ASDEX Upgrade LETTER
Max Planck Institute for Plasma Physics

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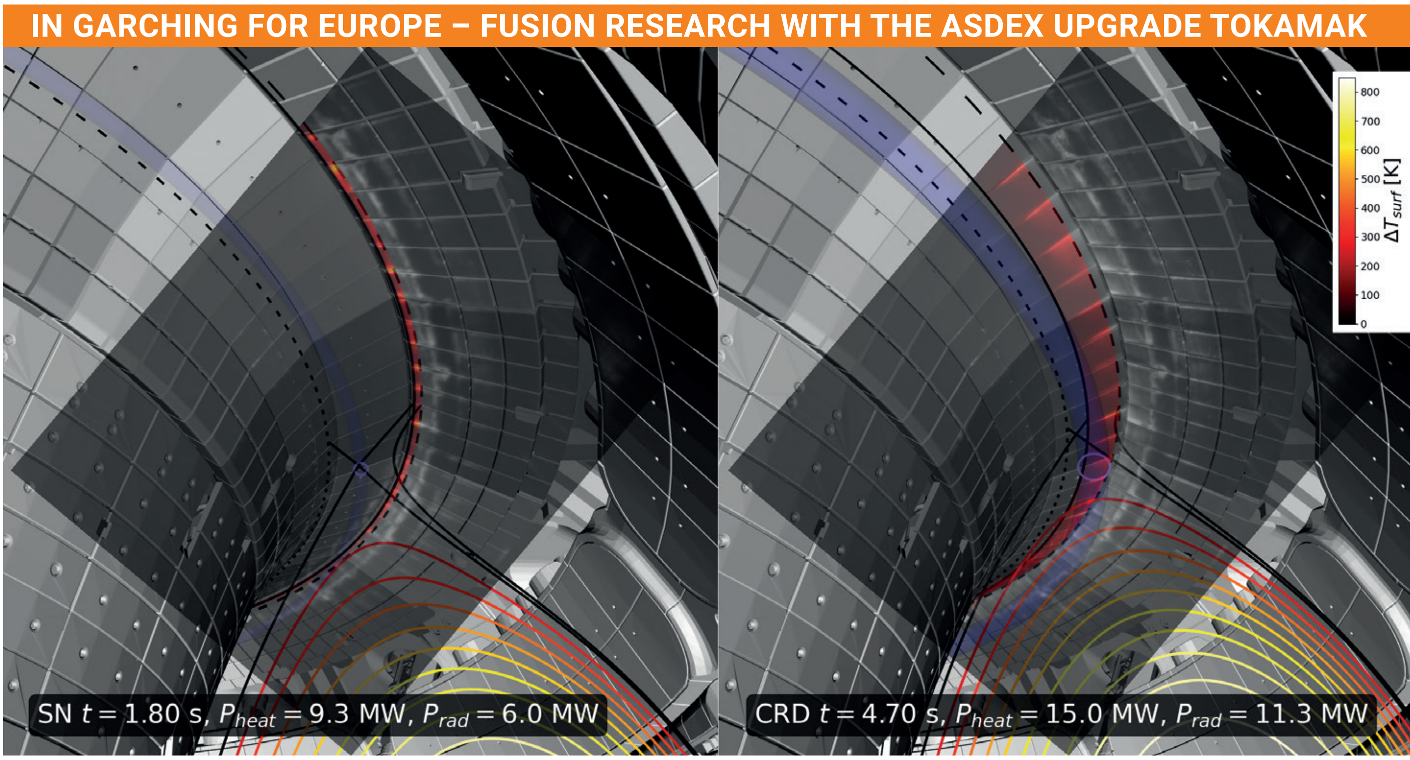
IN GARCHING FOR EUROPE – FUSION RESEARCH WITH THE ASDEX UPGRADE TOKAMAK



3D CAD drawings of the ASDEX Upgrade vessel overplotted by temperature maps in red and the X-point radiator position in blue, comparing the conventional single-null (SN, left) and the compact radiative divertor (CRD, right) (Image: adapted from T. Lunt, M. Bernert, et al., Phys. Rev. Lett. 130, 145102).

