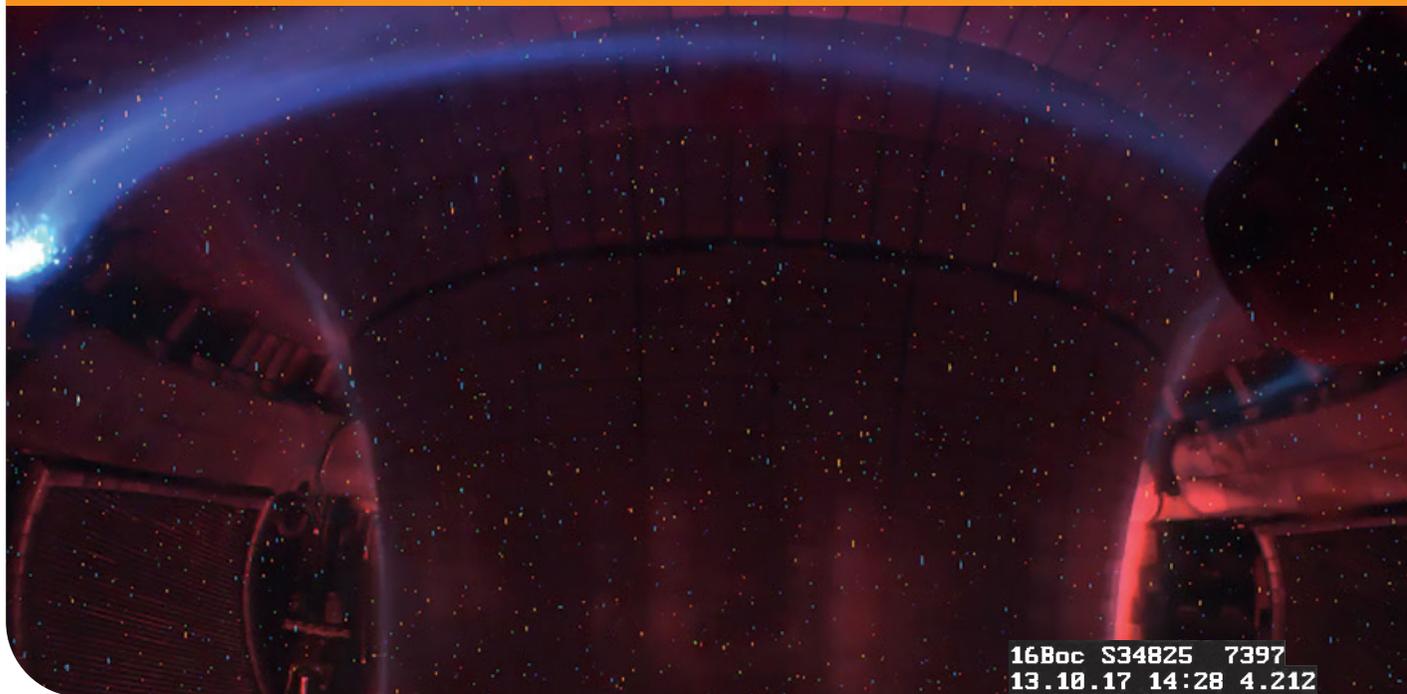


ASDEX Upgrade LETTER

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



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True color camera frame showing injection of boron powder in an ASDEX Upgrade plasma. The bright spot on the left shows the location where the powder dropped first interacts with the plasma.

PHOTO: T. LUNT



Prof. Dr. Sibylle Günter
Scientific Director of IPP

PHOTO: IPP

EDITORIAL This year's campaign at the ASDEX Upgrade tokamak lasted until the regular maintenance opening starting end of July. Despite the difficult conditions due to the COVID-19 pandemic and a related interruption of the campaign for six weeks, 87 per cent of the planned experimental programme was completed during the campaign. The EUROfusion MST1 experiments were also executed as planned, made possible by inviting our collaborators via video conferencing into the control room. This is a great achievement, for which I would like to congratulate the ASDEX Upgrade Team and our EUROfusion partners.

