ASDEX Upgrade LETTER

Max-Planck-Institut für Plasmaphysik

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

Fire and ice: an ultra-cold pellet produced from solid deuterium arrives in a hot ASDEX Upgrade plasma. While evaporating like a comet it serves for efficient particle fuelling.
PHOTO: IPP

Prof. Dr. Frank Jenko
Head of IPP division
Tokamak Theory
PHOTO: IPP

EDITORIAL

Happy birthday, ASDEX Upgrade! During the last 30 years of operation, many impressive experimental results have been obtained, several of which affected the course of fusion research on an international level. The ASDEX Upgrade Team can be proud of these remarkable achievements, which are certainly based on a great team spirit and various fruitful collaborations within EUROfusion.

Throughout the 2020s, ASDEX Upgrade will keep on making important contributions with respect to preparing ITER operation and developing an attractive DEMO design. Three perfect examples can be found in the present ASDEX Upgrade Letter. First, progress has been made towards a more complete understanding of tokamak divertor physics, which is a key aspect of extrapolating with high confidence to a fusion power plant. For this purpose, a new divertor Thomson scattering diagnostics has been brought into operation during the last experimental campaign. Second, substantial advances have been made recently regarding the increase of the core density via pellet fuelling, allowing for the creation of peaked density profiles. Several DEMO-relevant aspects are taken into account in this context, including real-time control. Third, initial studies on ASDEX Upgrade of negative triangularity L-mode plasmas have been carried out successfully, indicating a potential path towards high confinement in the absence of edge-localized modes.

Most of these experimental studies benefit greatly from close ties to theory and modelling. For instance, the question whether negative triangularity provides a viable path towards a fusion power plant can probably only be tackled with the help of continuous interaction between carefully diagnosed experiments and state-of-the-art gyrokinetic simulations. Such critical issues are addressed at IPP Garching, but also within the E-TASC program, helping to make sure that Europe continues to be a world leader in tokamak research.

F. JENKO

New insight in power exhaust

Divertor Thomson scattering diagnostic

Highlight from a recent ASDEX Upgrade experiment

The European fusion road map identifies solutions for the power exhaust problem as one of the most critical challenges for realizing a commercial fusion power plant. Already for ITER, steady-state power handling has to be demonstrated. Highly dissipative conditions in divertor and scrape-off layer (SOL), up to 90% of heating power dissipated by radiation, are now routinely obtained in several tokamaks – either by additional gas fueling to raise the density or by impurity seeding to lower the temperature by radiation. These divertor conditions are labelled as "detached" since the plasma-boundary interaction moves off the divertor targets by forming a neutral cushion for heat exhaust. However, a complete understanding of the tokamak divertor physics is necessary for a reliable extrapolation to a fusion power plant. To this extent, accurate knowledge of the electron density n_e and temperature T_e within the divertor volume is a crucial requirement.

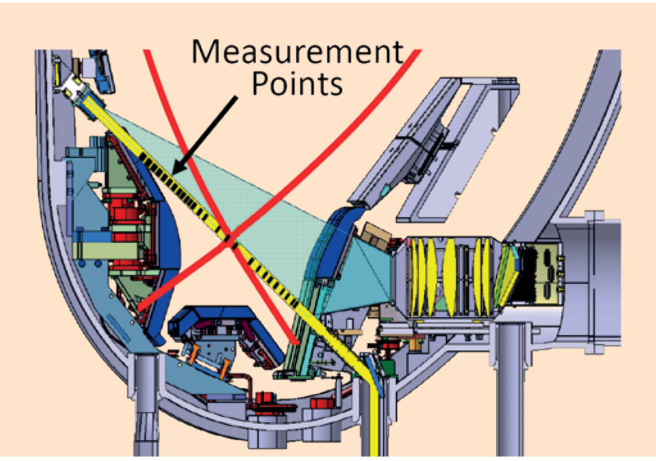

Figure 1: Schematic view of the divertor Thomson scattering system of ASDEX Upgrade. The 24 measurement points are denoted in black along the yellow laser.

