ASDEX Upgrade LETTER

Max-Planck-Institut für Plasmaphysik

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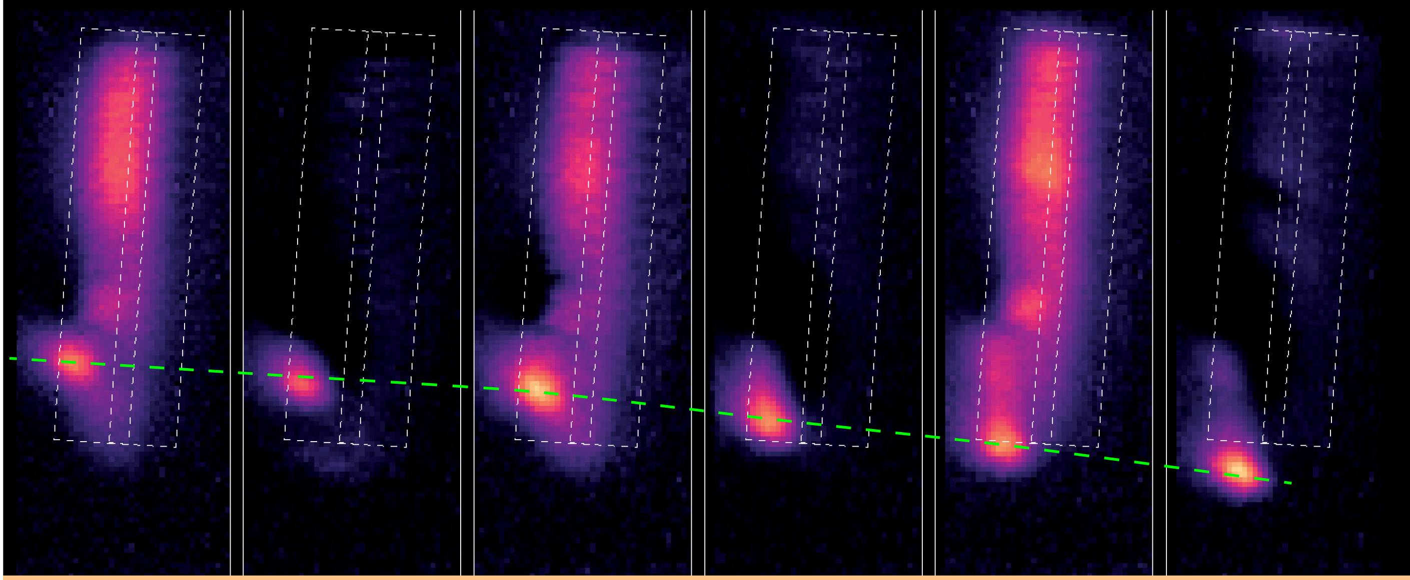
IN GARCHING FOR EUROPE – FUSION RESEARCH WITH THE ASDEX UPGRADE TOKAMAK



Sequence of IR camera images showing motion of molten tungsten across surface of sample.

ILLUSTRATION: K. Krieger

Prof. Dr. Ulrich Stroth
Head of IPP division
Plasma Edge and Wall

PHOTO: IPP, S. WINKLER

EDITORIAL

After a ten months shutdown, end of September 2018 ASDEX Upgrade was ready to start, but plasma operation had to wait seven more weeks for a necessary repair at the EZ2 flywheel generator. Finally, the successful restart end of November was applauded with great relief. A steam water leak during vessel baking on 19.11.2017 had caused serious damage, which had to be repaired by a joint effort of the entire team. In parallel, the diagnostic and plasma heating capabilities of ASDEX Upgrade were improved. Under the hands of skilled operators, the tokamak was quickly put back into operation and soon the scientific program could start with a successful hydrogen campaign in preparation for the start of ITER operation. In December, in discharge #32251 the ASDEX Upgrade plasma was heated for the first time with an ECRH power above 5 MW delivered by eight gyrotrons including the four gyrotrons from the new ECRH3 system.