Editorial

Prof. Dr. Arne Kallenbach Head of ASDEX Upgrade project (Photo: MPI for Plasma Physics)

ASDEX Upgrade is now well into the second half of the comprehensive upgrade and maintenance period. Both coils for the new upper divertor were installed in the vessel by October and the reinstallation of components and diagnostics has commenced. In parallel, maintenance of many components is ongoing, including vacuum seals, power supplies and neutral beams. While the neutral beam injection (NBI) box I is now equipped with radio frequency sources, the remaining three sources of box II will be fitted with a variable gap as tested in source 5 during the previous campaign. Overall progress is on track for the planned restart in September 2024. There is still a lot of work to be done, including the transition of control systems, diagnostics and software to the new virtual machines and storage shares that will replace the AFS system, which served us very well for many years but is now due for retirement.

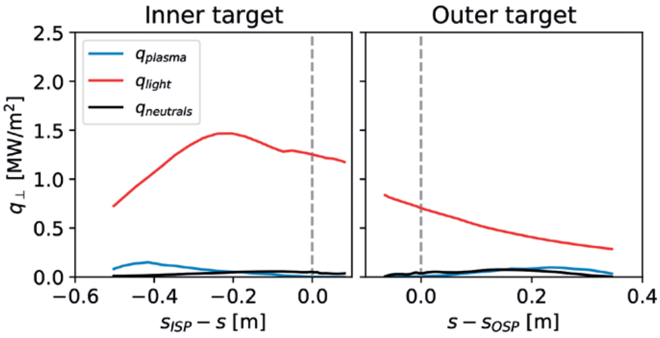
While analysis of data from the past campaigns is ongoing, discussions on the future direction of the field in the rapidly growing ecosystem of private companies are imminent. ASDEX Upgrade is well involved in the preparatory work for a future tokamak reactor. During the IAEA Fusion Energy Conference in October, the X-point radiator regime pioneered in ASDEX Upgrade was the subject of a number of contributions. Its most extreme variant, the Compact Radiative Divertor, could lead to an attractive solution for the power exhaust problem in a future reactor, as described below by Tilmann Lunt and Matthias Bernert. Transport modelling is also making good progress, as you will see in Clemente Angioni's contribution. A good fraction of the experimental time of the last campaign was devoted to disruption studies with shattered pellet injection. This joint venture of the ITER Organisation, EUROfusion and MPI for Plasma Physics allowed important investigations of the role of different shattering geometries and pellet species mixtures, as you will read in Gergely Papp's contribution.

NOVEL EXHAUST CONCEPT

The Compact Radiative Divertor

One of the major challenges for future fusion reactors is to reduce the enormous heat fluxes deposited onto the surrounding wall in the small areas around the magnetic strike points (solid and dotted lines in the title figure) of the divertor. At ASDEX Upgrade, a novel concept to tackle this power exhaust challenge, the Compact Radiative Divertor (CRD), was developed. It is based on the prior establishment of an X-point radiator (XPR), a phenomenon that has only recently become sufficiently controllable in ASDEX Upgrade. The XPR is a strongly radiating ring (see blue rings in the title figure) in the vicinity of the magnetic X-point, which extends only a few centimeters poloidally. It emits up to 30–40% of the exhaust power in the form of light, cooling the plasma to temperatures down to about 1 eV, where a significant fraction of the hydrogen atoms are electrically neutral and the energy of the remaining charged particles is negligible.

This allows the magnetic X-point to be placed much closer to the divertor target plates and a much more compact geometry of the divertor can be realised. Previously, this was not possible: In the vicinity of the X-point, the angle of incidence of the magnetic field lines on the target plates is much shallower. Any surface roughness or misalignment of the tiles would lead to an immediate overheating. Therefore, the angle of incidence was always kept above 2–3°. However, since the charged particles in the vicinity of the cold XPR do not carry significant energy, the power conducted along the field lines becomes irrelevant and this limitation can be overcome. The power deposition is dominated by the emitted light and is distributed over a larger area.The CRD was now carefully tested at ASDEX Upgrade: After ramping up the plasma current, nitrogen was injected into the plasma to initiate an XPR (title figure, left), and the X-point of the plasma was then moved towards the target. Despite the shallow field line incidence angles of the order of $\theta_\perp=0.2°$, no hot spots were observed on the target surface monitored by an infrared camera, even at a maximum heating power of P_{heat}=15 MW (see title figure, right). Also the extreme case where the X-point is placed directly on the divertor target surface ($\theta_\perp \to 0$) could be sustained. The experiments performed on ASDEX Upgrade exhibit a good energy confinement in the typical range of a high confinement mode (H-mode) and edge localized modes, which can lead to excessive heat loads on plasma-facing components, were substantially reduced or completely suppressed.