FIGURE: B. KURZAN, M. CAVEDON

During the last ASDEX Upgrade experimental campaign, the divertor Thomson scattering diagnostics (DTS) was successfully brought into operation [1]. Thomson scattering provides non-perturbative local measurements of both n_e and T_e that offer a unique and interpretation-free insight into divertor physics. The DTS system consists of 24 channels distributed from the inner to the outer divertor passing through the X-point. It is coupled to a 4-channel polychromator to measure T_e from ≈ 1 to 100 eV and n_e from 1×10^{19} m^{-3} to 1×10^{21} m^{-3}.

Dedicated experiments were performed to characterize, for the first time at ASDEX Upgrade, the behavior of n_e and T_e via DTS in the evolution from attached to detached plasma conditions [2]. The plasma has been swept vertically to measure the complete divertor volume while keeping the diverted plasma condition constant (see figure 2). The collected data set is a milestone for experimental divertor studies at ASDEX Upgrade, where such measurements were previously lacking, and provides verification and new insights into detachment physics. There are two highlights of this study. Firstly, the confirmation of the presence of a strong electron parallel pressure gradient at complete detachment, starting close to the separatrix and then extending over the entire SOL. Secondly, it is observed that the transition from the appearance of a parallel pressure gradient in the SOL to complete detachment exhibits a bifurcation-like behavior. In summary, two-dimensional n_e and T_e profiles provide valuable inputs for divertor modelling. Moreover, they can be combined with other diagnostic measurements, such as divertor spectroscopy, to calculate the particle balance and the impurity density in the divertor.

M. CAVEDON, B. KURZAN

[1] Kurzan B, et al., 2021 Journal of Instrumentation 16, C09012

[2] Cavedon M, et al., submitted to Nuclear Fusion

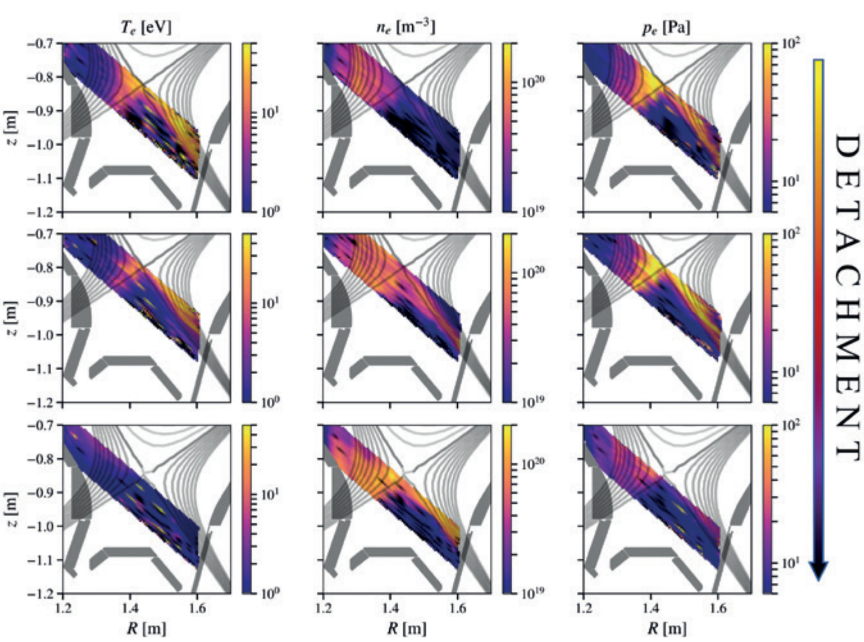

Figure 2: 2D distribution of T_e, n_e and p_e (left to right) from attached to detached divertor conditions (top to bottom) measured via divertor Thomson Scattering in L-mode.

