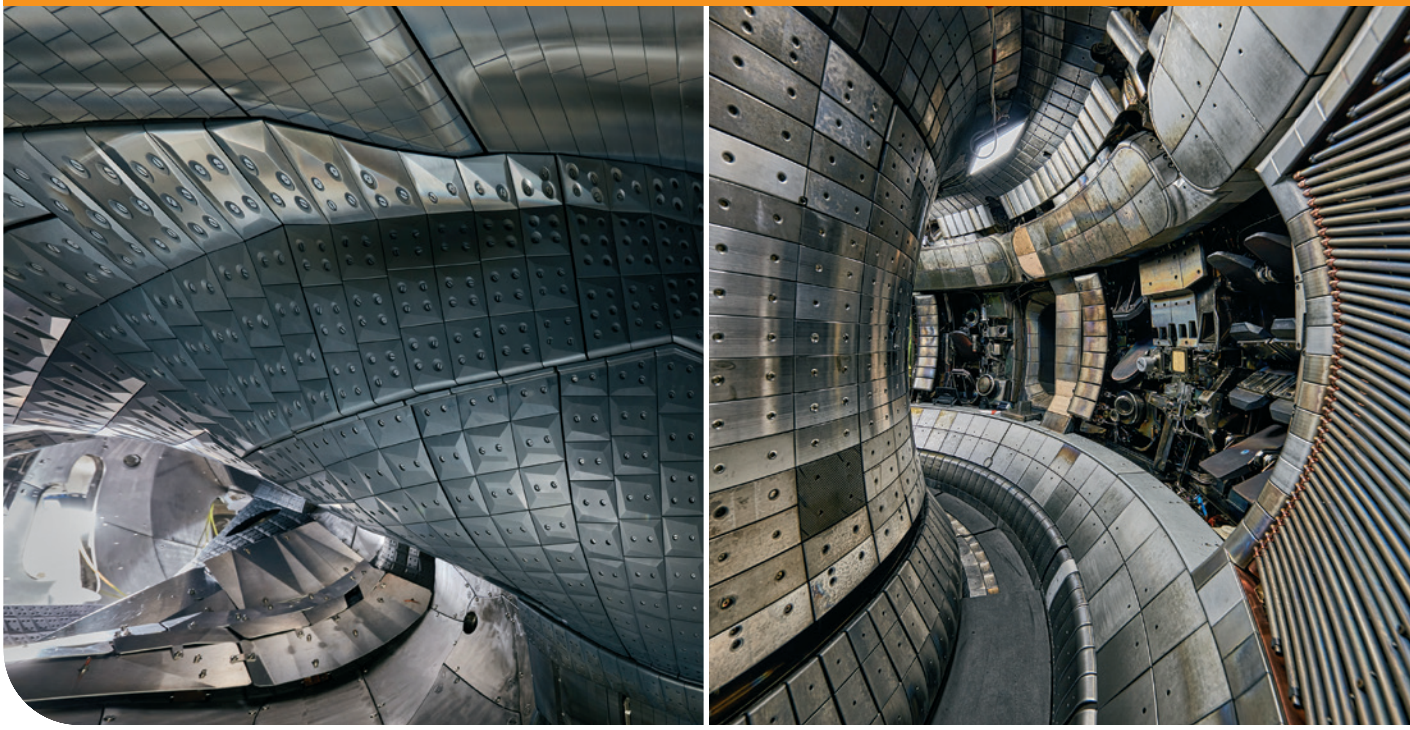
ASDEX Upgrade LETTER

Max-Planck-Institut für Plasmaphysik

No. 21 | December 2019

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



In-vessel view of the Wendelstein 7-X optimized stellarator and the ASDEX Upgrade tokamak

PHOTOS: IPP, B. LUDEWIG

Prof. Dr. Hartmut Zohm
Head of Tokamak Scenario Development division

PHOTO: IPP

EDITORIAL

After a regular maintenance opening, the ASDEX Upgrade tokamak resumed operation at the end of November 2019, with a number of upgraded diagnostics promising exciting results. In this issue of the ASDEX Upgrade Letter, the spotlight is on some important results of the 2018/19 campaign. These were obtained in the framework of both the EUROfusion MST1 and the internal IPP programme, a new element being a joint experiment between IPP's two fusion devices, the ASDEX Upgrade tokamak and the Wendelstein 7-X stellarator.

