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Investigation of the O2- and X3-mode heating in ASDEX Upgrade

H. Höhnle[1], W. Kasparek[1], J. Stober[2], A. Herrmann[2], R. Neu[2], U. Stroth[1]
and the ASDEX Upgrade Team[2]
[1] *Institut für Plasmaforschung, Universität Stuttgart, D-70569 Stuttgart, Germany*
[2] *Max-Planck-Institut für Plasmaphysik, EURATOM Association, D-85748 Garching, Germany*

Introduction

The improved H-mode in ASDEX Upgrade (AUG) is an ITER relevant operation regime with high confinement and densities near the Greenwald limit ($n_{GW} \propto I_p$, with I_p the plasma current). Since all plasma facing components were coated with tungsten, ECRH is needed to control tungsten accumulation [1]. To be effective, the ECRH power must be deposited in the plasma core ($\rho < 0.2$). This is typically fulfilled for the second harmonic X-mode at a frequency of 140 GHz and a magnetic field of 2.5 T. Under the constraint that the Greenwald density limit is close to the X2-mode cutoff ($1.2 \cdot 10^{20}$ m^{-3}) the operation regime in AUG is limited to plasma currents $\lesssim$ 1 MA. This in turn limits the safety factor q ($\propto B_\varphi/I_p$) to $q_{95} > 4$. There are two paths to circumvent this limitation and to achieve ITER relevant safety factors of $q_{95} \approx 3$. Both are related to non-standard ECRH scenarios in AUG: (i) Using O2-mode heating, the cutoff density is doubled and discharges at $q_{95} \approx 3$ near the Greenwald limit can be controlled by ECRH. (ii) The $q_{95} \approx 3$ can be realized at lower toroidal magnetic field B_φ, where the X3-mode can be used to heat the center. However, both heating scenarios suffer from reduced absorption of the wave.

O2-mode heating scenario

In the first scenario the low safety factor can be realized by high plasma currents $I_p > 1$ MA at $B = 2.5$ T. Due to the X2-mode cutoff the only possibility to heat the plasma is to use the second harmonic O-mode, which has twice the cutoff density of the X2-mode namely $2.5 \cdot 10^{20}$ m^{-3}.

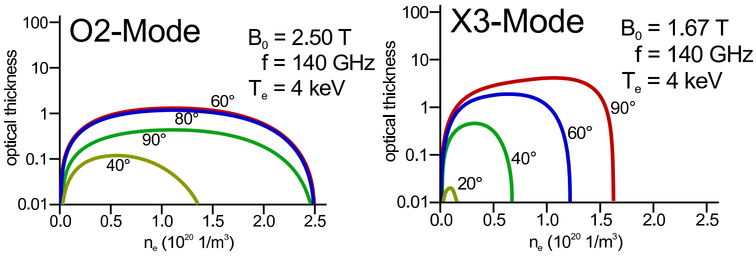

Figure 1: Angular dependence of the optical thicknesses of the O2- and X3-mode. [2, 3]

At temperatures of 4 keV the plasma is optically gray, which can be seen on the left hand side of Fig. 1 where the optical thickness of the O2-mode is plotted versus the density for different angles of injection. The absorption is incomplete, with a maximum at oblique injection at an angle $\measuredangle(\vec{k},\vec{B})$ of approximately 75°. In order to increase the absorption, a second pass of the microwave beam has to be accomplished. To achieve a well defined return beam, phase reconstructing mirrors were installed at the central column in AUG. Due to the small space between the plasma and the first wall, these mirrors have to be conformed to the inner wall of AUG. Thus holographic gratings must be used to realize the second pass. Two neighbouring tiles of the inner wall are combined to one holographic grating. For a correct second pass of the beam it is necessary to hit these tiles centrally. Then the second pass of the beams should aim to the upper passive stabilization loop (PSL) at the low field side, where no critical microwave absorbing materials are placed.

For the calculation of the holographic mirror the phases and angles of the incoming and outgoing beams on the neighbouring tiles have been calculated with the beam tracing code TORBEAM [4]. For a realistic heating scenario (central electron temperature: $T_e(0) = 3.2$ keV and density $n(0) \geq 1.2 \cdot 10^{20}$ m^{-3}) the absorption can be increased from 70 % single pass absorption, to 90 % with a 2nd pass of the beam.

With the results of the TORBEAM calculations it was possible to optimize the profiles of the grating with a boundary element method code [5]. To avoid possible erosion of small structures by the plasma, a trade off between smooth profiles and high efficiency had to be found. Also assembly limits reduce the efficiency of these profiles. We decided to use a 3rd-order holographic grating, which has an efficiency of $\gtrsim$ 90 % in TE and TM polarisations. The grating period and the height of the profiles are then $p \approx 5$ mm respectively $h \approx 3$ mm. The performance of the holographic mirrors could be demonstrated in resonator measurements, where one resonator mirror was replaced by a holographic mirror.

First high power measurements with a second pass of the heating beams are planned for this campaign. In order to monitor the location of the beam on the mirror, 4 thermocouples were installed at the edge of each mirror. This provides a feedback signal for the fast steerable launcher at ASDEX Upgrade.

X3-mode heating

Another way to decrease the safety factor is to reduce the toroidal magnetic field B_φ. Although close to the Greenwald limit, the density stays below cutoff, but now the X3-mode has to be used for central heating at a resonant magnetic field of $B = 1.67$ T. The disadvantage of the X3-mode is again incomplete absorption. The optical thicknesses of the O2-mode and the X3-mode are nearly the same (see Fig 1, right hand side).

