

Electron Cyclotron Resonance Heating in the Second Harmonic Ordinary Mode at ASDEX Upgrade

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Introduction

In the last years, the first wall of ASDEX Upgrade was changed from carbon to tungsten-coated carbon tiles in order to demonstrate the lower erosion and hydrogen co-deposition with tungsten. However, tungsten as high-Z material exhibits strong radiation at fusion relevant plasma parameters. In H-modes with good confinement and reduced gas puff at ASDEX Upgrade, the tungsten tends to accumulate in the plasma centre, eventually leading to a radiation collapse and the premature end of the discharge. Central electron cyclotron resonance heating was found to be a good candidate to reduce the tungsten concentration by changing the electron temperature gradient in the centre and increase the outward transport of the impurities [1, 2].

In the past, the usage of ECRH was limited due to the cutoff for central densities of $1.2 \cdot 10^{20} \text{ m}^{-3}$ of the typically used second harmonic extraordinary (X2) mode at 140 GHz for a magnetic field of 2.5 T. This limits the safety factors to $q_{95} > 4.5$ for high confinement discharges near the Greenwald limit ($n_{GW} \propto I_p$).

To enlarge the operational space of the ECRH to higher densities and lower safety factors, the polarisation can be changed to the ordinary mode (O2), having twice the cutoff density of the X2 mode.

O2-Mode Heating Scenario

At typical plasma parameter of ASDEX Upgrade ($n_e < 2 \cdot 10^{20} \text{ m}^{-3}$; $T_e < 5 \text{ keV}$) the O2 mode is afflicted with incomplete absorption; therefore the shine-through power and subsequent stray radiation can destroy components or diagnostics, which are sensitive on microwave radiation, like the electron cyclotron emission or the bolometer diagnostic at ASDEX Upgrade.

Therefore, a scenario was developed to increase the absorption of the O2 mode at ASDEX Upgrade in order to minimize the stray radiation and to maximize the central deposition ($r/a < 0.2$), having the possibility to control the tungsten concentration also in high density plasmas. A simulation with the beam-tracing code TORBEAM [3] for plasma parameters of $n_e(0) =$

$1.4 \cdot 10^{20} \text{ m}^{-3}$ and $T_e(0) = 3.5 \text{ keV}$ yields a single pass absorption of $\approx 70 \%$ [4]. This means that $\approx 30 \%$ are not absorbed, which is too high in the view of machine safety. However, with a second pass through the plasma centre an absorption of $> 90 \%$ can be achieved. Therefore two mirrors (for two 1 MW gyrotrons) at the central column of ASDEX Upgrade are needed. These mirrors have to be conformal to the wall, to avoid erosion by the plasma or disturbing the plasma. Simultaneously, the reflection has to be optimized for high absorption for the second pass in the plasma centre. These conditions are fulfilled for phase-reconstructing holographic reflectors, which were optimized for good efficiency in trade-off some manufacture limits [4].

Localisation of the Beam

To ensure the focusing of the beam on the holographic mirror, a new beam-localisation system was installed. The system is based on the Ohmic losses of the O2-mode beam on the surface of the tungsten coated holographic mirrors and the measurement of the resulting local temperature increase with NiCr-Ni thermocouples (diameter 0.25 mm and a few ms response time). In a first version with 4 thermocouples in each mirror the localisation possibility of system was tested on high power microwave and it was found, that a monitoring of the location of the beam on the surface (357 cm^2) is hardly possible with only 4 thermocouples [4]. Therefore the number of the thermocouples in the mirrors was enlarged to 8 per mirror (see also Fig. 1) in this campaign.

During the installation process, the thermocouples were tested on local heating of the holographic mirrors with a hot air gun and a similar response of the thermocouples was demonstrated. Unfortunately, after the mounting of mirrors at the inner column of ASDEX Upgrade and tests of the thermocouples on high power microwaves during plasma discharges, differences of the temperature response were observed. Such discrepancies can be caused by local variations of the Ohmic losses on the mirror surface or by small differences of the location of the thermocouple tip in respect to the mirror surface. For the next campaign the new version of the beam localisation system has to be tested additionally on local heating by strong microwaves.

Feedback Control Mechanism

In an O2-mode discharge in the 2009 campaign a non-expected density rise led to a change in the refraction index and to a movement of the beam to the bottom and finally out of the mirror, and therefore to the loss of the second absorption. Unfortunately, the bottom thermocouple was broken so we did not see the movement of the beam at all. The loss of 200 kW central ECRH (only one new gyrotron in O2-mode was available during this time) could have triggered a rising tungsten concentration leading finally to a radiation collapse [4].