Magnetic diagnostics will play a key role in the control of ITER plasmas. Also ASDEX Upgrade is equipped with an extensive set of different magnetic pick-up coils – during the vent, 500 feedthroughs had to be tested and repaired. In addition, as reported in this letter, internal and external diamagnetic flux measurements were made available to improve the magnetic equilibrium reconstruction for discharges with anisotropic plasma pressure as caused by strong ICR heating.

Of course, the ASDEX Upgrade and MST1 teams also used the tokamak downtime to work on the large amount of stored data from previous campaigns. As one example, in this letter you can find out what happens if tungsten transiently melts due to ELM power loads and how the motion of the liquid tungsten can be modelled in order to predict the consequences of local melting in the ITER divertor. A reliable modeling will help to estimate the lifetime of shaped divertor tungsten monoblocks in ITER. As a very different example of recent work on ASDEX Upgrade data you can read on an experimental study which aims at a better predictability of the core density profile shape in collisionless plasmas. In carefully designed parameter scans, where reactor-relevant values of the collisionality were systematically approached, the core transport model TGLF was validated. This model predicts increased density profile peaking when the collisionality is reduced, a property which would be very advantageous for achieving burning plasmas. U. STROTH

Highlight from a recent ASDEX Upgrade experiment

Core transport studies

Model validation towards reactor prediction

The physics of a burning plasma is an essential element in the design of an electricity-producing tokamak power plant. Present knowledge can be improved by combining experimental and theoretical research, in particular those studies which explore operational regimes reproducing, in present devices, aspects of the conditions which are expected in tokamak reactors like ITER or DEMO.

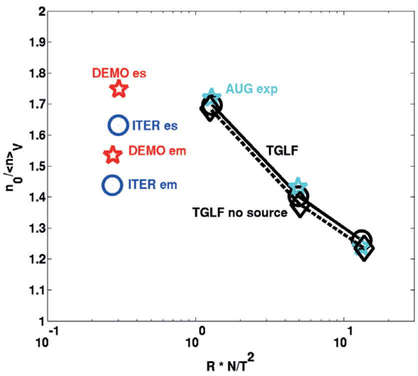
To define reactor plasma scenarios, the integration of the several operational goals and constraints in a single discharge, both at the core and the edge of the plasma, should be demonstrated. In these discharges, however, not all of the physically relevant plasma parameters can be simultaneously matched. Therefore these plasmas are only limitedly applicable to study the specific behaviour of a burning plasma from the physics standpoint, particularly in the core. This is why also a complementary approach is undertaken at ASDEX Upgrade. The goal is to achieve values of key parameters expected in the core of a reactor plasma, in particular the collisionality, the kinetic to magnetic pressure ratio β, the safety factor, the electron and ion heat fluxes in the appropriate ratio and normalized to the gyro-Bohm levels, as well as relative particle and momentum sources.

To this end, in 2018 dedicated experiments were carried out in ASDEX Upgrade aiming at the lowest possible density and thereby approaching reactor relevant collisionalities, even though at a much lower fraction of the Greenwald density limit at the pedestal top, i.e. the plasma edge, than expected in reactor plasmas. This has been realized by using increased peripheral particle transport produced by edge magnetic perturbations from the in-vessel RMP coils. The appropriate levels of particle, momentum and energy sources have been obtained by combining neutral beam injection and ion cyclotron resonant heating applied to plasmas at a magnetic field of 2.5 T and a plasma current of 0.8 MA. A shot-to-shot density scan and a power scan in each discharge allow the exploration of a range of conditions which enable a more direct extrapolation to the physical parameters of the core of a reactor plasma. The large amount of stationary plasma phases forms the database which then can be compared with the predictions of current theoretical transport models.

In particular, as shown in the figure, it is observed that under these conditions, with reactor-matched levels of particle sources, the density peaking factor increases with decreasing collisionality, with a very weak impact of the particle source. This is in quantitative agreement with the predictions of the theoretical transport model TGLF [developed at General Atomics by G. M. Staebler et al.], and fully consistent with the theory of a turbulent particle pinch. This result validates our current theory-based capability to predict the density profile shape of a reactor plasma.