FIGURE: M. CAVEDON

Density control with hydrogen ice pellets

Like any power plant, a future fusion reactor will need fuelling. The particle density in the plasma core is a critical parameter for the resulting fusion power, since the plasma edge density is limited by the Greenwald limit. In an efficient fusion reactor density profiles will have to be peaked.

While gas puffing is customarily used for fuelling in tokamaks today, this will not be possible in a fusion reactor. Because of the higher plasma temperatures, many particles will be ionized and then deflected by the magnetic field before they enter the hot, confined plasma. A study conducted as part of the DEMO reactor project, which considered different potential fuelling techniques, showed that only the injection of pellets – millimetre-sized bodies produced from hydrogen ice in the adequate isotope mixture of deuterium and tritium – can achieve sustainable operation in the required high-density regime. The massive pellets, injected at high speed, penetrate deep into the plasma with almost their full particle inventory and can thus create peaked density profiles.

ASDEX Upgrade has dedicated its pellet program mainly to resolve physics and technology issues for a reactor-relevant fuelling system. Based on these findings, powerful and adaptable pellet tools are developed. The recent years, experiments demonstrating that the high density required in the DEMO plasma core can indeed be achieved by pellet fuelling and also that mixed-isotope pellets can set the required plasma composition. During the 2021 campaign, a novel advanced control technique has been successfully implemented. It is based on two new units and was integrated step by step.

The first unit was added to the control system of the pellet launcher, which regulates the particle flux by the pellet repetition rate. Pellets are accelerated by the launcher in a centrifuge employing a scheme developed at IPP already 30 years ago. It ensures punctual pellet delivery, a basic prerequisite for precise control. The new tool can adapt the repetition rate in real-time to the flux request.

A first successful application is shown in the figure. Using the new tool, the gradual replacement of gas puffing by pellet fuelling was accomplished. With constant total fuelling rate but increasing pellet flux (solid red line in box e) the plasma density increases. This can be seen in the line averaged and core density (box b), the latter finally being significantly higher than the Greenwald density (solid green line). It should be noted that the initial energy stored in the plasma (box a) was kept almost constant while entering into the high-density regime.

To use pellets for feedback density control, a second new module called RAPDENS was added to the discharge control system of ASDEX Upgrade. RAPDENS, a software tool developed in collaboration with the Dutch DIFFER institute, calculates the desired particle flux to establish the targeted density. It uses a one-step ahead control-oriented plasma transport model and adjusts density profiles estimated by the model using validated real-time data.

The recent achievements mark significant progress for a reactor grade fuelling system – but several questions remain for future work. For example, the DEMO team recently identified the need for a more adequate handling of unusual events or malfunctions such as missing or broken pellets. This imperfect pellet delivery becomes evident by comparing pellet arrival (box c) and pellet request (box d).

Not only DEMO will benefit from these improvements to density control. The new JT-60SA tokamak, being built in Naka in the context of the ITER Broader Approach, will integrate these new units in its pellet system.

P. T. LANG

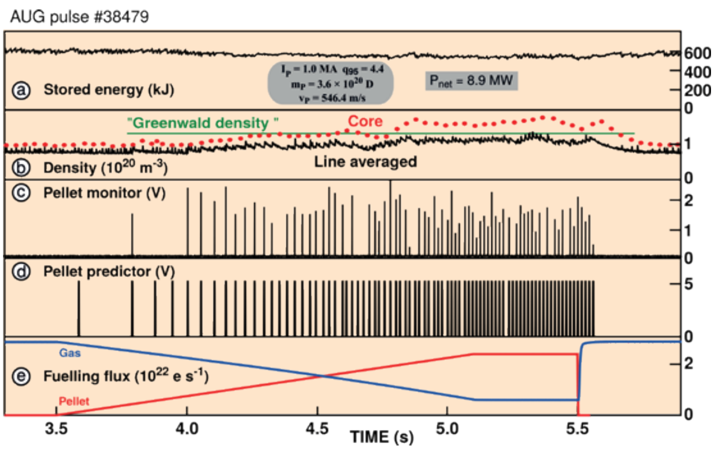

Figure: This kind of experiment has been performed many times – but probably not in such a clean way. Gas puffing is gradually replaced by a smooth increase of the pellet flux. Due to the higher efficiency of pellet fuelling, the plasma core density rises strongly. A higher core density – and in a fusion reactor also a higher fusion power – can be achieved with the same fuelling rate.