The ASDEX Upgrade programme concentrated once more on the avoidance of ELMs, aiming at a quasi-continuous exhaust. Major progress has been achieved by modifying the edge ballooning stability with the aim to enhance the high- n MHD activity at the foot of the pedestal region. That way, the induced continuous transport keeps the edge pressure gradient below the onset condition for type-I ELMs.

In the so-called "flux pumping" discharges, following theoretical predictions, it has been shown that $m/n = 1/1$ activity provides a magnetic dynamo at high β -values. This effect causes an outward redistribution of poloidal magnetic flux. This discovery not only provides an explanation for the broad q profiles with q on axis above one in the so-called hybrid scenarios. It also allows for efficient current drive by ECRH on axis, still ensuring the preferred broad current profiles.

Finally, boron powder injection into ASDEX Upgrade has been investigated in collaboration with our colleagues from PPPL. Such a method could be of particular importance for superconducting machines like ITER and Wendelstein 7-X as it allows for boronization without switching off magnetic fields.

The new campaign will start in December. We are looking forward to an exciting campaign and collaboration with our EUROfusion colleagues. We welcome warmly the newly appointed task force leaders Emmanuel Joffrin (CEA) and Marco Wischmeier (IPP) as well as their deputies: Antti Hakkola (VTT), Benoît Labit (SPC), Emmanuelle Tsitrone (CEA), and Nicola Vianello (Consorzio RFX).

S. GÜNTER

Sawtooth suppression by magnetic flux pumping

Achieving a high energy and particle confinement is essential for efficient operation of future burning plasmas. In tokamaks, high performance can be achieved by elevating the central safety factor q , which describes the helicity of the magnetic field lines, to values around one.

A safety factor above one ensures the suppression of the sawtooth instability, which would otherwise reduce performance and could trigger other deleterious instabilities. At high plasma pressures, MHD modes can modify the current profile, leading to a flat elevated central q profile. The underlying mechanism leading to this anomalous evolution of magnetic flux can be referred to by the general term “magnetic flux pumping”.

At DIII-D, flux pumping was observed in the presence of a $m=3/n=2$ tearing mode. It also appeared after applying a slowly rotating $n=1$ magnetic perturbation via in-vessel coils which induces a helical deformation of the central flux surfaces. A theoretical model suggests that flux pumping can occur in the presence of a saturated

axis, q_0 , assumes values greater than one. Thus, the core q profile stays clamped around one. Simulations suggest that the strength of the flux pumping mechanism increases with core pressure, which stems from the pressure-driven nature of the 1/1 quasi-interchange mode.

At ASDEX Upgrade, using the imaging motional Stark effect diagnostic (IMSE) and the IDE equilibrium solver, changes of q as small as 0.1 are measurable, even in the plasma center. This, together with the current drive capabilities of the electron cyclotron resonance heating systems, makes ASDEX Upgrade the ideal device to test these simulations. To this end, in discharges featuring a 1/1 mode, central co-current electron cyclotron current drive (ECCD) was applied in several steps to decrease q_0 and trigger sawteeth. At the same time, heating power scans were performed to increase the core pressure over the threshold necessary for the mode to suppress sawteeth. In the following, the normalized pressure β_N is considered as a proxy for the plasma core pressure.

The figure shows the results of the scans. At a given ECCD current, β_N needs to exceed a certain threshold to enter the sawtooth-free regime. At a