The important impact of electromagnetic effects, proportional to β, is identified by the modeling work. Consistent with theory, transport modeling predicts that an increase of β reduces the turbulence-driven density peaking. To experimentally explore this dependence, new experiments at higher current and lower field are planned to reach higher values of β, while also improving matching in safety factor and heat flux ratio.

E. FABLE



Peaking factor of the electron density, defined as the ratio of the central density, n_0, to the volume averaged density, ‹n›, as a function of the collisionality parameter R N / T^2 (major radius R in meters, density N and electron temperature T at mid-radius in 10^{19} m^{-3} and keV respectively), as measured in ASDEX Upgrade and predicted by ASTRA/TGLF simulations with (black circles, solid line) and without (black diamonds, dashed line) the particle source. ASTRA/TGLF predictions for ITER and DEMO in the electrostatic limit ("es"), and including electromagnetic effects ("em")

FIGURE: E. FABLE et al, to be submitted to Nuclear Fusion (2019)

PHOTO: T. GÖRLER

Nuclear Fusion Award 2018 to IPP scientist

Professor Arne Kallenbach, the ASDEX Upgrade project leader, received the Nuclear Fusion Award 2018 for his paper "Partial detachment of high-power discharges in ASDEX Upgrade". In this paper it is investigated how to protect the divertor zone at the bottom of the plasma vessel. The method involves transforming the direct contact into detachment, a mostly indirect one. The power flux expected at the plasma boundary layer in ITER amounts to 15 MW/m, which is normalized to the plasma radius because constant width of the deposition zone is assumed. Two-thirds of this power flux can be simulated by the much smaller ASDEX Upgrade. Detachment could lower the load on the divertor from 45 to less than 2 MW/m^2. The annual Nuclear Fusion Award honours outstanding works published in the "Nuclear Fusion" journal, and, for the second year in a row, went to an IPP scientist.

I. MILCH

Diamagnetic flux measurements

Both internal and external diamagnetic flux (Φ) measurements are now available on the ASDEX Upgrade tokamak. Φ is the small difference in total toroidal flux with and without plasma. The plasma energy content inferred from this measurement (W_{dia}) and the energy content calculated from the magnetic equilibrium reconstruction (W_{MHD}) should be equal for plasma discharges with isotropic pressure. Anisotropic pressure arises when the perpendicular and parallel energy of ions are unequal. A magnetic flux changing in time induces a voltage in a loop, so that the time integral represents the magnetic flux. The integration is performed by analogue electronic integrators developed by IPP. Loops in the poloidal direction, both around the inside and the outside of the vacuum vessel, measure the toroidal magnetic flux generated by the toroidal field (TF) coils and the plasma (fig. 1). Magnetic probes oriented in the toroidal direction measure the local toroidal flux generated by the TF coils only. Φ is calculated by digitally subtracting this compensation flux from the measurement flux. External Φ measurements have limited bandwidth because the diffusion time of the toroidal field generated by the plasma current through the vacuum vessel acts as a low-pass filter. Nevertheless, it is valuable to understand how to achieve an external Φ measurement, because radiation levels in next generation tokamaks prevents the use of internal coils.

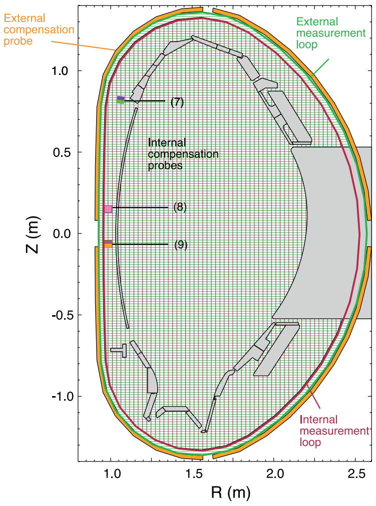


Fig. 1: Cross section of ASDEX Upgrade with internal and external measurement loops and with one external and five internal compensation probes. Squares with two colours indicate probes that are installed at the same poloidal but in opposite toroidal positions. The number in brackets refers to the last number of the signal name.

