ASDEX Upgrade LETTER
Max Planck Institute for Plasma Physics

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

View into ASDEX Upgrade with stabilized runaway electron beam. (Image: MPI for Plasma Physics)

Editorial

In 2022, ASDEX Upgrade enjoyed another successful experimental campaign with a program strongly focused on the physics and technology needs of ITER and future fusion reactors. This campaign, similar to previous years, was carried out in close collaboration with the EUROfusion Work Package Tokamak Exploitation program. This partnership, together with a multi-faceted internal program, produced a wide range of impressive results that demonstrate the scope of the ASDEX Upgrade program, which aims to address critical challenges facing magnetic confinement fusion (MCF) reactors. The results highlighted in this letter directly contribute to these challenges and also serve to demonstrate the breadth and quality of the research being performed at this facility.

Researchers at ASDEX Upgrade have developed the control technology to capture, confine, and safely terminate run-away electron beams produced during disruption events. This ability has been robustly integrated into the ASDEX Upgrade discharge control system, providing an important tool for the study and understanding of runaway electron beams. A second major challenge for MCF is developing robust exhaust solutions, which requires understanding of plasma behaviour in the outermost region of the plasma. To facilitate this understanding, a more complete collisional radiative model has been developed that significantly improves the accuracy of Helium-beam based electron temperature measurements in the region. Finally, the impact of 3-D perturbations (MP) on the power threshold (P_{LH}) required for achieving high confinement plasmas (H-mode) was investigated in detail. This is a critical question for ITER, which plans to use MPs, but is limited in the amount of heating power available to reach H-mode. ASDEX Upgrade experiments demonstrate that MPs only increase P_{LH} above a certain threshold in the MP field amplitude, which is higher than the one required to suppress ELMs, providing a ray of hope for ITER, and a clear guide of how the MP coils in ITER should be applied.

These are just a few of the achievements from the latest experimental campaigns. In 2023 ASDEX Upgrade will be undergoing a major upgrade of the upper divertor. Experiments utilizing the new divertor capabilities are planned for fall of 2024.

R. M. McDermott

Dr. Rachael M. McDermott, Head of the new division Physics of the Plasma Edge at the Max Planck Institute for Plasma Physics (Photo: MPI for Plasma Physics)

Runaway electron studies in support of ITER

Tokamak operation requires active feedback control to achieve a sustained stable discharge. If the control is lost, the discharge will terminate abruptly with a so-called disruption. During such a disruption the device experiences both high thermal and structural loads. These loads are routinely mitigated using massive gas injection (MGI), a safety technique that injects a highly radiative impurity, e.g. argon, during the disruption.

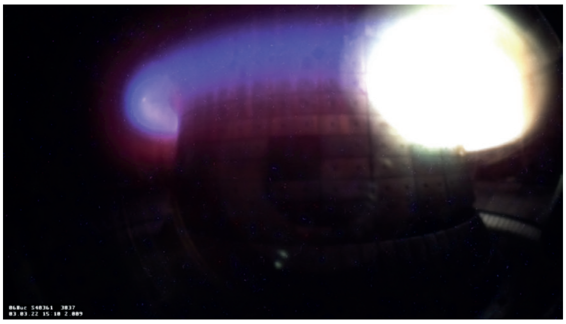


Figure 1: View into ASDEX Upgrade showing the non-benign termination of the runaway electron beam, indicated by the strong light emission from synchrotron radiation on the right-hand side of the view. (Image: MPI for Plasma Physics)

For larger devices such as JET and especially ITER, another phenomenon is a significant issue. This is the generation of so-called runaway electrons during the disruptions. Electrons are strongly accelerated toroidally during the disruption, leading to a weak interaction with the background plasma. This in turn allows them to gain even higher kinetic energy in a runaway fashion. For large devices it is predicted that a significant fraction of the plasma current can be transferred to these runaway electrons, potentially causing damage to the plasma

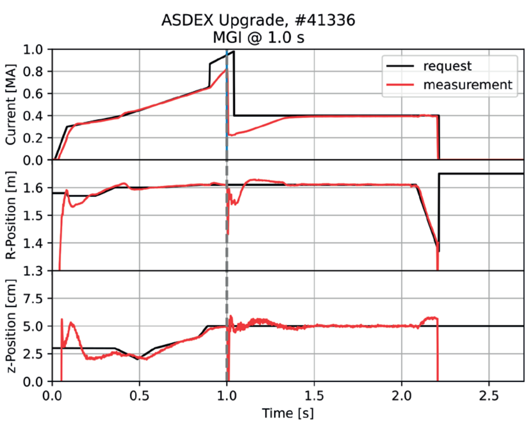


Figure 2: Trajectories of measured and requested control quantities showing the stabilization of the runaway electron beam after 1 second and the radial compression starting from 2.1 seconds. (Figure: B. Sieglin)

facing components if unmitigated (Figure 1). In ASDEX Upgrade runaway electrons are not generally generated during disruptions. This is an issue, if one wants to study their generation and mitigation in support of large devices.