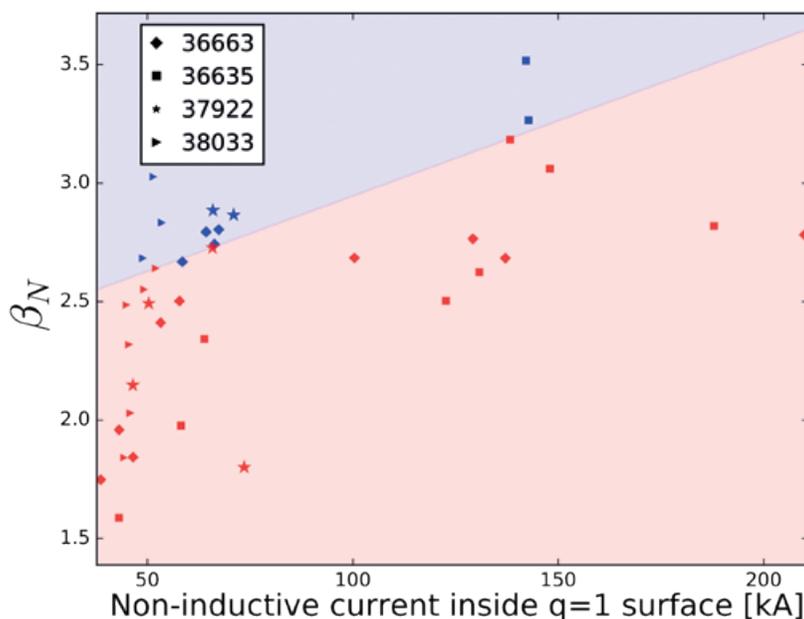
higher ECCD current, this threshold increases. In the sawtooth-free phases, while neoclassical current diffusion predicts q_0 to drop below one, the measurement revealed that the central q profile remained flat and clamped around one. This indicates an anomalous modification of the central current profile, which could be caused by the 1/1 mode through flux pumping. In the cases just below the threshold, the sawteeth are very sporadic. In the long phases between those sawteeth, q_0 does not drop as quickly as the neoclassical current diffusion model predicts. This suggests that the flux pumping mechanism still plays a role, but is

not strong enough to completely suppress the sawteeth.

Thus, these experiments support the theory that at sufficiently high plasma pressure, the central q profile automatically clamps to one through the magnetic flux pumping mechanism, enabling sawtooth-free, high-performance plasma operation. If this extrapolates to future machines, it could alleviate the necessity for complicated current shaping actuators to achieve advanced tokamak scenarios.

A. BURCKHART

Highlight from a recent ASDEX Upgrade experiment

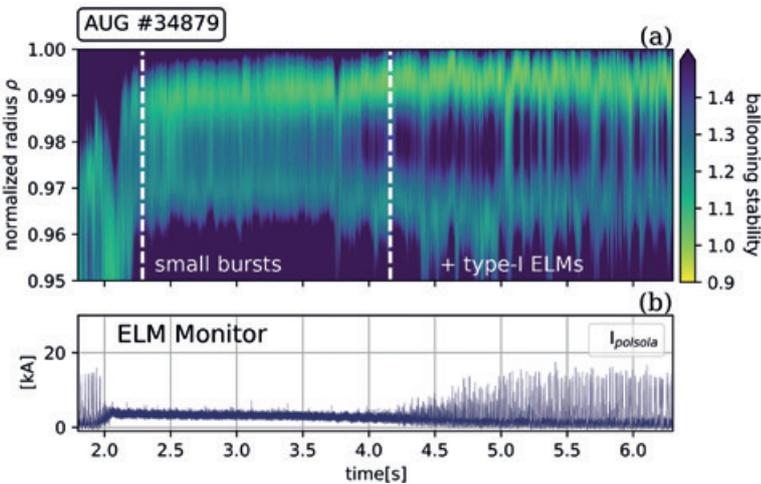


Experimental parameter scan, β_N versus central non-inductive current. Blue symbols represent sawtooth-free cases, red symbols phases with sawteeth.

FIGURE: A. BURCKHART

$m=1/n=1$ interchange-like mode [Krebs et al, PoP 2017]. This mechanism generates an effective negative loop voltage in the plasma core, preventing the central current density from peaking and thereby flattening the core q profile. The mechanism is self-regulating since the mode activity decreases if the safety factor on the magnetic

Ballooning instability in quasi-continuous exhaust operation



(a) Contour plot of ballooning stability for #34879, (b) Outer divertor shunt current used as ELM monitor

FIGURE: G. HARRER

3 s until the end of the discharge, resulting in a gradual reappearance of type-I ELMs in addition to the small QCE bursts. The upper part (a) of the figure shows contours of the calculated ideal ballooning stability at the plasma edge ($0.95 < \rho < 1$) over time. Dark blue regions are ballooning stable whereas yellow regions show stability factors < 1 , indicating instability. The time trace of the outer divertor tile current is used as ELM monitor, see the lower part of the figure (b).