FIGURE: L. GIANNONE

Vacuum field measurements with a steady value of TF coil current are used to establish the relative sensitivity of the measurement loops and compensation probes. The integrators are triggered in the flat top phase of TF coil current. The resolution is significantly improved by measuring only the small flux changes in this phase. Small misalignments of the loops and probes with respect to the ohmic heating and poloidal field coils as well as to the plasma current lead to unwanted flux contributions, which must be corrected. Two otherwise identical discharges with negative and positive toroidal magnetic field were used to determine the correction proportional to the plasma current.

Excellent agreement of the external and five internal Φ measurements with the values calculated from the real-time and offline magnetic equilibrium reconstruction is typically found for discharges with mainly neutral beam injection (NBI) power, where no significant anisotropic pressure contribution is expected (fig. 2). The ability to compare the two independent methods of determining the plasma energy content is valuable.

The direct Φ measurement, internal as well as external, is available in real-time and can be used to control the poloidal beta, automatically including the pressure contribution from energetic ions. For example, in discharges with dominant ion cyclotron resonant heating at low density, Φ from experimental measurements is more negative than the values calculated by magnetic equilibrium reconstruction. This indicates that W_{dia} is greater than W_{MHD} due to the anisotropic energetic ion content. The internal measurement of Φ is an important tool for quantifying the fast changes in W_{dia} due to energetic ion losses in the presence of magnetohydrodynamic instabilities.

L. GIANNONE

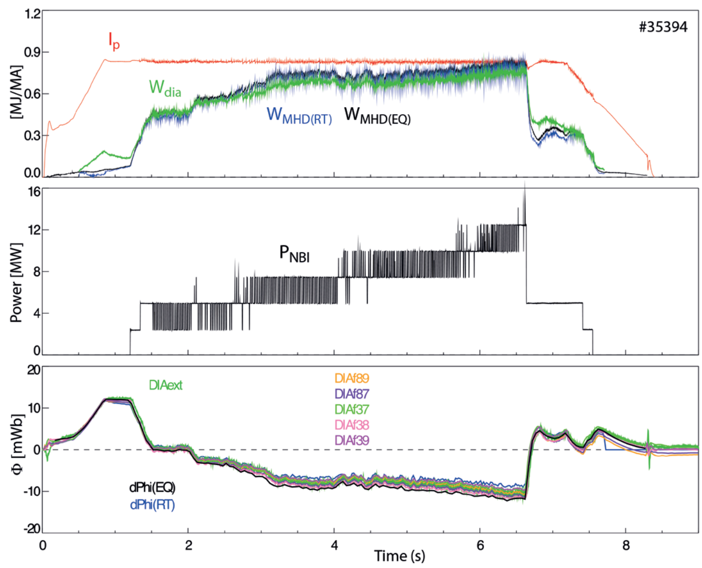


Fig. 2: Time traces of plasma current (Ip), plasma energy content W_{dia} and W_{MHD}, NBI power P_{NBI} and the Φ values from external (DIAext) and five internal (DIAfxx) measurements together with values calculated from the real-time (dPhi(RT)) and offline (dPhi(EQ)) equilibrium. The poloidal beta is 1.8 at the maximum of injected NBI power.

FIGURE: L. GIANNONE

Validation of surface melt modelling

Direct observation of ELM-induced tungsten melt motion

On ASDEX Upgrade experiments were performed to investigate repeated transient melting of tungsten induced by edge-localised modes (ELMs). The experiments were aimed at the provision of high-quality data of key quantities for validation of the MEMOS-3D melt motion code, being used as the principal simulation tool for the prediction of melt damage and associated plasma-facing component lifetime on ITER. The experiments complement and extend similar studies on JET. On ASDEX Upgrade, samples were installed in special tiles mounted on the Divertor Manipulator, allowing exposure to specific discharges without further modification due to subsequent plasma operation and rapid retrieval of samples for post-mortem analysis. Most critically, the probe head instrumentation provides measurement of current drawn and the opportunity to electrically insulate samples. Thus, the melt motion with and without net current flow can be studied.

