary to start the EBW heating regime. This illustrates the efficiency of the EBW heating.

In 2012, the first step in the construction of the transmission line for the new 14 GHz microwave heating system has been completed. The output of two klystrons is combined into one oversized transmission line. Each klystron is capable of amplifying a signal in the range of 13.75-14.5 GHz up to a power of 2.5 kW. It was possible to generate first plasmas.

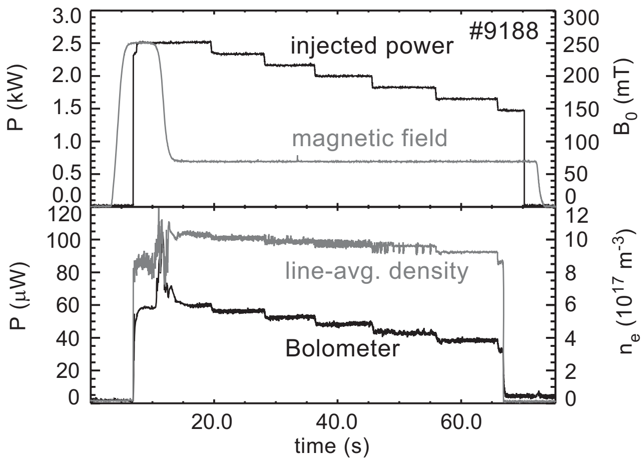

Figure 1: Time traces of a discharge with EBW heating at harmonics of the ECRF, where the injected microwave power was decreased stepwise until the plasma extinguishes.

An upgrade of the magnetic field system now allows for fields up to 500 mT, which corresponds to the fundamental ECRF of 14 GHz. With the full-wave code IPF-FDMC, the influence of density fluctuations on the coupling efficiency to EBW was studied in a 2D geometry. The coupling region is usually located at the edge of fusion plasmas, where so-called blobs occur. These blobs appear – in the frame of the electromagnetic wave – as localised density structures. As a starting point, the influence of a single blob is investigated. Depending on the size, blobs can strongly modify the shape of the wave electric field. This generally reduces the overall conversion efficiency. Moreover, additional mode conversion regions can appear inside the blob, which is a concern if localized EBW heating is desired.

Global Turbulence and Confinement Studies

Zonal potential structures were detected in probe data simultaneously measured with two 64-pin arrays, which were set up at different toroidal positions. The data allowed to conditionally evaluate the spectral components of turbulent cross-field transport at some time around these zonal structures as trigger events. Maximum zonal-potential amplitudes come along with minimum transport levels on intermediate scales. At this stage, the transport reduction is attributed to modifications of the phase relation between density and electric-field fluctuations (see figure 2) in the relevant spectral range rather than to a reduction in the fluctuation levels. Hence, the cross phase turns out to play a key role in triggering the transport reduction. The subsequent relaxation of the cross phase is accompanied by a reduction in the amplitudes, which keep transport at low levels for longer than the zonal structure's life time.

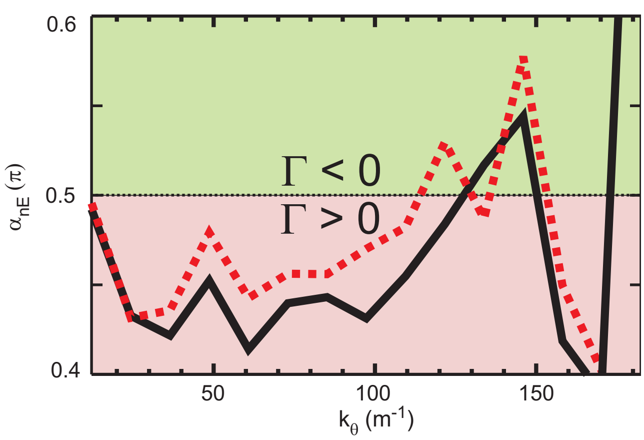

Figure 2: Average spectral cross-phase distribution (solid) compared to the momentary one (dashed), when the zonal-potential amplitude is maximal.

