

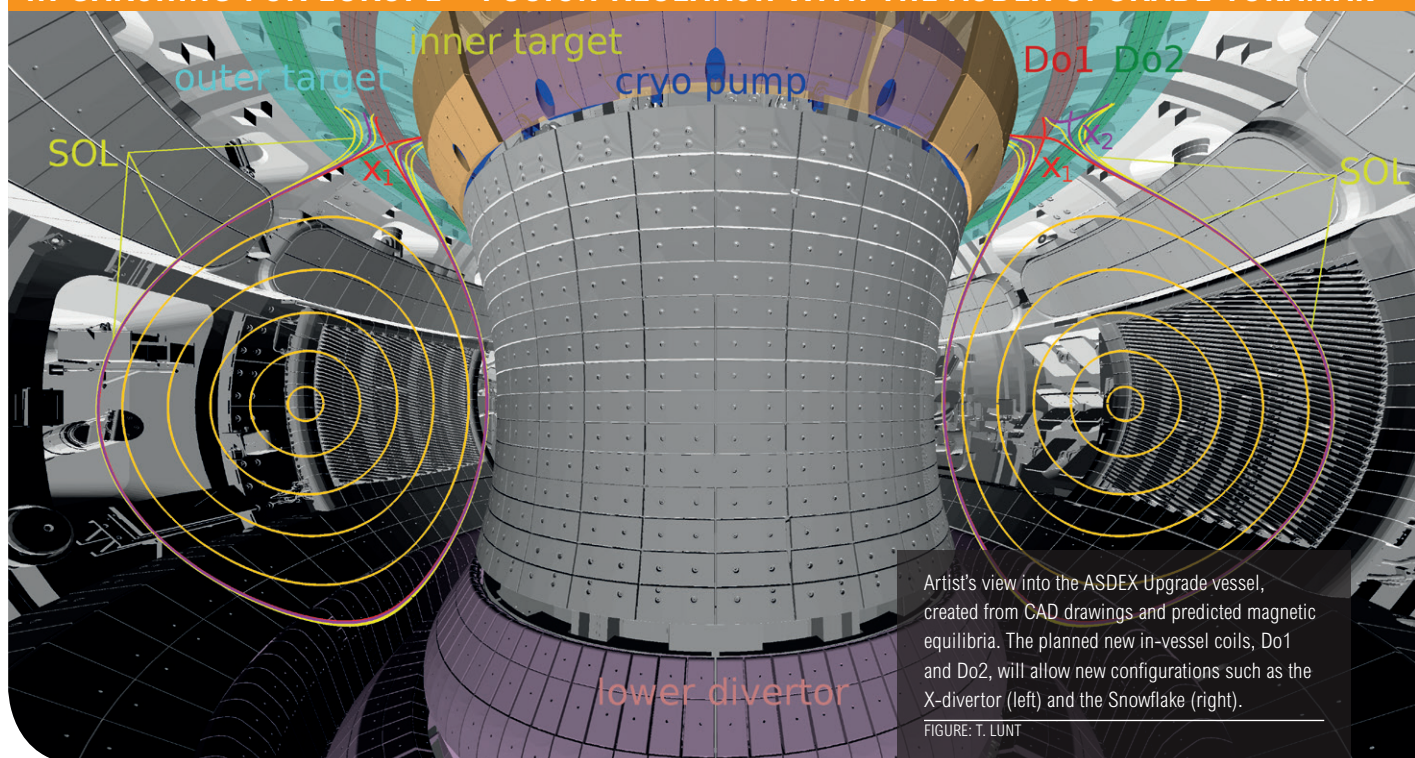
ASDEX Upgrade LETTER



Max-Planck-Institut
für Plasmaphysik

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



Artist's view into the ASDEX Upgrade vessel, created from CAD drawings and predicted magnetic equilibria. The planned new in-vessel coils, Do1 and Do2, will allow new configurations such as the X-divertor (left) and the Snowflake (right).

FIGURE: T. LUNT



Prof. Dr. Antony Donné
EUROfusion Programme
Manager

PHOTO: EUROfusion

EDITORIAL

ASDEX Upgrade is one of the three medium-sized tokamaks which are contributing to the EUROfusion programme. Given its specific shape, metallic plasma-facing walls and high heating power, ASDEX Upgrade, in conjunction with JET, is an important element on the step ladder towards ITER. EUROfusion is extremely pleased with the high-quality scientific output of ASDEX Upgrade, which improves our understanding of many plasma phenomena. This letter presents two examples.