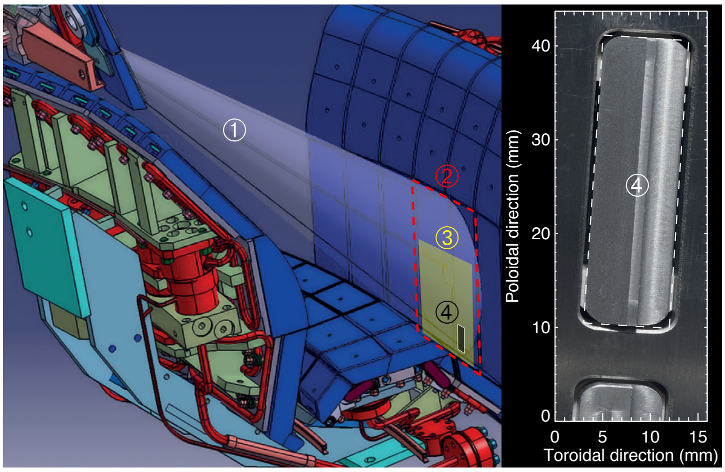
In the initial experiment, two principal sample geometries, a sharp protruding edge and an inclined surface, were exposed to Type I ELMy H-mode plasmas with ELM energy densities comparable to those obtained during the JET melt experiments with identical sample geometries. In conjunction with the MEMOS-3D modelling results, net currents drawn by the samples quantitatively validated the picture of strong surface thermionic emission being the main driver for current flow through the samples and the resulting ***jxB*** force on the melt layer. In particular, the considerably lower current density through the molten surface area of the sloped sample in comparison to the leading-edge case, and the resulting strongly reduced melt displacement in the poloidal direction, are powerful evidence for the assertion that the lower probability for electron escape from the surface is the main driver for the decreased current density.

In a second set of experiments focused on the sloped sample, the current measurements have been complemented by surface temperature measurements obtained with an IR camera system directly viewing the plasma-exposed surface of the sample (see schematic view). The camera was operated with a reduced field of view extending only across the melt sample and its close vicinity thereby increasing its image acquisition rate to 2 kHz. This allowed for the first time unique, ELM-resolved observation of melt motion. The poloidal velocity of the melt layer can be extracted and is found to be in the range expected for a ***jxB*** driving force at the levels of net current detected during the exposure. The cover figure shows the lateral distribution of ELM-induced temperature excursions across the exposed melt sample. The sequence covers the three consecutive ELM power transients in the 18 ms time interval, t=4.193-4.211 s, of ASDEX Upgrade discharge 34506, each followed by an image frame recorded in between ELM peaks. The dashed green line shows the trajectory of melt movement.

The results of both experiments have been crucially important by confirming the assumptions being made in the predictive melt modelling of shaped ITER divertor monoblocks in support of the recently finalised design of the ITER divertor target modules.

The system is prepared and awaiting machine time for a third experiment with exposure of new, electrically floating, leading-edge samples, in which the flow of replacement current compensating the loss due to thermionic emission will be prevented. The resulting melt patterns are expected to be very different to the electrically connected case and should provide the definitive test of the mechanism driving melt motion.

K. KRIEGER



Schematic view of experimental setup: CAD view of an ASDEX Upgrade divertor segment with line of sight (1) of the infrared camera system viewing at the probe head of the Divertor Manipulator system (2) which allows to expose two adjacent outer divertor target tiles. Also shown are full viewing area of the IR camera (3) and region of interest around the installed melt sample (4).

FIGURES: K. KRIEGER

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