SOLPS-ITER simulations of heat loads on the divertor targets for a DEMO-like plasma. The power deposition is dominated by the light emitted from the XPR (Image: adapted from IAEA FEC, London, 2023, EX-D-1757).

The CRD offers many attractive features for a DEMO-like fusion reactor: Since the divertor volume can be reduced, more space is available for the confined plasma and the magnetized volume can be used more efficiently. The design of the divertor structures and plasma facing materials can be simplified. The external shaping coils require lower currents and therefore exhibit lower forces, and the vertical stability of the plasma might also be improved. Furthermore, the ability of the XPR to dissipate power appears to scale favourably towards a reactor. Recent simulations show that even in a reactor scale device, the heat loads are predicted to be below the material limits and mainly dominated by radiation (see figure in text). These simulations also indicate a high neutral pressure at the divertor, which is required for the efficient removal of the Helium ash in a reactor.

A number of challenges have been identified and are being analyzed, such as the accessibility or the stability of a CRD, but are not considered to be show-stoppers. If these challenges can be overcome, the CRD configuration is a potential game changer for a reactor, simplifying its design and significantly reducing its cost. Research into the CRD and its prospects in a reactor is ongoing: The new in-vessel coils in the upper divertor of ASDEX Upgrade will allow to investigate an even more extreme form of the CRD as well as other alternative divertor configurations.

The details of the CRD are discussed in T.Lunt, M.Bernert et al, Phys. Rev. Lett. 130, 145102 (2023)

T. Lunt, M. Bernert

PREDICTION OF L-MODE CONFINEMENT

Full-radius theory-based transport modelling

In a tokamak fusion reactor the high confinement (H-mode) regime is usually used for the high fusion power phase due to its superior confinement quality compared to the low confinement (L-mode) regime. At the same time, the initial and final phases of each tokamak discharge, as well as the possibility of reaching the H-mode, depend critically on the confinement properties of the L-mode regime. Moreover, since the L-mode does not feature an edge pedestal, which is usually limited by magneothydrodynamic stability, it has plasma profiles that are completely determined by transport. Therefore, the L-mode can be completely predicted by a transport model which is applicable from the core up to the last closed flux surface. Recent progress in the development of the Trapped Gyro-Landau Fluid (TGLF) model [1] for tokamak turbulent transport has solved the long-standing problem of the under-prediction of transport at the plasma edge. This new TGLF-SAT2 model [2] opens up the unprecedented possibility of predicting global confinement properties, previously described only by empirical scaling laws, through a full-radius theory-based transport modelling approach, a true paradigm shift.

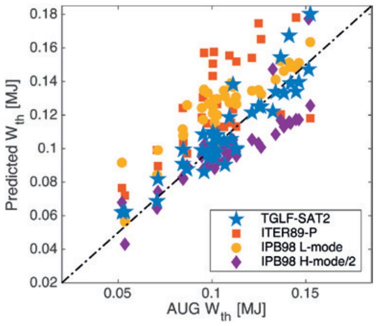


Figure 1 Predicted stored energy with ASTRA/TGLF-SAT2 and with scaling laws (the H-mode one divided by 2) as a function of the experimental stored energy, for a database of ASDEX Upgrade (Image: adapted from [2]).

Recent experiments in ASDEX Upgrade [2,3] have explored the dependence of L-mode confinement on all the main engineering parameters, plasma current, magnetic field, plasma density and heating power, as well as on the electron to ion heating fraction. A corresponding full-radius modelling activity has been performed with the transport code ASTRA and the TGLF-SAT2 transport model, in which no measured data have been used [2,3]. This new approach adopts a two-point model for the temperature boundary condition and, analogous to the experimental setup, includes a peripheral gas puff in feedback to match the desired particle content. For the first time these simulations provide a complete predictive capability of the entire energy confinement properties of the plasma, without taking any input from measured temperature and density profiles. Agreement was found for the kinetic profiles and in all the investigated dependencies on global engineering parameters. Figure 1 shows that ASTRA/TGLF-SAT2 predictions of the stored energy are closer to the experimental results than those from scaling laws for L-mode plasmas [2].