Firstly, beautiful work is being done by means of Resonant Magnetic Perturbation (RMP) coils to mitigate Edge Localized Modes (ELMs). In future devices such as ITER and DEMO, the heat loads due to unmitigated ELMs would severely limit the lifetime of divertor target plates. Rotating the perturbed 3D magnetic field structure induced by the RMPs makes it possible to study in detail their effects on MHD modes and turbulence. This can help to develop scenarios in which the ELMs can be suppressed or mitigated, and to understand the underlying mechanisms.

Secondly, the machine is now equipped with a 30-channel Correlation Electron Cyclotron Emission system (in collaboration with MIT) for measuring electron temperature fluctuation profiles. Most of the turbulence measurements made on many fusion devices have until now used density fluctuations which are much easier to diagnose. Also having information on the fluctuations in the temperature profile will help to improve theoretical models, such as the gyrokinetic GENE code, and thereby enhance understanding of anomalous plasma transport processes.

Apart from the exciting scientific results, this letter also describes a planned upgrade of the ASDEX Upgrade tokamak. I am delighted that IPP and EUROfusion are together investing in the future with the aim of tackling one of the main challenges in DEMO: viz. managing the steady-state heat loads on the divertor plates. IPP is currently designing an additional upper divertor for testing various advanced divertor configurations. This innovative concept has been granted financial support from EUROfusion since it can lead to a feasible Plasma Exhaust Concept for DEMO. I am eagerly looking forward to the results.

A. DONNÉ

Modification of the local edge stability

To limit the peak power load to the first wall produced by edge localized modes (ELMs) in the high-confinement mode (H-mode), it will be necessary to mitigate or ultimately suppress them in future fusion devices. One promising method is to use a non-axisymmetric magnetic perturbation (MP) produced with a set of dedicated, toroidally-distributed magnets. This additional MP field breaks the axisymmetry of the tokamak plasma and causes a three-dimensional (3D) displacement of the flux surfaces. This reduces the power heat load with the disadvantage of a lower plasma pressure.

The resulting 3D flux surface geometry is characterized experimentally by high-resolution edge diagnostics. The toroidal variation can be observed even with diagnostics at a single toroidal location by enforced rigid rotation of the 3D structure. The rotation is produced by a phased sinusoidal current variation in the MP coil system by using their flexible power supply system called BUSSARD. The figure (a) shows the MP coil configuration chosen for this experiment. The toroidal symmetry number is 2, which is also used for ELM suppression. The phase difference between upper and lower MP-coil currents is -90 degrees, where the plasma deformation is found to be largest for the plasma investigated. The toroidal variation of the radial plasma boundary position is obtained using, for example, electron density profiles measured by the lithium beam (LIB) diagnostic. The displacement of the plasma boundary can be compared to predictions of 3D magnetohydrodynamic (MHD) equilibrium codes such as VMEC or JOEKE. The predictions are in very good agreement with the

experimental results (see figure (b)). The physical origin of the 3D geometry is ideal MHD kink modes, which are excited by the MP field.

Apart from the rigidly rotating 3D displacement, one observes near the plasma edge additional ideal MHD modes with a typical frequency of 1 kHz. These modes have a strong ballooning character, the displacement being much larger on the low-field side of the plasma. These modes appear only around every second field line where the radial displacement within the 3D MHD geometry vanishes (see Figure (c)). These experimental

observations served as motivation for a collaboration with the University of Wisconsin to perform stability analysis (infinite-n ideal ballooning) of a well-benchmarked 3D ideal MHD equilibrium from the VMEC code. The stability calculations predict the strongest

instability at exactly the location where it is observed.