There is a proven technique to generate runaways, namely, the forced disruption via MGI of argon into a circular plasma during the plasma current ramp-up. By default the discharge control system (DCS) tries to perform a controlled automated ramp down of the discharge, when a disruption is detected, in order to bring the device into a safe state. This limited the possibilities to study runaway electrons in the past. The reaction of the DCS was adapted, for these experiments, in order to keep control of the resulting runaway electron beam. After the injection of argon the control goal is changed to control both the position of the runaway electron beam as well as its current.

This proved successful in achieving a stable runaway electron beam (cover picture) with the properties desired for experimental studies. During the experiment a maximum current of 0.6 MA and a maximum duration of four seconds were achieved. The ability to control the runaway electron beam has allowed the investigation of a benign termination scenario. Figure 2 illustrates the requested (black) and achieved (red) trajectories for the current, the radial and vertical position, R and z, of the plasma, and the runaway electron beam. The injection

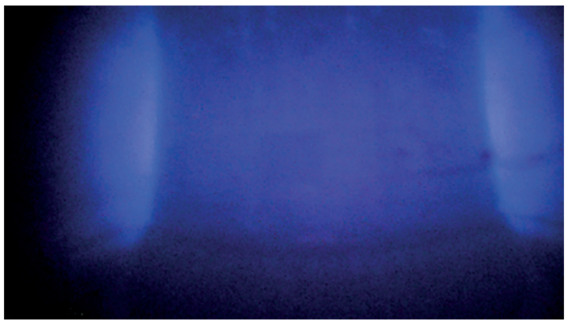


Figure 3: View into ASDEX Upgrade showing the benign termination of the runaway electron beam. (Image: MPI for Plasma Physics)

of argon occurs at 1 second, triggering a disruption and generating the runaway electron beam. After 1 second, the requested current is adjusted (in this case to 400 kA). The position of the runaway electron beam is stabilized, and the current is ramped to the request value.
A combination of a strong deuterium gas puff in combination with a radial compression of the runaway electron beam proved successful to achieve a benign termination. The compression is started after 2 seconds. During the compression the resonance conditions of the magnetic flux surfaces is changed, leading to the occurrence of macroscopic MHD mode activity. The runaway electrons interact with the MHD modes leading to their abrupt isotropic de-confinement (Figure 3). This distributes the energy carried by the electrons over a large surface area, thereby protecting the plasma facing components.

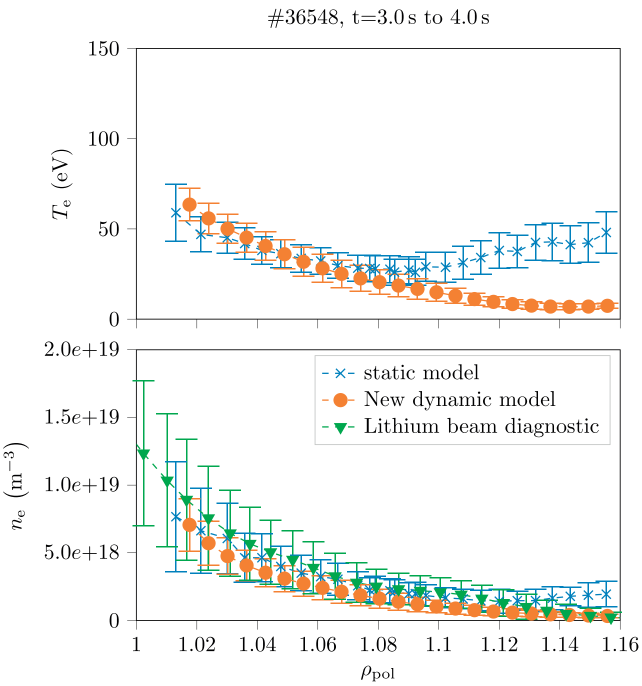
The control abilities gained during these experiments enable further more detailed studies of runaway electrons in ASDEX Upgrade.