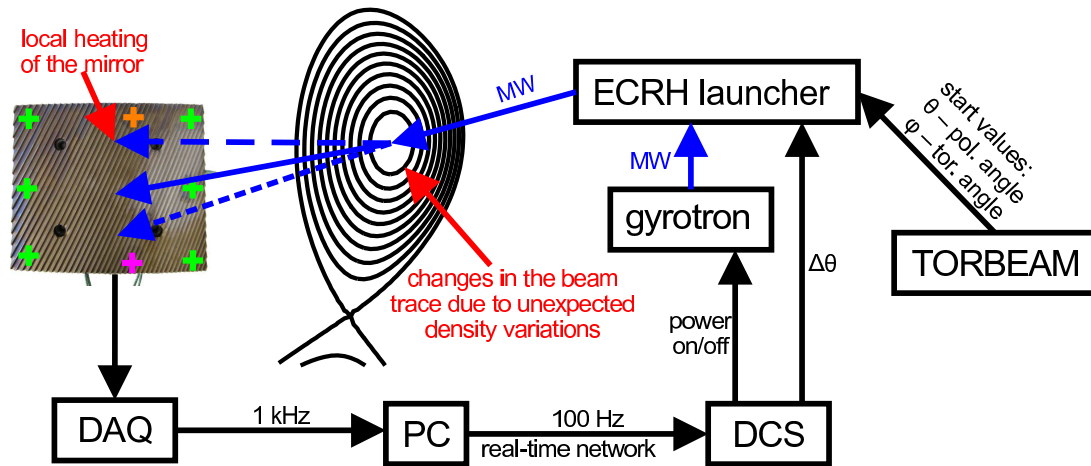


Figure 1: Circuit for the real-time feedback control of the O2-mode heating scenario.

Because of these results in 2009 a feedback control system based on the thermocouples was developed. In Fig. 1 the feedback circuit is sketched. With TORBEAM the poloidal and toroidal injection angles for central deposition and central hit of the O2-mode beam onto the holographic mirror at the expected plasma parameter and magnetic configuration are calculated offline and adjusted at the ECRH launcher. Density variations lead to a movement of the beam on the mirror during the discharge and to different temperatures on the mirror surface, which are measured with the thermocouples (green, violet and orange crosses in Fig. 1). The data acquisition (DAQ) transfers the measured data to a PC where the data are offset corrected, filtered and transmitted via the real-time network to the discharge control system (DCS). Here a controller calculates the new poloidal injection angle and transmits it to the launcher. A real-time toroidal angle adjustment is not possible with the ECRH launcher but luckily it is also not needed. This can be seen in Fig. 2, where the poloidal and toroidal injection angles, to center the beam onto the holographic mirror, were calculated with TORBEAM for a variation in the central density. The red and green curves belong to different density shapes (green peaked profile and red flat profile) and the blue curve to magnetic configuration with higher triangularity. It can be seen that the variation of the poloidal injection angle is much larger ($\Delta\theta \approx 6^\circ$) than that for the toroidal injection angle ($\Delta\phi \approx 0.7^\circ$).

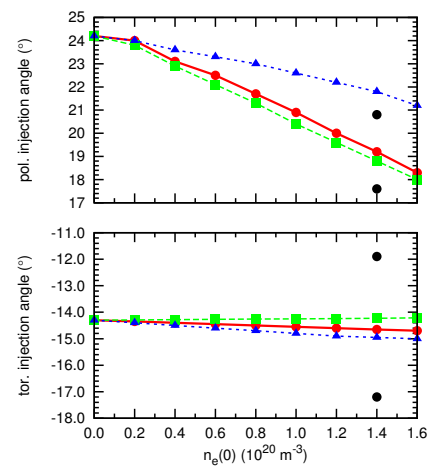


Figure 2: Poloidal and toroidal injection angle for central deposition and central hit of O2-mode beam onto the holographic mirror versus the central density.

The black dots in Fig. 2 show the poloidal ($\Delta\theta_{HM} \approx 3^\circ$) and toroidal ($\Delta\phi_{HM} \approx 5^\circ$) dimension of the holographic mirror for the flat profile with a central density of $1.4 \cdot 10^{20} \text{ m}^{-3}$. Therefore, it is sufficient to adjust the poloidal injection angle with the response of the thermocouples in the top (orange) and in the bottom (violet) of the holographic mirrors.

Additionally, an interlock is realized for all thermocouples (orange, violet and green crosses) if the temperature of the holographic mirror is getting too high during a discharge.

First Experiments with the Feedback Control

First tests with O2-mode injection during a feed-forward angle scan in a plasma discharge show a different response of the thermocouples on local heating. The bottom thermocouple of one holographic mirror shows a higher response to the local Ohmic losses of the beam than the top one, therefore the control algorithm has to be adjusted to the behaviour of each single thermocouple. In first tests of the response of the algorithm to a manually misaligned beam, the amplification factor and other control parameters were tuned until the feedback loop shows the expected behaviour.

Summary

In the 2009 campaign the first discharges with the O2 mode was demonstrated without the feedback algorithm [4]. Here the problem was the limited ECRH power and the loss of the second absorption due to density increase and the outwards movement of the beam off the holographic mirror.

The feedback control based on thermocouples in the holographic mirror is scheduled to react on these density changes. In first experiments, with a manually misaligned injection angle, the expected behaviour of the feedback algorithm could be demonstrated; also the interlock was tested successfully.

Heating experiments in discharges with high plasma current and a safety factor of $q_{95} = 3.5$ are planned at the end of this campaign.

References

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