P.T. LANG

References:

https://www.tandfonline.com/doi/full/10.1080/15361055.2020.1864172

P. T. Lang et al., "Actuator development step by step: pellet particle flux control for single- and multi-source systems", Fusion Science and Technology, in print

30 years of ASDEX Upgrade On 21 March 1991, ASDEX Upgrade generated its first plasma. Over the next 30 years, in 38,700 plasma discharges ASDEX Upgrade worked on plasma scenarios for JET, ITER and DEMO. Some highlights: The suitability of tungsten for use as wall material has been demonstrated, methods to stabilise ELMs and neoclassical tearing modes have been developed, as well as techniques to mitigate the effect of disruptions and to drive the plasma current continuously. "In many respects," says project leader Arne Kallenbach, "ASDEX Upgrade can be seen as a 'blueprint' for a tokamak fusion power plant. The prototype discharges developed over 30 years, together with newly developed computer codes, provide reliable information for a power plant." Because the Covid-19 pandemic prevented a festive event, the anniversary was celebrated by an online presentation, a photo exhibition, and a year-round social media campaign: **#happybirthdayasdexupgrade30** I. MILCH

Negative triangularity plasmas

One of the key requirements for a future nuclear fusion reactor is a plasma scenario that both features a high energy confinement time τ_E and is compatible with the envisaged divertor solution. For the latter, in particular, type-I edge-localized modes (ELMs) must be avoided, which are pertinent to operation in the high-confinement mode (H-mode). One mode of operation that has been shown to exhibit improved confinement without typical type-I ELMs in the TCV tokamak in Switzerland, and more recently also in DIII-D in the US, is the so-called negative triangularity – or negative delta – configuration. Unlike typical tokamak plasmas, which show a normal "D" shaped plasma, the shape is inverted horizontally in negative delta plasmas (see figure 1).

The improved confinement in negative triangularity plasmas is usually attributed to a suppression of turbulence connected to trapped electrons (TEMs), but there are few experimental studies in this regard. Moreover, it is not yet known, whether and to what extent turbulence driven by ion temperature gradients (ITGs) is affected.

First studies on ASDEX Upgrade indicate that good confinement can be reached in L-mode plasmas, i.e. without ELMs. In particular, input powers of up to 10 MW have yielded a high plasma pressure compared to the magnetic field pressure ($\beta_N \approx 2.4$) at an energy confinement well above L-mode level. These experiments are now being analyzed and gyrokinetic simulations will be crucial in the evaluation of the prevailing turbulence drive and its possible suppression.

An explanation for the lacking transition into the H-mode has been proposed. As figure 2 shows, the plasma edge is deeply ideal ballooning unstable. For the negative delta case (blue), the operational point is close to the stability boundary (solid line). In contrast, during the positive delta phase of the discharge, the stability boundary (red) is at larger pressure gradients and edge current densities. Since the pedestal top pressure is connected to the normalized pressure gradient, the boundary in the negative delta case prevents the pedestal pressure from increasing any further. As a result, the pressure at the pedestal top and therefore the magnitude of the edge radial electric field well is limited.

This explains why values of the radial electric field typically seen at the L-H transition on ASDEX Upgrade (about -15 kV/m) are not reached in negative triangularity plasmas. In figure 3, the ECRH input power (green) is stepped, and the edge radial electric field gets shallower as the power is increased, supporting the above hypothesis. In non-peeling ballooning limited plasmas, an increase in heating power is usually accompanied by a deepening of the radial electric field well at the edge, eventually leading to an L-H transition. This is not the case in the negative delta plasmas investigated on ASDEX Upgrade.

