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Improved H-mode operation in fully W-coated ASDEX Upgrade – new demands for Electron Cyclotron Resonance Heating –

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Introduction

The improved H-mode scenario in ASDEX Upgrade refers to H-mode operation with normalised plasma pressure (β) and scaled energy confinement (H-factor) well above the values planed for the ITER standard H-mode scenario. This beneficial behaviour is connected to a specific evolution of the plasma current profile and the related MHD modes. Prior to the full coverage of the plasma facing components with tungsten in late 2006 this scenario was accessed over a wide range of $3.1 \leq q_{95} \leq 5.5$ [1]. Also for the fully W-coated unboronized device an operational window has been found with similar H-factors [2], but only with central ECRH added to the dominant NBI heating, as well as continous D_2 fueling to suppress the accumulation of W and the related plasma instability. As described in [2], ECRH has to be deposited inside $\rho_{tor} < 0.2$, resulting in an increase of the central transport, an effect still under study. Additionally, high power operation requires N_2 puffing, to control the divertor power-load in a range compatible with power limits of the W-coatings of the divertor tiles. The need of central ECRH and additional puffing of D_2 and N_2 narrows the operational range for improved H-mode significantly. Major aspects are discussed in the next sections together with possible solutions based on the exploration of ECRH schemes so far not used for improved H-mode operation in ASDEX Upgrade.

Suppession of sawteeth: counter-ECCD

In the full-W device strong sawteeth are observed during the high performance phase, in contrast to small (4,3) NTMs or fishbones observed prior to the full tungsten coverage. Their appearance must be related to a lower q on-axis, i.e. higher current density on-axis. The latter may be due to faster current penetration as a consequence of the additional gas puffing (lower T_e) or changes in the Z_{eff} profile, both under investigation. These strong sawteeth are known to trigger NTMs and to limit β. It is well known that ECCD can be used to suppress sawteeth [3,4,5], either as counter-ECCD in the plasma center or co-ECCD outside the q=1 surface. Since central EC heating is required to counteract W-accumulation, only counter-ECCD in the plasma center is an option. Making use of the flexible launching systems, the EC beams were injected with 20$\deg$ toroidal angle, driving about 40 kA on-axis counter-current. Figure 1 compares MHD-spectrograms for a reference case prior to full W coverage and two nitrogen seeded cases in the full W device, one with perpendicular ECRH and one with counter-ECCD as described above. In the latter case sawteeth disappear and the original (4,3)-NTM reappears.

Density and q_{95} limitation due to X2-cut-off: O2- and X3-heating

An operational limitation using 2nd harmonic X-mode ECRH is the cut-off density which equals to n_{GW} at 1 MA plasma current for the highest frequency (140 GHz). Central heating at this frequency requires $B_t \approx$ 2.5 T, resulting in $q_{95} =$ 4.6 for $\delta \approx 0.25$. q_{95} cannot be reduced significantly because higher currents increase the plasma density above the cut-off and lower magnetic fields require lower frequencies, which have lower cut-offs. The situation becomes even worse when aiming for higher values of the triangularity, resulting in higher density and higher q_{95} at constant current. There are two options to overcome this problem. One is the use of O2-heating, which doubles the cut-off density and therefore allows significantly higher currents. The other option is X3-heating at lower toroidal magnetic field. In the latter case the cut-off is increased by 33% and q_{95} drops linearly with B_t. Stationary flat top phases have been achieved with both scenarios in ASDEX Upgrade, with X3-heating q_{95} for type-I ELMy H-modes could thus be lowered to 3.3, experiments to raise the current by 10% to reach the ITER target of 3.0 are under way. Both schemes suffer from incomplete single pass absorption. The optical thickness increases as T_e^2. About 70% (O2) and 90% (X3) single pass absorption are calculated for 3 keV central electron temperature. This value of T_e is about the lower limit found for improved H-modes operation. For the handling of the non-absorbed power in case of O2-heating a W-coated reflector grating has been installed on the high field side, reflecting the wave in the right angle and keeping the polarisation to allow a second pass through the plasma center, thus doubling the optical thickness of the plasma. In case of X3-heating additional absorption on the X2 resonance on the high field side can be achieved if the toroidal field is tuned appropriately. For details on the O2 and X3 heating see [6]. Due to incomplete single-pass absorption, stray radiation has to be monitored and measures for machine safety have to be taken. A sniffer-probe [7] has been installed which has successfully been integrated into the safety system and two more are foreseen to get a good toroidal coverage. The inclusion of the probe has significantly improved the safety of ECRH operation. Cut-offs and poor absorption immediately switch off the ECRH power. Still, at 3 keV electron temperature, the non-absorbed part of the O2 heating did hardly show up on the sniffer probe mounted on the outboard midplane. A possible explanation is the conversion to X-mode by multiple reflections which subsequently can be absorbed along the resonance in the upper and lower parts of the elongated plasma where the density is below the X-mode cut-off. The high power density of the O-mode which hits the inner wall after the first pass has therefore to be monitored by other means. Thermocouples were integrated into the reflector plates and will be taken into operation soon. Additionally, measurements with an infrared camera are planned.