Large ‘type-I’ Edge Localized Modes (ELMs) – driven unstable by the combination of pressure and current gradients across the H-mode pedestal – pose a serious threat to first wall components of future reactor-grade machines such as ITER. More benign exhaust properties are expected in the Quasi-continuous Exhaust (QCE) regime investigated on ASDEX Upgrade. Here, edge relaxation bursts occur only in the last millimeters of the confined plasma region, provided the shape of the flux surfaces is highly elongated and triangular. These bursts occur with a frequency of several kHz, much faster than the plasma facing components cool down, leading to quasi-continuous exhaust. Recent infrared thermography measurements on ASDEX Upgrade showed the footprint of the heat flux on the divertor tiles increase by a factor of four in the QCE regime compared to the heat flux in between type-I ELMs, emphasizing the advanced power exhaust capabilities of the QCE regime.

While linear ideal MHD theory describes type-I ELMs as coupled peeling-ballooning instabilities affecting the whole pedestal, the outmost plasma edge near the separatrix has been linked to narrow ballooning instabilities. Using the ideal ballooning stability code HELENA, we were able to show that QCE plasmas are indeed prone to ballooning instability near the last closed flux surface. The figure shows results for an ASDEX Upgrade discharge, where the QCE regime is achieved from 2 s onward. The plasma elongation then was slowly reduced from

From the start of the QCE regime, a ballooning unstable region is visible at $\rho \geq 0.99$ which is slightly shifted outward with the change of plasma shape after 4 s. At the same time, the steep gradient region $0.97 < \rho < 0.99$ is found to have improved ideal ballooning stability, which coincides with the reappearance of type-I ELMs.

Scans in the ballooning mode operational space showed that for cases without type-I ELMs, ballooning modes reach into the plasma up to $\rho = 0.99$. Changes in the local magnetic shear in the altered plasma shape move the ballooning modes further out, and, under these circumstances, type-I ELMs reappear. It is conjectured that a wide enough region affected by ballooning modes can cause enough transport to keep the whole pedestal away from the type-I ELM peeling ballooning stability boundary. A high performance QCE plasma hence needs an ideal ballooning unstable region that is wide enough to guarantee a narrowed pedestal width resulting in peeling-ballooning stability and the absence of type-I ELMs. Importantly, this mechanism to suppress type-I ELMs is located near the separatrix, where absolute density and collisionality in ASDEX Upgrade are comparable to those expected in ITER and DEMO. Future studies will therefore investigate whether the QCE regime can be extrapolated to ITER and DEMO.