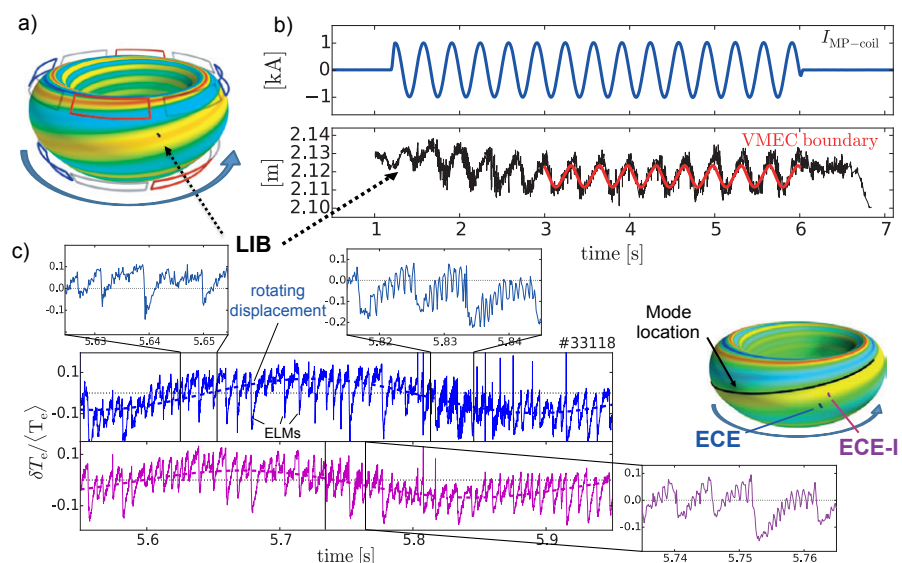
The local magnetic shear, which has a stabilizing effect on MHD instabilities, is modified along the field lines by the 3D distortion. The ballooning modes appear around the „bad“ field line with the lowest magnitude of the integrated local magnetic shear. Other effects, such as a change in the curvature due to the 3D geometry, play a minor role. This mechanism also reasonably explains the observed reduction of the plasma pressure in H-mode due to application of MPs. It suggests that the 3D perturbation of the local magnetic shear modifies the edge stability boundary towards lower edge pressure gradients, resulting in a higher ELM frequency and lower pressure.

M. WILLENSDORFER

Highlight from a recent ASDEX Upgrade experiment

MP coil set at ASDEX Upgrade and a 3D equilibrium induced by an MP field (a). The colours indicate the sign of the coil current (red = positive, blue = negative) and the direction of the radial displacement (red = outwards, blue = inwards). The blue arrow indicates the rotation direction of the MP field. Current of one MP coil and measurements of the boundary displacement (b) at the position of the lithium beam diagnostic (LIB, black) and predictions from VMEC (red). Time traces of electron temperature fluctuation during rotation of the 3D geometry (c) observed by the electron cyclotron emission diagnostics (ECE, blue) and ECE imaging (ECE-I, purple). The 1 kHz ideal MHD mode in-between ELMs is only visible at a certain field line, which is characterized by the displacement (indicated by sinusoidal dashed lines) crossing zero from positive to negative values.

FIGURE: M. WILLENSDORFER



The new upper divertor

Alternative power exhaust concepts for ASDEX Upgrade

One of the challenges in fusion research is extraction of the power produced in a future reactor. In ASDEX Upgrade the lower divertor is normally used for this purpose. In this conventional configuration an X-point divides the plasma into a confined region of closed field lines and a small outer region of open field lines, known as the scrape-off layer (SOL). A problem is the small area around the strike lines, in particular the outer one, where the SOL hits the divertor target and a large fraction of the total power is deposited.

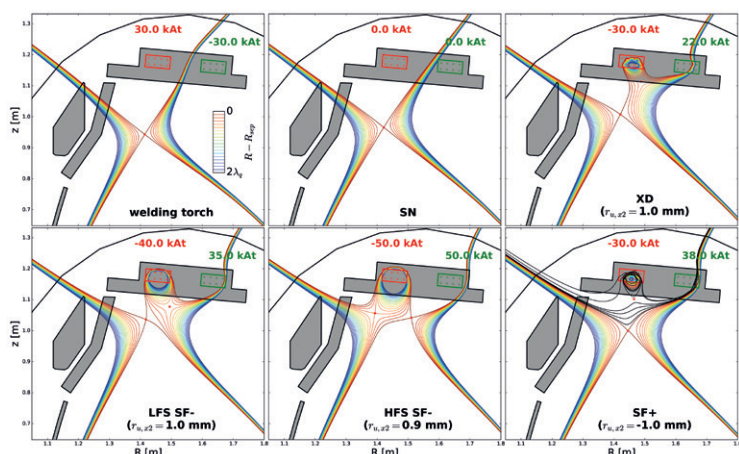
magenta-coloured separation line. In addition to this geometrical splitting of the power flux, the region around X_2 is expected to convert the plasma heat into electromagnetic radiation more efficiently. Thus, the heat load of the outer target is mitigated in a twofold manner. In an X-divertor (left part of the cover picture) the secondary X-point is very close to the target surface and thus the plasma-wall interaction region is maximized. However, this configuration will challenge the manufacturing accuracy of the divertor owing to the extremely small field line incidence angles occurring at the target surface.