With the preparation of ITER operation being one of the major goals of the ASDEX Upgrade programme, a recent focus has been on the physics important for ITER commissioning, namely the operation in hydrogen and helium that will not produce fusion neutrons. It is necessary to assess at an early stage the ability to control the L-H transition and ELMs in ITER. A crucial question is whether H-mode operation can be achieved in these working gases. Important results on the behaviour of the L-H threshold with different gases are reported in this newsletter, complementing previous findings from JET and nicely demonstrating the powerful European stepladder approach using devices of different size, but similar geometry.

While ELMs need to be strongly mitigated in ITER, it is now becoming clearer that in DEMO they may not be acceptable at all. Hence, the EUROfusion MST1 programme has put a strong emphasis on ELM-free operation modes. This Letter shows that fusion plasma physics still holds surprises, since it reports on a stationary ELM-free regime that had not been seen before and was discovered rather 'by accident'.

Finally, a fundamental problem of fusion plasma physics, namely the turbulent transport of energy and particles, has been addressed for the first time in a direct similarity experiment between tokamak and stellarator, showing the benefit of operating two major devices of these lines at IPP in parallel. This is just the start for studies of this kind, and we expect to learn much more about the fundamentals of magnetically confined plasmas during the coming years.

H. ZOHM

H-mode power threshold in mixed species plasmas

Highlight from a recent ASDEX Upgrade experiment

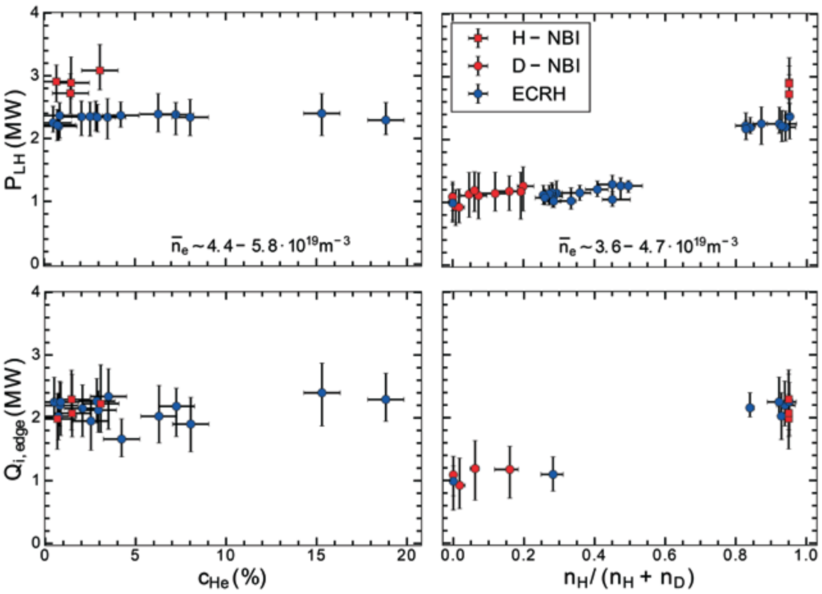
The high-confinement mode (H-mode) is a regime of improved plasma confinement which is currently foreseen for a future fusion reactor. To pass from the low-confinement mode (L-mode) to H-mode, a heating power threshold (P_{LH}) must be exceeded. Systematic studies at several fusion devices revealed that P_{LH} scales inversely with the mass of the main hydrogenic plasma species. During the pre-nuclear phase of ITER, H-mode operation will be first explored in hydrogen plasmas. Owing to limited external heating power during ITER's first operational phase, it would be highly desirable to find means to decrease P_{LH} in hydrogen plasmas and thus maximize the operational window for the H-mode. At JET it was observed that in hydrogen plasmas heated by neutral beam injection (NBI) P_{LH} is reduced by 20 percent when adding about 5 percent of helium. Furthermore, it was found that a linear scaling of P_{LH} with the inverse of the mean ion mass does not apply for mixed hydrogen-deuterium plasmas. Here P_{LH} rises with increasing relative hydrogen content ($n_H/(n_H+n_D)$) only at very low and high values for $n_H/(n_H+n_D)$. This non-linear behavior further enhances the uncertainty in predicting H-mode access in deuterium-tritium plasmas.