Density-blob sizes as detected by fast-camera measurements in the scrape-off layer (SOL) of TJ-K were tested for dependence on the drift scale ρ_s. A similar ρ_s scaling for blobs outside the confinement region is found as for drift waves inside. This supports the hypothesis of a connection between edge and SOL dynamics as suggested in earlier studies, where blobs have been found to be fed by drift waves. Moreover, radial blob velocities are found to be close to theoretical expectations for interchange driven dynamics. SOL turbulence was characterized in more detail via multi-probe measurements in limited TJ-K plasmas. In fact, cross-phase analyses showed the more interchange-like nature as compared to the confinement region.
First detailed analyses of Langmuir-probe data from the edge turbulence data base were undertaken. Turbulent fluctuations from the plasma boundary region of seven fusion experiments showed comparable characteristics. It turned out that radial outward motion is immanent to blobs in the SOL. Density holes, occasionally dominating plasma edge fluctuations, can contribute to effective outward transport, too, via inward propagation. On inter-machine basis, the structure-size scaling with ρ_s is again found comparable in edge and SOL. The scaling found suggests a rather Bohm-like magnetic-field dependence of the turbulent diffusivity.

Reflectometry Simulations with IPF-FD3D and European Collaborations

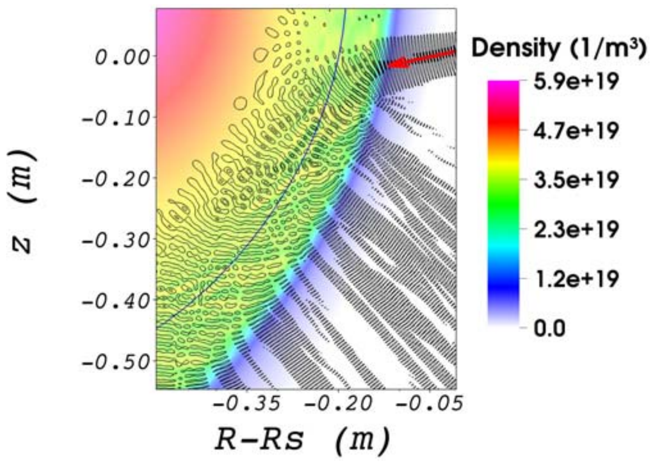

Figure 3: Setup of the simulation box with plasma profile and GENE turbulence, with overlaid contours of the reflectometer wave field.

Doppler reflectometry is an important diagnostic for density fluctuations and poloidal flows on fusion experiments. The 2D and 3D capable fullwave code IPF-FD3D is a finite difference time domain code that solves Maxwell's equations and the electron equations of motion in a cold plasma. The main research thrust in Doppler reflectometry is the investigation of the scattering efficiency of turbulent plasmas. In collaboration with ASDEX Upgrade and IPP Garching, the experimental situation for Doppler reflectometry measurements is being recreated in simulation. An important aspect is the incorporation of plasma turbulence in the synthetic reflectometer. To this end, the turbulence code GENE is employed (in collaboration with T. Görler, IPP) to give a physically consistent estimate of the fluctuations under the conditions encountered in experiment. This way, a comparison of the poloidal turbulent fluctuation spectra is possible.

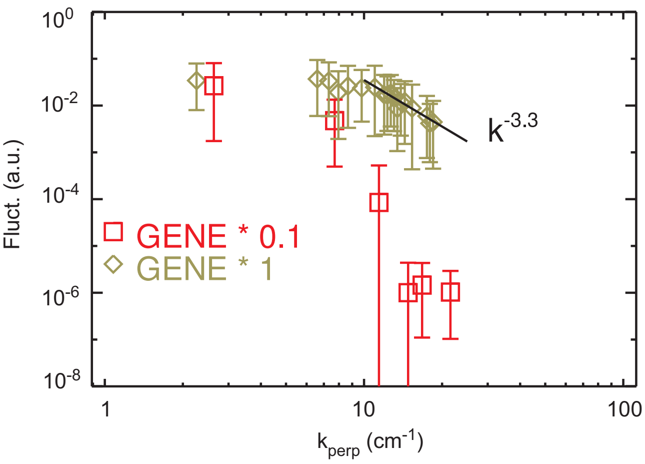

Figure 4: Simulated spectra from IPF-FD3D. The spectral index goes from -3.3 at high fluctuation level to about -8 at attenuated fluctuation strength.