An important criterion to evaluate the different divertor configurations and their suitability in a reactor is their ability to reach the detached divertor state. Detachment occurs when the plasma in front of the target becomes so cold that the power and even the ionized particle fluxes drop substantially. In a second stage of extension, detachment might be further facilitated by closing the divertor with baffles, which increases the neutral gas pressure in the divertor region.

While alternative divertor configurations have been investigated in other machines, such as TCV, DIII-D and NSTX, ASDEX Upgrade has world-leading heating capabilities with respect to its size, as well as excellent diagnostics coverage. EUROfusion acknowledges these features in funding this project to assess the feasibility of alternative divertor solutions for DEMO.

The new upper divertor with internal coils, Div-IIo, is the next step for ASDEX Upgrade towards investigation of advanced fusion reactor concepts. Design of the divertor structure, the cryo-pump and the coil is ongoing. First hardware installations will be carried out in 2020/21.

T. LUNT



The planned upper divertor in ASDEX Upgrade allows a large variety of configurations. Apart from investigating the effects described in the text they can be used for code validation in terms of thermal loads or for material testing. The red and green physical quantities represent the coil currents multiplied by the number of coil windings (kA = kiloampere turns). The upper right and the lower left boxes show the configurations of the front page.

FIGURE 1: T. LUNT

In order to distribute the exhausted power over a larger area, alternative configurations will be investigated with a new, modified upper divertor. The cover picture shows the planned installations: two in-vessel coils, Do1 and Do2 (red and green), a new cryo-pump (blue) and a modified inner (yellow) and outer (cyan, transparent) divertor target. Owing to their proximity to the plasma, comparatively small currents are sufficient to modify the magnetic geometry significantly. Apart from a primary X-point, X_1 , a secondary X-point, X_2 , divides the SOL into two parts in Snowflake configuration (as shown in the right hand side of the cover picture) indicated by the



Dr. Benedikt Geiger
PHOTO: IPP, BEATE KEMNITZ

Osthoff Plasma Physics Prize for Benedikt Geiger

Benedikt Geiger was awarded the Hans Werner Osthoff Plasma Physics Prize 2016, which honours outstanding achievements in the field of plasma physics and serves to support junior scientists in particular. The IPP scientist, born in 1982, is internationally known for his investigations on magnetic confinement of fast plasma ions. He developed an optical measuring system at ASDEX Upgrade that affords new insight into the motion and confinement of fast ions. In 2015 he was selected in a competition sponsored by the Helmholtz Association as head of a group of young IPP scientists to work in the field of particle transport. Professor Hans Werner Osthoff donated the prize named after him in 1994 in commemoration of his years of study at Greifswald, on the occasion of the establishment of IPP's site at Greifswald.

I. MILCH

Correlation Electron Cyclotron Emission diagnostics

Plasma turbulence plays a complex role in the transport of heat, particles, and momentum in fusion experiments. Often, turbulence is the dominant driver of transport in fusion plasmas, exceeding neoclassical levels by orders of magnitude. Experimentally, turbulence can be measured as small fluctuations in the plasma temperature, density, potential, and magnetic field. Such experimental measurements can be compared to predictions from turbulence codes, such as nonlinear gyrokinetic codes, to assess how accurately these codes are representing reality. The more accurately one can measure these fluctuations and investigate their dynamics and interactions, the more confidently one can predict the performance of future fusion devices.

To this end, a newly upgraded core turbulence microwave diagnostic system, known as correlation electron cyclotron emission (CECE), was recently installed on ASDEX Upgrade. This diagnostic is the result of a multi-year collaborative effort with the Massachusetts Institute of Technology (MIT) Plasma Science and Fusion Center (PSFC) in Boston, USA.