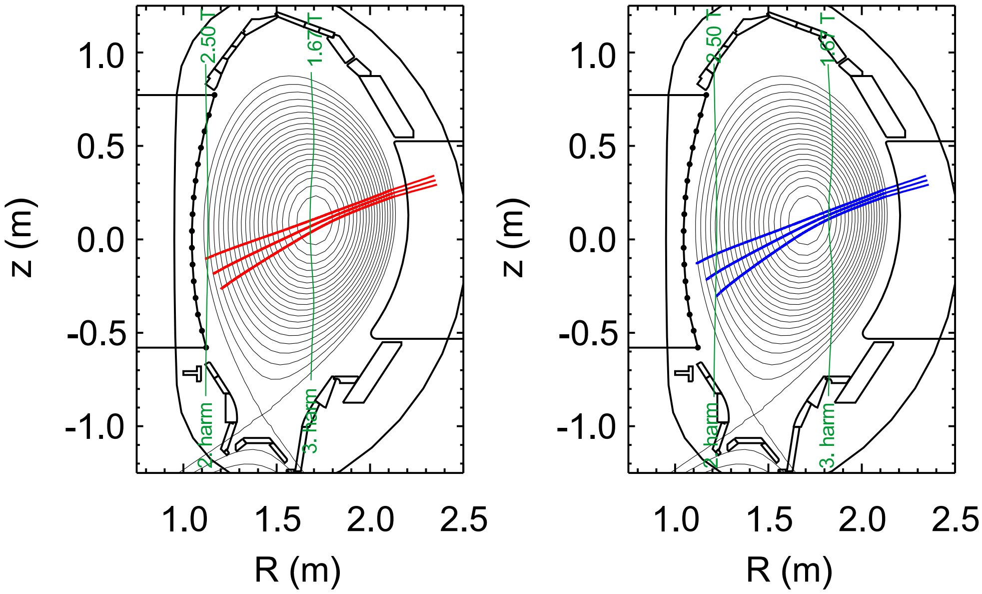

Figure 2: TORBEAM calculations for the X3-heating scenario at a magnetic field of 1.67 T (left, red) and 1.8 T (right, blue).

Figure 2 (left) shows a TORBEAM calculation for on-axis magnetic field of 1.67 T with realistic electron temperature and density profiles ($T_e(0) = 2$ keV; $n_e(0) = 1 \cdot 10^{20}$ m^{-3}). It can be seen, that the 2^{nd} harmonic resonance lies mostly outside the plasma. But if the magnetic field is raised to $B = 1.8$ T the 3^{rd} harmonic resonance is still in the plasma center ($\rho \approx 0.2$) while the X2-resonance is moved inside the plasma at the high field side (right hand side of Fig. 2). In this case the beam hits the X2-resonance and the non-absorbed power ($\approx$ 40 % of the injected power) is absorbed at the plasma edge and the X2-resonance acts as a beam dump.

The practicability of this approach could be demonstrated in experiments at $B = 1.67$ T and $B = 1.8$ T. The time traces of two otherwise identical discharges are plotted in Fig. 3. Only the magnetic field was changed from 1.67 T (red curves) to 1.8 T (blue), so safety factors of $q_{95} = 3.2$ and 3.4 were achieved at $I_p = 1$ MA and densities of $n_e \approx 1.1 \cdot 10^{20}$ m^{-3}. It is not understood yet why the temperature at the higher magnetic field is $\approx$ 1 keV higher than at the lower field. In the phase before the heating pulse the higher temperature points to better confinement in the

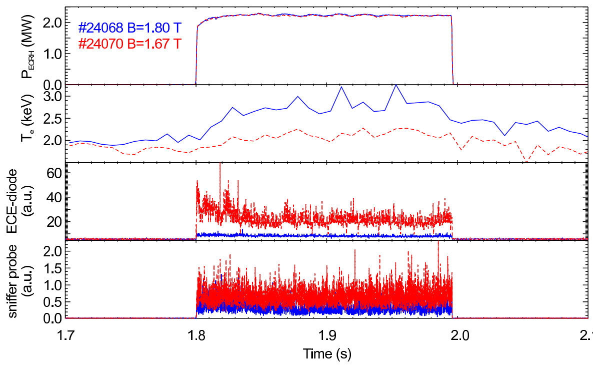

Figure 3: Discharges with X3-heating and B= 1.67 T (red, dashed) and 1.8 T (blue). From top to bottom: ECRH power, electron temperature, ECE-diode and sniffer probe.

high-field case. Higher temperatures cause a better absorption of the X3-mode and so the central temperature increases, leading to a positive feedback loop. In other words the ECRH generates itself a better absorption. The lower plots in Fig. 3 show the stray radiation of the non absorbed microwaves, measured with a diode, which is an interlock for the protection of the ECE diagnostic, and a sniffer probe [6], which is located at the launcher port and looks directly to the absorption region. It can be clearly seen, that the stray radiation for the higher magnetic field is much lower than that for the lower one. This is due to the higher temperature of the electrons and the X2-resonance which is inside the plasma at the higher magnetic field.

Summary

For ITER relevant discharges in AUG, two new heating scenarios were developed. Both are based on ECRH, which is used for tungsten accumulation control. With the O2-mode the X2-cutoff, which is reached for higher plasma currents, can be overcome. However a second pass of the non completely absorbed beam must be realized with holographic gratings. First high power measurements are planned in this campaign.

The same applies for the X3-mode scenario, where relevant parameters are achieved at $B = 1.67$ T. For the X3-mode heating scenario, first experiments could be carried out at magnetic fields of 1.8 T, where the X2-resonance acts as beam dump on the high field side. This scenario leads to complete absorption although the absorption in the core (at X3-resonance) is limited to 60 %. This could be demonstrated in experiments at AUG.

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