G. HARRER (ÖAW)



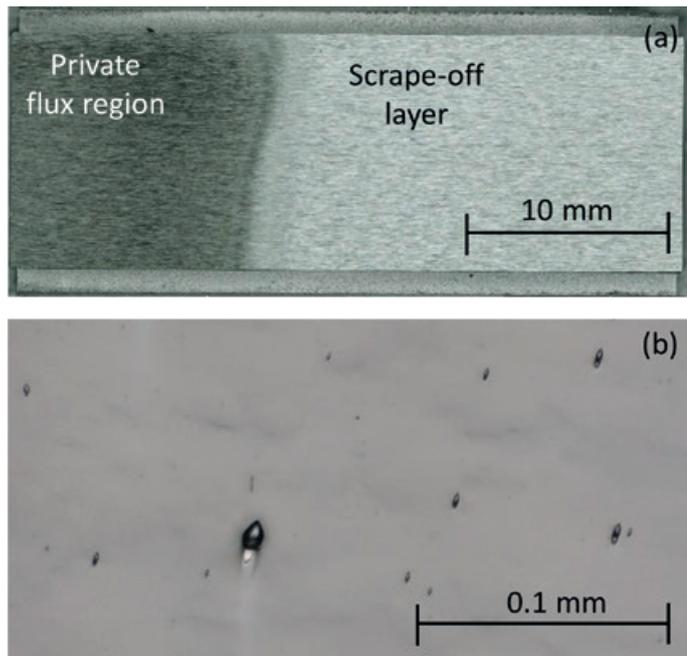
Prof. Michael Kaufmann,

director at IPP from 1978 to 2007, passed away in spring 2020. He was not only an outstanding scientist, promoting important new developments such as the full-W wall on ASDEX Upgrade, but also an equally successful science manager. With the Europeanization of the ASDEX Upgrade experiment via its programme committee, he implemented the joint use of the European fusion facilities, which is now taken for granted, at a very early stage. Michael Kaufmann also promoted many careers, always taking meticulous care to ensure that the employees received the full credit for their work. IPP – and with it all fusion research in Germany – owes Michael Kaufmann so much. We will remember him with honour and gratitude.

H. ZOHN

A closer look at films deposited during boron powder injection

Boron powder injection is presently under active investigation as a tool to complement the use of pre-run glow discharge boronization for conditioning of plasma facing components (PFC). Boronization improves the PFC by depositing films that absorb impurities and enable high plasma purity and low plasma density. However, the procedure requires the magnetic field to be switched off, which prevents its routine applicability in superconducting devices such as Wendelstein 7-X or ITER.



(a) Picture of a W sample divertor tile after exposure to plasma fluxes during boron powder injection. The darker coloration in the 'private flux region' suggests net deposition of boron. (b) High-resolution microscopy of the polished samples gave the first evidence of deposition of solidified droplets of size 1-10 microns.

PHOTOS: IPP

In contrast, injection of boron powder in fusion plasmas has recently been shown to mimic the effects of boronization without shutting down the magnetic field. When fully developed, this technique could be used in long-pulse, superconducting devices with continuous operation of the magnetic field.

In June 2020 a new experiment, studying the boron film deposition on the divertor tiles was successfully conducted at ASDEX Upgrade, with remote participation from the United States due to global travel restrictions.

This experiment marked the latest chapter of a fruitful collaboration between IPP and Princeton Plasma Physics

Laboratory (PPPL). It started in October 2017 with pioneering investigations of real-time wall conditioning by boron powder injection in tokamak plasmas. For these experiments an Impurity Powder Dropper (IPD) developed by PPPL was installed on ASDEX Upgrade. The findings, which were disseminated at the following PSI conference [1], showed that boron injection facilitated low collisionality operation and extended the beneficial effects of prior glow discharge boronization. The technique has been repeatedly applied in ASDEX Upgrade to produce conditions for ELM suppression experiments.

In addition, it was found that powder injection can be used for different applications. For instance, injection of boron nitride powder was observed to increase the radiative power exhaust by up to 80 per cent, with a confinement improvement similar to N_2 gas injection. Additional benefit is a substantially lower production of ammonia [2], which is a critical issue when using N_2 in ITER.

Following the initial encouraging results at ASDEX Upgrade, several IPD systems have been installed and used in fusion devices around the world including DIII-D, KSTAR, EAST, Wendelstein 7-X and LHD. While the benefits of wall conditioning by boron powder in terms of plasma performance have been broadly confirmed, a demonstration of the ability of growing boron films on tungsten PFCs remained elusive. This was the goal of a recent ASDEX Upgrade experiment, which utilized tungsten samples manufactured in the USA to be exposed to divertor plasmas during the injection of boron powder.

After exposure, initial inspection of samples showed regions of net material deposition, particularly in the private flux region. High-resolution microscopy of the polished samples gave the first evidence of deposition of solidified droplets.

Analysis of the exposed tiles is currently ongoing in IPP's post-mortem surface analysis labs to determine composition and thickness of the boron-rich layer and droplets. The dataset will complement studies on DIII-D, a carbon-wall device, where graphite samples have been exposed to the divertor plasma using the Divertor Materials Evaluation System (DiMES) [3]. Future studies will focus on hydrogen retention in such deposited layers, a big challenge for DEMO type fusion devices.

A. BORTOLON (PPPL), F. LAGGNER (PPPL)

[1] A. BORTOLON ET AL. 2019, NUCL. MATER. ENERGY, 19, 384

[2] R. LUNSFORD ET AL. 2019, NUCL. FUSION 59 126034

[3] A. BORTOLON ET AL. 2020, NUCL. FUSION 60 126010