First results have been obtained with a GENE run of an L-mode discharge. The main spectral feature is the spectral index, which gives the exponential decay of the spectrum towards higher wavenumbers. It was found that this index depends on the magnitude of the density fluctuations. The 7 % fluctuation level from GENE already seems to lead to non-linear saturation of the reflectometry signal. If the fluctuation strength is artificially attenuated, a different spectral index is received. This will be further investigated.
International activities have been continued under the European Reflectometry Code Consortium (ERCC) and EFDA-ITM umbrella. The ERCC has been founded for pooling reflectometry simulation know-how from European research institutions. There are several meetings, video conferences and code camps each year with participants from IPF, IPP, CEA, CIEMAT, LPMI (Nancy), FZJ, and IST (Lisbon) to discuss simulation techniques. Activities within the Integrated Tokamak Modeling (EFDA-ITM) task force under ID WP12-ITM-EDRG-ACT3 have been continued. The European 3D reflectometer code for use on ITER has been further developed.

Scientific Staff

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Publications

Publications

Articles, Books and Inbooks

Aho-Mantila, L., M. Wischmeier, K. Krieger, V. Rohde, A. Hakola, S. Potzel, A. Kirschner, D. Borodin and ASDEX Upgrade Team: Outer divertor of ASDEX Upgrade in low-density L-mode discharges in forward and reversed magnetic field: II. Analysis of local impurity migration. Nuclear Fusion **52**, 103007 (2012).

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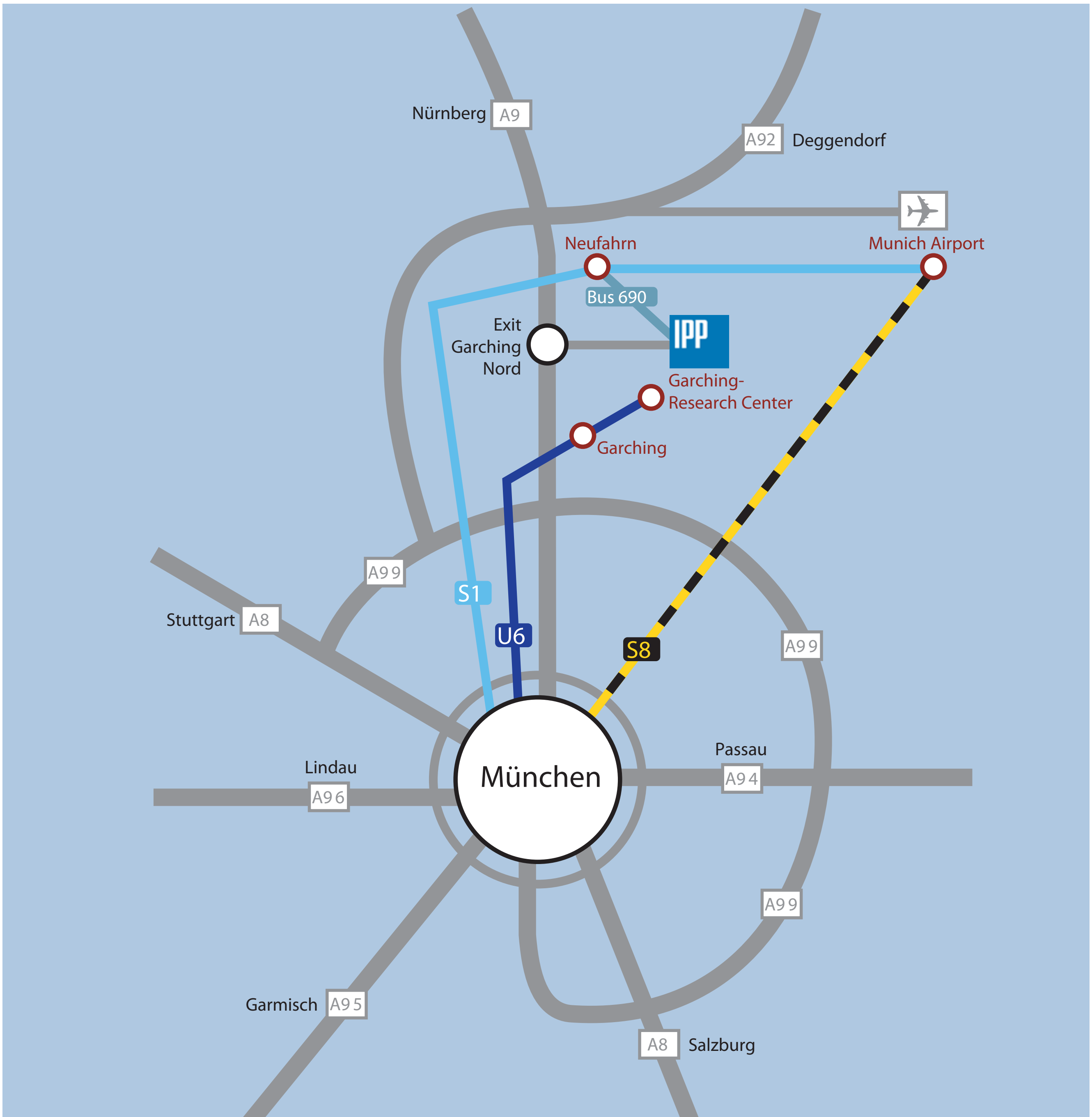
Appendix