NTM suppression in combination with central ECRH

Experiments for NTM-suppression with ECCD have been pioneered on ASDEX Upgrade [8]. The dependence on the toroidal angle has been studied showing a maximum efficiency for a relatively small angle of 5 degrees [9] (***narrow ECCD***). For large angles ($>$15 degrees, ***wide ECCD***) the efficiency could be improved by modulation of the ECCD, heating only the O-point of the rotating island [10]. These effects could be related to the driven current density j_{ECCD}, which was maximum at 5 degrees, although the total driven current was larger at larger angles. This effect is strongly related to the injection geometry with absorption close to the mid plane on the high field side. In this case the flux surface is essentially vertical at the resonance over the whole beam cross-section. In such a geometry the deposition width in terms of ρ, i.e. perpendicular to the flux surface does hardly depend on the beam width. It is only determined by the optical thickness along the beam and is usually a few mm for perpendicular injection for an electron temperature of a few keV. On the high field side there are no trapped particles which is beneficial for ECCD, which also requires a parallel component of the beam with respect to the magnetic field. Due to the thermal spread of $v_{||}$, which enters the resonance condition at non-perpendicular launch, the deposition width perpendicular to the flux surface increases with the toroidal injection angle and the peak power density decreases. Decreasing peak power density and increasing ECCD efficiency result in the highest j_{ECCD} around 5 degrees.

As summarised in the introduction, in W-covered ASDEX Upgrade the resonance layer has to cross the $\rho_{tor} = 0.2$ surface to allow central heating (in principle the ASDEX Upgrade ECRH system is capable of multiple frequencies [11], but the cut-off problems are more severe for the lower frequencies). This means that the favourable scheme for NTM stabilisation on the high field side has to be abandoned. New schemes at the bottom or top of the respective resonant flux surface have to be developed, such that a fraction of the ECR system can be used for NTM stabilisation and another fraction for central heating. In preparation, effects of the launching geometry on j_{ECCD} have been analysed on the basis of a recent high beta discharge centrally heated by ECRH using the TORBEAM code [12] as shown in fig. 2. With the resonance of the high field side the narrow and wide current drive schemes can be reproduced. In case of a feedback controlled NTM mitigation using the fast steerable mirror as actuator as planned for ASDEX Upgrade (and ITER) the working point cannot be at the minimum value of ρ and therefore not at the mid plane of the plasma. For this reason also the current profiles for an upward and a downward tilted mirror angle are shown for 5 degrees toroidal angle (red and blue curves). This geometry variation changes the peak current density by a factor of 5, which would have been quite difficult for a control algorithm especially for limited ECCD power anyway. With the resonance in the plasma center, the maximum of the current density at low toroidal angles does not exist, since the flux surface is not vertical at the resonance. Several mirror positions are compared for a toroidal angle of 15 degrees. For a mirror located above the midplane it is beneficial to direct the beam to the upper part of the resonant flux surface. The maximum of j_{ECCD} is only about 30% of the narrow deposition on the high field side, but beneficial is the rather small variation of the current profile for the range of mirror movement expected for feedback control. First experiments with this scheme will start in autumn. They will finally allow to decide if modulated heating in the O-point has to become the standard for NTM stabilisation experiments in fully W-covered ASDEX Upgrade. Comparing the results from fig. 2 to earlier results suggests that cw-operation could still just be sufficient. We also note that the proposed deposition geometry with a central resonance is more similar to the foreseen geometry for NTM stabilisation in ITER.