The dependencies of confinement on the plasma current and the magnetic field [3] are known to be significantly different in both L-mode and H-mode scaling laws. As shown in figure 2, full-radius ASTRA/TGLF-SAT2 transport simulations can predict both the strong current scaling dependence and the virtually negligible magnetic field dependence of ASDEX Upgrade L-mode plasmas. Dedicated modelling shows that these very different dependencies are mainly produced by the stabilizing effect of the ExB shearing rate, which increases with increasing current and decreasing magnetic field. However, when only the magnetic field is decreased, the ExB shearing effect is compensated by the transport increase produced by the magnetic field dependence of the gyro-Bohm factor. Finally, in modelling the dependence on plasma size, beyond the possibilities of single devices, the full-radius ASTRA/TGLF-SAT2 predictions are closer to the Gyro-Bohm limit, and therefore more optimistic than those obtained by the IPB L-mode scaling law.

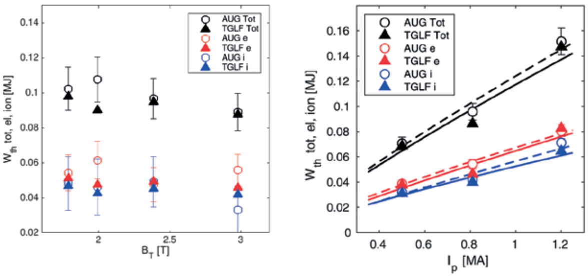
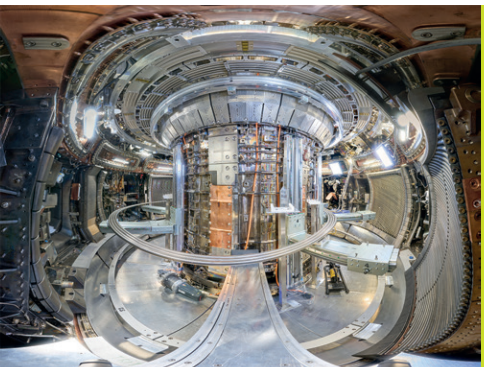


Figure 2 Current (left) and magnetic field (right) dependencies of the total, electron and ion stored energies in NBI heated ASDEX Upgrade L-mode plasmas, experimental (open symbols) and full-radius ASTRA/TGLF-SAT2 (full symbols) results (Image: adapted from [2,3]).

[1] G.M. Staebler et al 2021 Nucl. Fusion 61 116007.
[2] C. Angioni et al 2022 Nucl. Fusion 62 066015.
[3] C. Angioni et al 2023 Nucl. Fusion 63 056005.

C. Angioni



(Photo: V. Rohde, MPI for Plasma Physics)

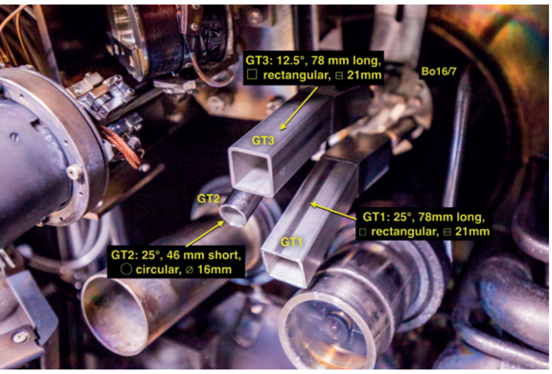
Good news from the ASDEX Upgrade vacuum vessel!

In the midst of the summer holiday season, a remarkable milestone was reached: The in-vessel coils of the new upper divertor were successfully installed. The photo shows the first coil with 4 turns already lifted and inserted into its housing and the second one still in bending phase. After months of rigorous training and thorough preparation with the mock-up, the ASDEX Upgrade team successfully achieved the precise bending of the coils within the planned timeframe, underscoring the dedication and expertise of the professionals involved in this landmark project. The in-vessel coils mark a significant step towards enhancing the device's capabilities.