These issues were studied in the latest hydrogen campaign at ASDEX Upgrade. Discharges, both in hydrogen plasmas with helium doping and in mixed hydrogen-deuterium plasmas, employed power ramps sufficiently slow to pinpoint P_{LH}. Two types of auxiliary heating were used to change the ratio of electron to ion heating: Electron cyclotron resonance heating (ECRH), which exclusively heats the electrons, and NBI, which predominantly heats the ions. All experiments were conducted at an electron density high enough to ensure energy transfer between electrons and ions.

In contrast to the JET results, hydrogen discharges in ASDEX Upgrade with helium concentrations of up to 20 percent showed no reduction of P_{LH}, independent of the heating scheme. However, it was observed that NBI heated hydrogen plasmas tend to have a higher P_{LH} than ECRH plasmas. Former P_{LH} studies at ASDEX Upgrade showed that the total ion heat flux at the plasma edge ($Q_{i,edge}$) is a critical parameter for H-mode access. Therefore, the new experiments were complemented by power balance calculations to separate $Q_{i,edge}$ and the electron heat flux at the plasma edge, $Q_{e,edge}$. The analysis revealed that $Q_{i,edge}$ is constant at the L- to H-mode transition independent of helium concentration and heating scheme, while $Q_{e,edge}$ is higher in NBI than in ECRH discharges. Consequently, more NBI power has to be applied compared to ECRH to reach the critical value of $Q_{i,edge}$. Discharges in hydrogen-deuterium plasmas at ASDEX Upgrade show that P_{LH} is constant at the level of pure deuterium for $n_H/(n_H+n_D) < 0.5$ whereas it is constant at the level of pure hydrogen for $n_H/(n_H+n_D) > 0.8$. Power balance calculations show that $Q_{i,edge}$ follows the behavior of P_{LH}.

These ASDEX Upgrade results suggest that adding helium to hydrogen plasmas in ITER is not expected to lead to a significant decrease of P_{LH}, while they are consistent with the existence of a critical ion heat flux for accessing H-mode. More discharges in hydrogen-deuterium plasmas are planned at ASDEX Upgrade to extend the determination of P_{LH} and $Q_{i,edge}$ to the range of $n_H/(n_H+n_D)$ between 0.5 and 0.8, where the transition from the level of pure deuterium to the level of pure hydrogen can be expected to take place.

U. PLANK



P_{LH} (top) and $Q_{i,edge}$ (bottom) at the L- to H-mode transition in hydrogen-helium plasmas versus the volume averaged helium concentration (left) and in mixed hydrogen-deuterium plasmas versus the relative hydrogen content (right).

FIGURE: U. PLANK

Tokamak versus stellarator

Transport in ASDEX Upgrade and Wendelstein 7-X

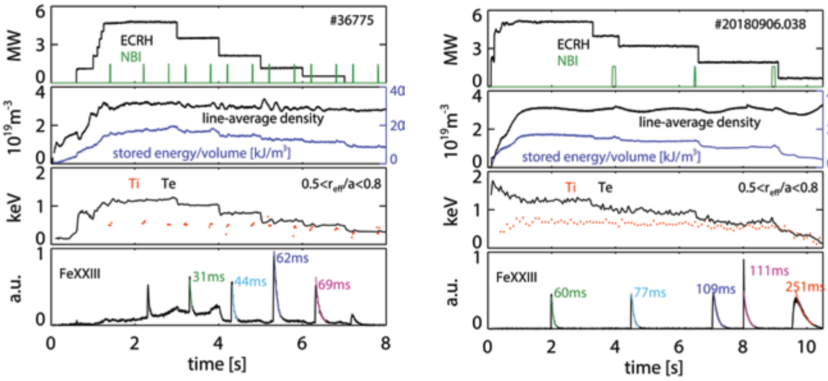
The two experimental devices of IPP, ASDEX Upgrade and Wendelstein 7-X, both feature similar minor radii and magnetic field strengths but differ significantly in terms of their magnetic field geometry. ASDEX Upgrade is based on the tokamak principle and has a plasma volume of 13 m^3, while Wendelstein 7-X follows the stellarator approach and confines plasmas of up to 32 m^3. The level of neo-classical transport is small in both devices. Tokamaks yield low neo-classical transport by default, and reduced neo-classical transport was one of the main optimization criteria for Wendelstein 7-X, such that the confinement properties are ultimately limited by micro-turbulence. The latter appears above certain critical temperature and density gradients and is one of the main unresolved challenges of magnetic fusion research.