Future studies will focus on confirming this effect. To better understand the impact of TEMs and ITGs on confinement quality, experiments with different heating schemes and powers will be conducted. The results of these experiments will be compared with predictions from gyrokinetic simulations to see if negative triangularity could be an option for a future reactor.

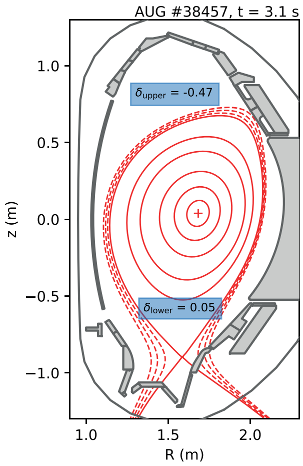

Fig. 1: Flux surfaces of a plasma of ASDEX Upgrade with negative triangularity (#38457)

GRAPHIC: IPP

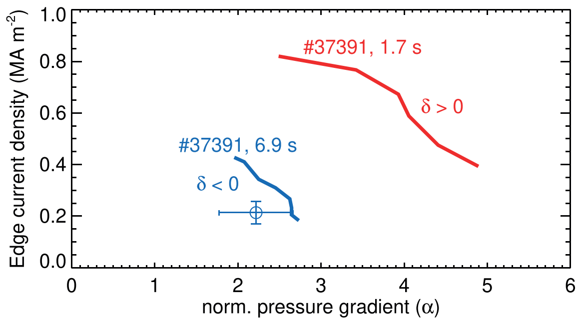

Fig. 2: Peeling-Ballooning stability diagram for negative (blue) and positive (red) triangularity.

GRAPHIC: IPP

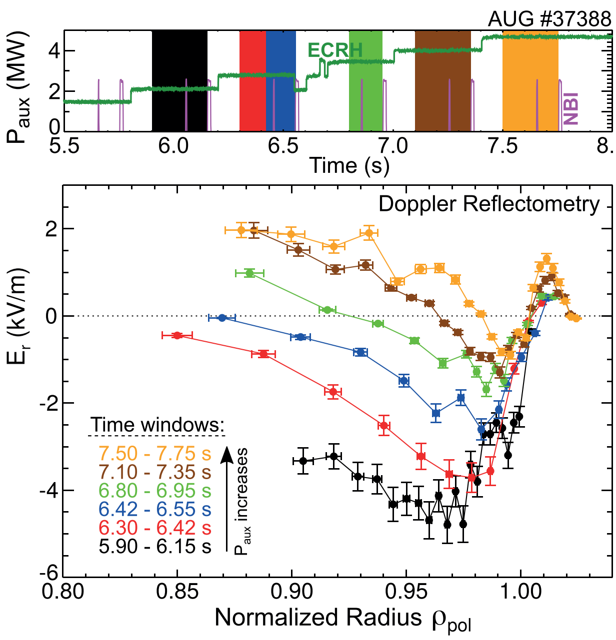

Fig. 3: Steps of the ECRH heating power (top) with indicated times for corresponding radial electric field profile measurements. The radial electric field does not deepen with increasing heating power.

GRAPHIC: IPP

T. HAPPEL, J. HOBIRK, T. PÜTTERICH

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Max-Planck-Institut für Plasmaphysik
Boltzmannstraße 2
85748 Garching/Munich
Germany

Coordination: Prof. Dr. Hartmut Zohm
Contact: Dr. Anja Gude
Phone: +49 89 3299 1274
Fax: +49 89 3299 2580
E-Mail: anja.gude@ipp.mpg.de
Subscribe at augletter@ipp.mpg.de

For more information see the website www.ipp.mpg.de
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