I. Zammuto

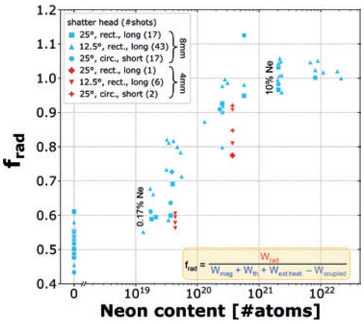
Shattered Pellet Injection studies in support of ITER

Tokamaks are susceptible to the sudden, unplanned termination of the plasma discharge. These events, known as disruptions, pose risks due to damage caused by large electromagnetic forces, local heat loads, currents induced in components, or by the generation of relativistic (runaway) electron beams. On a medium-sized tokamak such as ASDEX Upgrade, the routine mechanism for mitigating disruptions is a controlled shutdown via the rapid injection of large quantities of neon gas. In a large tokamak such as ITER, however, the gas does not penetrate deep enough for effective assimilation, and due to the large distance of the injection system from the plasma edge, the material cannot be delivered quickly enough.



SPI shattered heads inside ASDEX Upgrade (Image: G. Papp)

ITER will therefore employ a disruption mitigation system based on shattered pellet injection (SPI), using cryogenic pellets made of hydrogen, neon, or mixtures thereof. However, the amount of material needed by ITER requires pellets the size of a champagne cork, which would not ablate properly in the plasma. The solution is to break up the large pellet into fragments using a shatter head just before it enters the plasma. In addition to optimising the required quantity and material composition of the pellet, the size distribution and penetration speed of the resulting fragments must also be optimised for effective disruption mitigation.

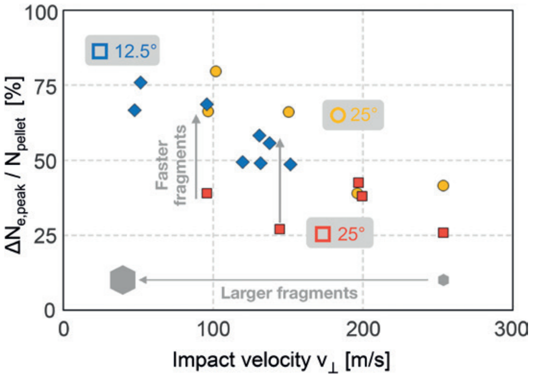


Radiated energy fraction showing strong dependence on the neon content. The pellet size (colours) or the shatter head (point types) show a lesser, complex dependence. (Image: P. Heinrich, Theory and Simulation of Disruptions Workshop 2023).

To investigate this problem, ITER has funded a uniquely flexible SPI system for ASDEX Upgrade. It has 3 independent pellet generation cells and flight tubes, with 3 different shatter heads on each end. The injector can vary the pellet diameter by a factor of 8, the length/diameter ratio by a factor of 3, the pellet speed by a factor of 10 (depending on the mass), and is capable of automatically generating and firing pellets made from a wide range of deuterium, neon and mixtures thereof. A major upgrade of SPI-relevant diagnostics - hundreds of new photodiode channels, 5 new foil bolometer cameras, and improved ultra-high speed video imaging - have been installed in the 2020 and 2021 openings in preparation for the SPI.

Approximately 1400 pellets were fired during SPI commissioning in the laboratory. The resulting fragment sprays were recorded with ultra-high speed cameras and analysed using sophisticated computer vision techniques. The selection of the shatter heads for installation inside ASDEX Upgrade was based on this laboratory analysis, with the aim of maximising experimental flexibility and decoupling the desired fragment size distribution from the penetration speed. Over 200 ASDEX Upgrade discharges were dedicated to SPI exploitation in 2022. In a collaboration between MPI for Plasma Physics, ITER and EUROfusion, a wide range of pellet and shattering parameters have been studied in different target plasmas. Analysis and modelling of the unique data set is still ongoing, but a few key insights have already emerged. The total fraction of plasma energy radiated away and its spatial asymmetry show strong dependence on the pellet composition (total number of neon atoms) but complex sensitivity to the shattering geometry. Pellet material assimilation – our ability to increase the plasma density to prevent runaway electron beam formation - favours large pellet fragments with high penetration velocities. This supports the current ITER SPI design with its 15 degree impact angle.

Pellet assimilation (peak density normalised to pellet volume) vs. impact velocity, $v_\perp$. Larger fragments (lower $v_\perp$) and faster parallel penetration speed (lower impact angle at the same $v_\perp$) lead to better assimilation. (Image: M. Lehnen, IAEA-FEC 2023)



G. Papp

Imprint

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