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

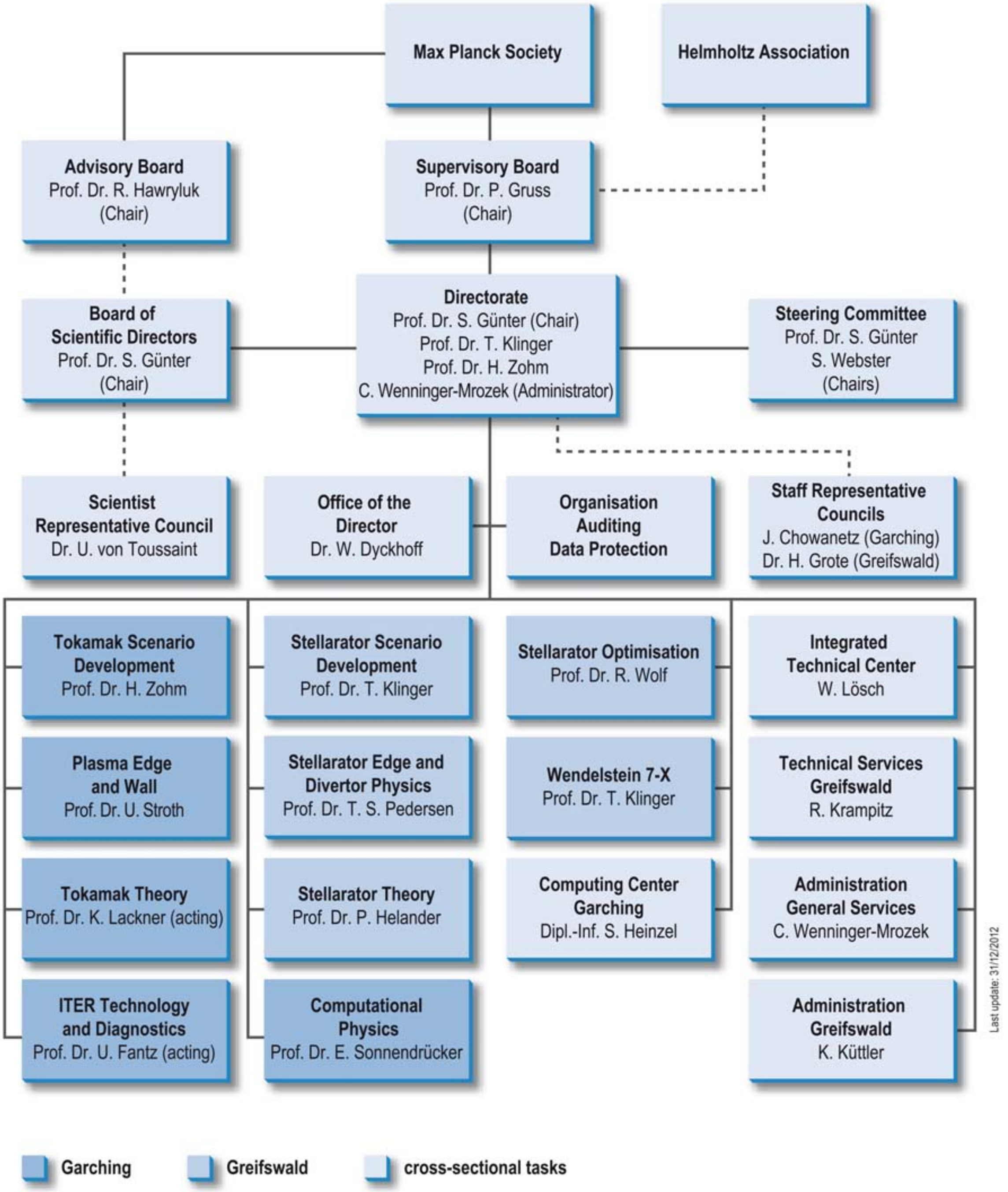
Funding

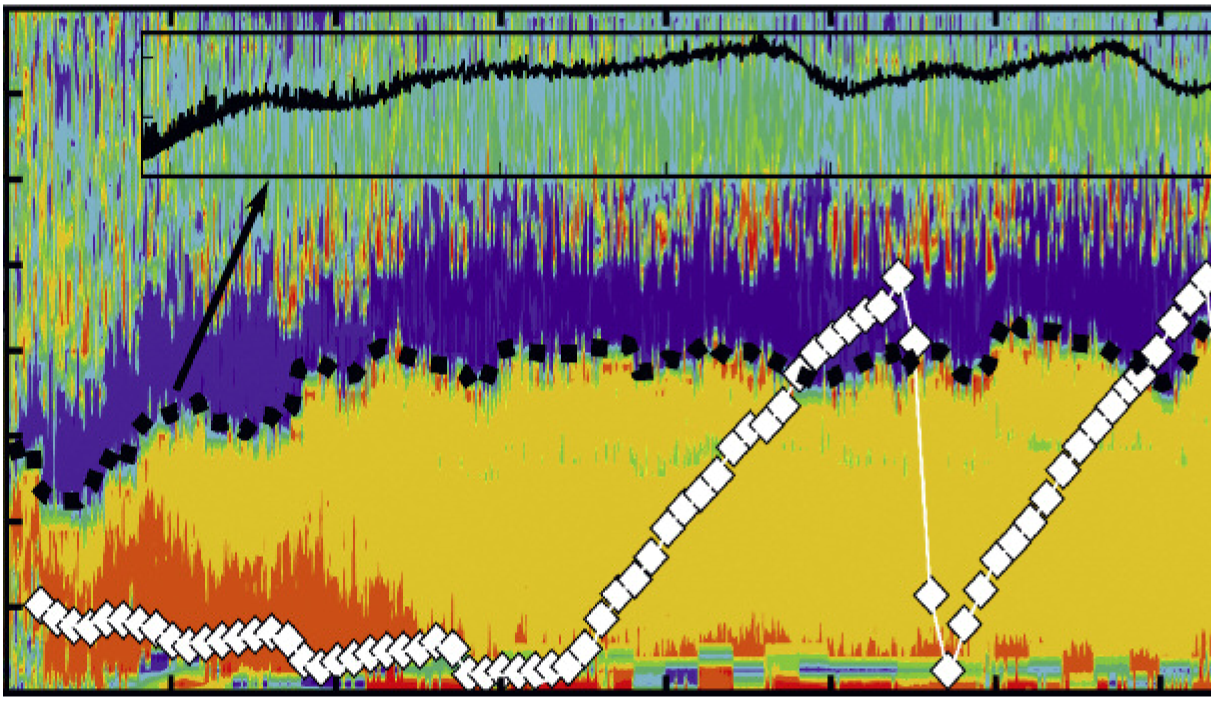
In 2012 IPP received approx. 7 % of its total funding from EURATOM. Of the basic national funding 90 % is met by the Federal Government and 10 % by the states of Bavaria and Mecklenburg-West Pomerania. EURATOM baseline support and national funding amounted to approx. 112 million euros.

Scientific Staff

At the end of the year IPP had a total of 1.119 members of staff, 413 of them worked at IPP's Greifswald site. The workforce comprised 282 researchers and scientists, 41 postgraduates and 57 postdocs. In addition, 11 guest researchers used the research infrastructure.

Organisational Structure





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Further Information
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