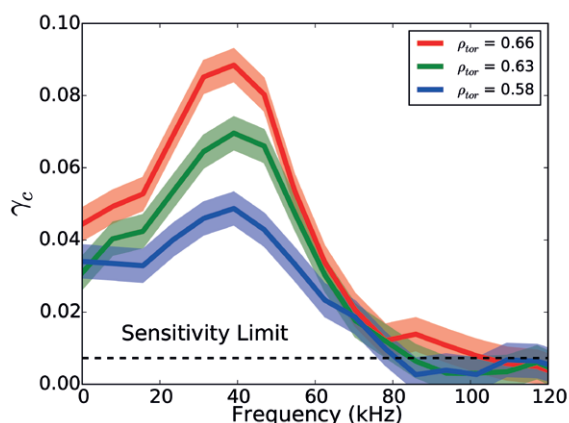
The CECE diagnostic measures long-wavelength electron temperature fluctuations (≥ 2 cm) in the core of the ASDEX Upgrade plasmas. The radiometer frequency determines the measurement location, since the cyclotron frequency depends on the magnetic field, which varies with radius. The diagnostic utilizes many closely-spaced radiometer channels to collect electron cyclotron emission from the tokamak plasma. Channels typically collect emission around 110 GHz, with 100 or 200 MHz bandwidth filters spaced by 125 MHz (~ 2 mm) or 250 MHz (~ 4 mm) respectively, though these filters are all interchangeable.

The signals of two closely-spaced channels are then correlated in order to detect fluctuation levels that would be beneath the noise floor of a single channel. If the two channels are spaced closely enough that their separation is smaller than a turbulent correlation length, but far enough that they do not measure the same plasma volume, then the correlation will keep the turbulent fluctuation information but get rid of thermal noise. With this procedure the diagnostic measures electron temperature fluctuation levels down to a few tenths of a percent.

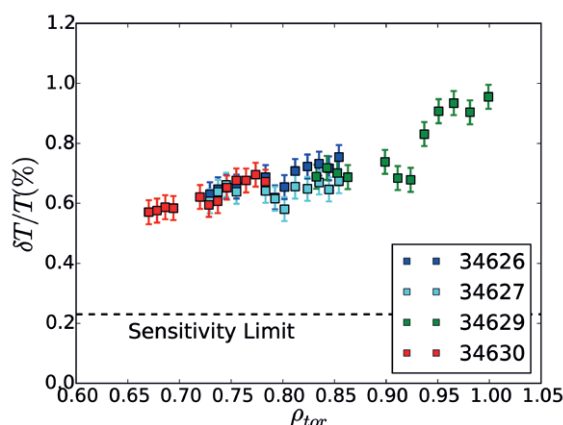
Recent upgrades to the system have increased the number of channels from six to thirty, allowing measurement of fine radial profiles and radial correlation lengths, as well as decreasing electronic noise. The upgraded system was installed on ASDEX Upgrade in spring 2017 and has already successfully measured fluctuation profiles in many plasma discharges. The 100 MHz bandwidth channels help with fine radial correlation length measurements, while the 200 MHz bandwidth channels allow wider fluctuation profile measurements.

Experimentally, CECE brings plasma physics closer to a fundamental understanding of turbulence in fusion plasmas. In addition, comparisons with CECE measurements help improve gyrokinetic codes such as GENE, ensuring that they correctly represent the plasma turbulence measured in ASDEX Upgrade before being used to make predictions for future devices, such as ITER and beyond.

A. CREELY



Temperature fluctuation spectra (plotted as complex coherence between adjacent channels) measured with the new CECE diagnostic on a 2.5 T L-mode plasma. Uncertainty, which is reduced in the new system, is represented as shaded regions. Spectra can be compared to gyrokinetic simulations for validation.



Temperature fluctuation profile measured with the CECE diagnostic from four near-repeat L-mode discharges. Magnetic field scanned approximately two percent between shots to move channel locations. Channel spacing is approximately 5 mm. Only the 200 MHz bandwidth channels were used in this profile. ρ_{tor} is the square root of the normalized toroidal magnetic flux.

FIGURES: A. CREELY