With the two devices available, this challenge can now be approached from different perspectives. First comparison experiments in low-density L-mode plasmas were performed at ASDEX Upgrade with the aim of reaching the same line-average electron density and applied Electron Cyclotron Resonance Heating (ECRH) powers as previously observed in Wendelstein 7-X. In addition, dedicated impurity injections of iron were performed to obtain information on particle transport. As shown in the figure below, iron was injected during each ECRH level, resulting in sharp increases of core-localized Fe XXIII radiation that are followed by characteristic decays on time scales between 20 and 300 ms.

When comparing the two experiments we can first note that the electron density and applied heating power were reproduced very well in ASDEX Upgrade. In addition, the experimental time-traces show similar ion and electron temperatures, as well as similar levels of the normalized plasma stored energy.

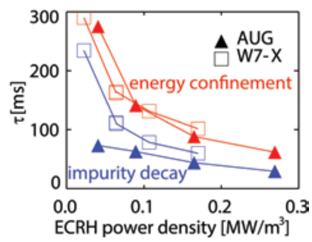
This similarity of the two plasmas in Wendelstein 7-X and ASDEX Upgrade becomes even clearer when plotting the measured energy confinement and impurity transport times as a function of the applied ECRH power density. The observed values from Wendelstein 7-X and ASDEX Upgrade exhibit a clear decay with the applied power density and are very close to each other. While confinement degradation with the applied heating power is expected for turbulent transport, the observation of similar values is not as obvious given the very different magnetic field structures of the two experiments. Possibly the same fundamental turbulent transport mechanisms are present in Wendelstein 7-X and ASDEX Upgrade that provide similar confinement properties. However, more detailed investigations and comparisons with gyro-kinetic simulations are needed. In addition, new comparison experiments are planned to check whether the observed agreement in low-density plasmas can be reproduced during high density operation.

B. GEIGER, UNIVERSITY OF WISCONSIN-MADISON



Representative time traces of comparison experiments at ASDEX Upgrade (left) and Wendelstein 7-X (right). From top to bottom, the applied heating power, the electron density and stored energy per volume, the average electron and ion temperatures for normalized radii between 0.5 and 0.8 and the observed levels of FeXXIII radiation are shown.

FIGURE: B. GEIGER

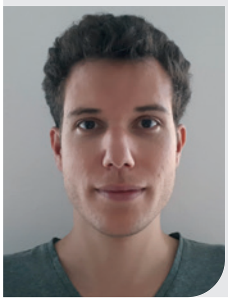


Energy confinement time and impurity decay time as a function of ECRH power density.

FIGURE: B. GEIGER

Dr. Michael Faitsch

PHOTO: PRIVATE



EPS Doctoral Award to Michael Faitsch

IPP postdoctoral fellow Dr. Michael Faitsch is one of the four prizewinners who received the PhD Research Award 2019 from the Plasma Physics Division of the European Physical Society (EPS) for the outstanding quality of their doctoral theses. In his thesis on "Divertor Power Load Studies at ASDEX Upgrade and TCV" Michael Faitsch reveals that an external magnetic perturbation can significantly change the power load to the divertor plates, as already reported in ASDEX Upgrade Letter No. 16 (2016). He developed a model that excellently describes these results. At the TCV tokamak in Switzerland, he investigated the influence of the plasma geometry on the divertor power load. His thesis, according to the laudation, is of great practical and theoretical importance.

I. MILCH

Stationary ELM-free H-mode in ASDEX Upgrade

Because of its superior confinement properties, the H-mode is presently regarded as the preferable operation regime for a future fusion power plant. It suffers, however, from a major drawback – periodic instabilities called edge-localized modes (ELMs). When extrapolated to large-scale fusion devices, they lead to unacceptably high heat loads on the divertor plates. Concurrently, H-mode operation requires ELMs for the expulsion of impurities from the plasma. In fact, full suppression of ELMs usually results in impurity accumulation and ultimately radiative collapse. Even though a few steady-state modes of operation without ELMs are known, each of them has different drawbacks. Therefore, the development and exploration of alternative ELM-free high-confinement regimes is very important for the success of fusion research.