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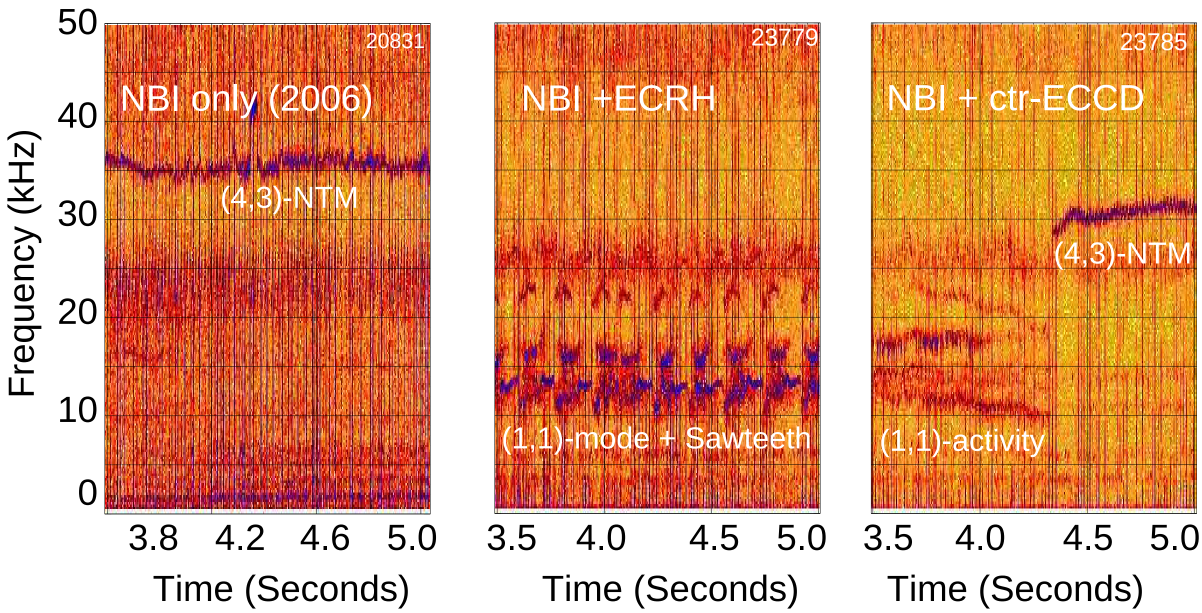

Figure 1: Spectrograms of H-modes using optimised early heating schemes for improved H-mode operation. All are at I_p =1MA, $B_t = 2.4 - 2.5$T, 7.5 MW NBI, similar shape. Left: prior to W-coverage of outboard limiters in main chamber, NBI only, no gas puff; middle: fully tungsten covered plasma facing components, D_2 and N_2 puffing as described in introduction, 1.6 MW perpendicular ECRH; right: as middle but EC beam inclined by 20 degrees toroidally delivering 40 kA of counter-ECCD on axis.

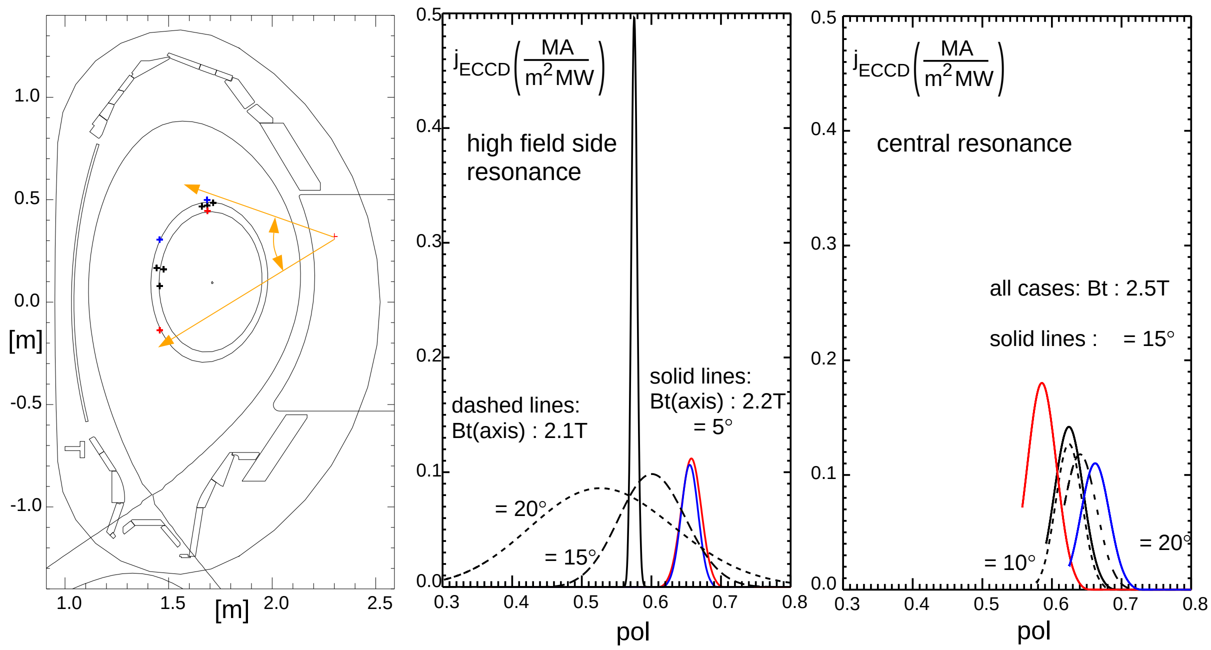

Figure 2: Beam tracing results for j_{ECCD} with the resonance on the high field side (B_t = 2.1 - 2.2 T, middle) and in the center (B_t = 2.5 T, right). On the left the position of the maxima is shown in the poloidal cross section of the torus, together with a sketch of the launching geometry. Kinetic and (scaled) magnetic data from discharge 24061 at 3.5 s (B_t = 2.5 T).