B. Sieglin

IMPROVED EDGE PROFILE ACCURACY

New model for the helium beam diagnostics

To understand the edge plasma of fusion experiments, a variety of diagnostics are utilized. Many of these, including the thermal helium beam at ASDEX Upgrade, are based on beam emission spectroscopy. Similar to other beam emission diagnostics, neutral particles (here thermal helium) are locally injected into the plasma vessel. By the interaction with the plasma, atomic transitions are excited, leading to measurable radiances that are detected by an optical system. For the ASDEX Upgrade He-beam diagnostics, 27 lines of sight measure the emission of the neutral helium cloud along the injection direction. For each line of sight, the emission is split into multiple spectral components, including four helium transitions, which are measured in a polychromator with a sampling rate of 900 kHz. With the help of a collisional radiative model, this light emission can be used to determine the temperature and density of the electrons at the plasma edge.



Temperature and density profiles created by the new ("dynamic model") and old collisional radiative model ("static model") in comparison. For the density comparison, the lithium beam diagnostic was added. Especially in the temperature one can see a significant difference between the models, whereas the new evaluation also corresponds to the expected physical behaviour. This work was recently published in the journal Plasma Physics and Controlled Fusion.

Collisional radiative models are used to calculate the interaction between the neutral injected atoms and the plasma, which is mainly caused by electron collisions. Other processes, like recombination of helium ions with electrons and excitations via charge exchange, are orders of magnitude weaker. For the evaluation of measured intensities, the models are required to describe the real processes in the plasma as accurately as possible. Based on existing atomic data, scientists at the Max Planck Institute for Plasma Physics have developed a novel collisional radiative model. In addition to the electron-neutral collisions and the spontaneous emission, which dominate the state transitions, two additional processes are included. These are the dynamic state occupation of the injected helium atoms in the plasma, which is especially important to describe the transition between the two spin states of helium, and the reabsorption of self-emitted radiation, which was, until now, only treated for pure helium plasmas.

The density profiles evaluated with the new model agree with the lithium beam diagnostic, as did the previous static collisional radiative model. However, the electron temperature profiles have been greatly improved by the dynamic model and no longer show non-physical increases in the direction of the wall. This apparent temperature increase was due to the absence of the dynamic state occupation in the old model. It is especially important to include this effect in regions of low electron density, which causes low transition rates and makes accurate modelling of the transitions even more important. The reabsorption depends not only on the plasma parameters, but also on the helium injection rate. It could be shown that the effect scales with the helium injection and causes, for the usual rates, only a small improvement of the fit and no significant changes in the resulting temperatures and densities.

With the new model, even more accurate temperature and density profiles can now be calculated, which are used for physical studies at the plasma edge. This includes the study of decay lengths, background profiles for filament measurements and grants reference profiles for theory and modelling.

D. Wendler

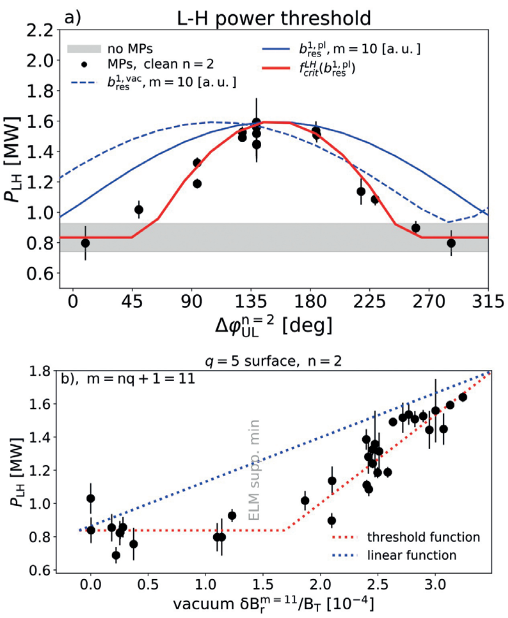
Rachael M. McDermott becomes a director at Max Planck Institute for Plasma Physics

Since February 1, 2023 Rachael M. McDermott is a Scientific Member of the Max Planck Society and Director in Garching. She leads an experimental division strongly involved in the operation of ASDEX Upgrade. Her department operates key diagnostics and systems for the interpretation of ASDEX Upgrade plasmas and will focus on understanding the physics of the plasma edge and its implication for the core plasma performance.