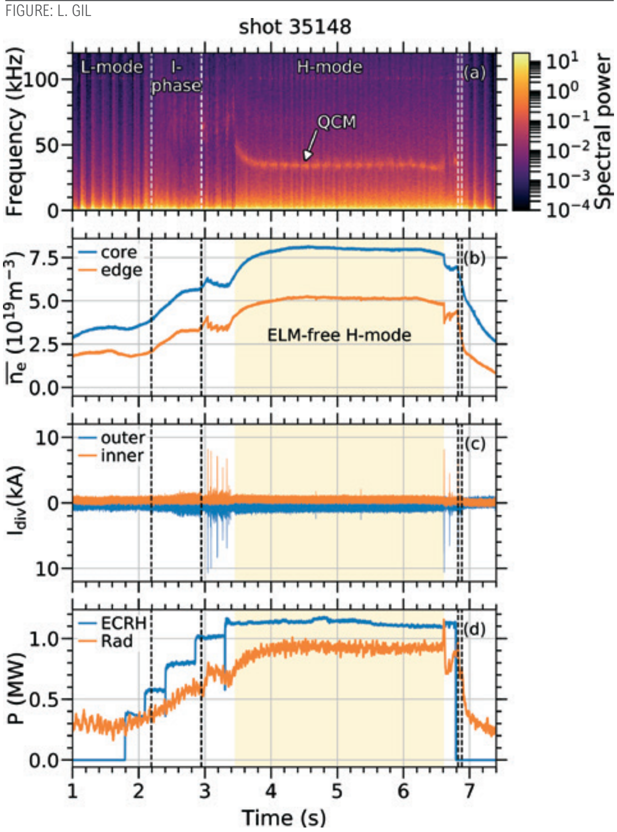
A stationary ELM-free H-mode scenario has recently been established and successfully demonstrated in ASDEX Upgrade by applying central Electron Cyclotron Resonance Heating (ECRH) with adequate fueling. It was naturally obtained with the ion magnetic field gradient drift pointing towards the X-point and without fresh boronization for wall conditioning. This regime exhibits several features which are desirable for extrapolation to future reactors, such as dominant electron heating, low input torque, compatibility with low input power, high density, good energy confinement and no impurity accumulation despite the absence of ELMs.

The figure shows an example of such a discharge with constant deuterium fueling and a sequence of ECRH steps. As the heating power is increased, the plasma undergoes several transitions: from low confinement (L-mode) to an intermediate phase (I-phase), then H-mode with ELMs and finally H-mode without ELMs. The ELM-free H-mode extends until after the end of the plasma current flattop phase, being limited in duration only by the inductive current drive.

During transition to the ELM-free H-mode the density increases strongly and the quasi-coherent mode (QCM) – an electromagnetic instability at the plasma edge – appears. It was discovered in ASDEX Upgrade by means of a microwave reflectometer optimized for edge density fluctuation measurements with high spatial and temporal resolution. This diagnostic was designed and built in 2001 by Instituto de Plasmas e Fusão Nuclear (IPFN) of Instituto Superior Técnico (IST) in Lisbon, Portugal, as part of a long-standing collaboration with IPP dating back to the 1980s. The QCM seems to be responsible for enhanced transport losses as its appearance and disappearance are correlated with corresponding changes in edge and divertor parameters. This enhanced transport may be the key to achieving steady-state ELM-free operation without impurity accumulation.

Time evolution of edge reflectometry phase spectra (a), line-averaged electron density (b), divertor shunt currents showing the occurrence of ELMs as transient excursions in the H-mode phases before and after the ELM-free H-mode (c) and ECRH and radiated power (d) in a discharge with a stationary ELM-free H-mode.

FIGURE: L. GIL



The scenario shares several key features with Alcator C-Mod's EDA H-mode: For example, it is obtained by electromagnetic wave heating in a tokamak with metallic plasma facing components and features an edge QCM producing outward plasma transport, which enables steady-state ELM-free operation with good confinement. The EDA H-mode has been extensively researched and is responsible for important accomplishments, such as the highest volume-averaged plasma pressure ever achieved in a fusion device. Obtaining and studying similar regimes in other fusion devices is therefore extremely relevant to the quest for fusion energy. The stationary ELM-free H-mode achieved in ASDEX Upgrade is an important step towards this goal. This promising regime will be the subject of future experiments in order to better understand its physics and scaling, allowing a more reliable assessment of its compatibility with large-scale devices such as ITER and DEMO.

L. GIL, IPFN/IST, UNIVERSITY OF LISBON

IMPRINT

ASDEX Upgrade Letter – published by

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
Archive: www.ipp.mpg.de/augletter

Max Planck Institute for Plasma Physics is associated with the European Fusion Programme and the Helmholtz Association of German Research Centres.