Effect of magnetic perturbations on the L-H power threshold

Future fusion devices will have to avoid the peak power load to the first wall produced by edge localised modes (ELMs) in the high confinement (H-mode). To suppress ELMs in ITER, it is intended to use non-axisymmetric magnetic perturbation (MP) fields from external coils. Because the very first ELM after the transition from the low confinement (L-mode) to H-mode (L-H transition) can already damage the first wall in ITER, it is foreseen to employ MPs already in L-mode. Previous studies at different tokamaks including DIII-D, KSTAR and MAST have shown that the application of MPs can increase the required heating power to access H-mode (L-H power threshold, P_{LH}). An increase in P_{LH} may challenge the access to H-mode in ITER, because the initial available heating power will be marginal above the predicted P_{LH}. It is, therefore, important to study the dependencies of P_{LH} on the MP field and to understand the physics behind the observations.

To study the impact of MPs on P_{LH}, previous studies at ASDEX Upgrade (F. Ryter, Nuclear Fusion, 2012) have been extended towards higher MP-field strength and different alignments of the MP field. Both parameters are crucial to achieve ELM suppression with MPs. From 2017 to 2020 a total of 15 discharges including 34 useful L-H transitions, both with and without MP field with a toroidal symmetry number of 2, have been performed. The phase difference between upper and lower MP-coil currents ($\Delta\varphi_{UL}$) varies the alignment of the MP field.



(a) L-H power threshold (P_{LH}) versus the MP-field alignment $\Delta\varphi_{UL}$ with n=2. Radial field perturbation b^1_{res} from MARS-F at a rational surface (m/n=10/2) at the edge using the plasma response (solid blue) and the vacuum field (dashed blue). (b) P_{LH} versus the applied relative vacuum field perturbation of the poloidal mode component (here m=11) that is important for the plasma response. P_{LH} increases only above a minimum field strength. The blue dotted line illustrates a linear function and the red dotted line a threshold function. The linear MARS-F calculations combined with the threshold function is shown in (a) as red line. (Figure: M. Willensdorfer, reproduced from [1]. CC BY 4.0)

Figure (a) shows the dependence of P_{LH} on $\Delta\varphi_{UL}$ compared to the radial field perturbation at the plasma edge from linear resistive MHD calculations obtained with the MARS-F code. The strongest increase in P_{LH} is observed when $\Delta\varphi_{UL}$ is between 130° and 180°. The maximum of the radial field perturbations is in the same range of $\Delta\varphi_{UL}$ when the plasma response is considered (solid blue line), while the pure vacuum field perturbation (dashed blue line) is not sufficient to predict $\Delta\varphi_{UL}$ that maximizes P_{LH}. This is the same $\Delta\varphi_{UL}$ that is optimal for ELM suppression, which implies that $\Delta\varphi_{UL}$ alone cannot be used to avoid an increase in P_{LH} while reliably sustaining ELM suppression.

Analysis of the field strength of the applied vacuum field perturbation shows that P_{LH} only increases when a critical MP strength, MP_{crit}, is exceeded (figure (b)). This threshold behaviour is also the cause that a linear relation between b^1_{res} from the MARS-F code (solid blue line) and P_{LH} does not fully describe the $\Delta\varphi_{UL}$ dependence of P_{LH}. Combining the linear MARS-F calculations with a threshold function as in figure (b) reproduces the experimental behaviour (red line in figure (a)).

The radial electric field (E_r) at the edge, especially its shear, is known to be a key parameter for the L-H transition. Measurements of E_r show that MPs flatten its profile at the edge and shift it towards more positive values. This suggests that more heating power is needed to re-establish an E_r shear similar to that without MPs. The flattening of the E_r profile at the edge shows the same threshold behaviour with respect to the MP field strength as the increase of P_{LH}, confirming their connection.

In ASDEX Upgrade the minimum MP-field strength to sustain ELM suppression is below MP_{crit}, opening a small window in which ELM suppression is possible without an increase in P_{LH}. In order to predict the width of this operational window for ITER, it is necessary to understand ELM suppression and the increase in P_{LH} individually since they may scale differently.

[1] M. Willensdorfer et al, Physics of Plasmas 29, 032506 (2022)

M. Willensdorfer

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