Enhancing O-2 mode electron cyclotron heating capabilities at ASDEX Upgrade

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Introduction

The ASDEX Upgrade Tokamak has been equipped with a solid tungsten divertor, which allows to gain experience in operation under ITER-like heat loads [1]. Progress has been made in controlling high power ($P_{heat} \approx 20$ MW) discharges, where the power normalized to the major radius (R_0=1.65 m) is approaching ITER relevant values [2]. The potential threat from the accumulation of tungsten in the plasma center can be effectively avoided, if the central heating power density is high enough. In principal, the electron cyclotron resonance heating (ECRH) system [3] at ASDEX Upgrade (AUG) is able to fulfil this task, but it has to be operated in the O-2 mode, since the plasma density in these experiments usually exceeds the X-2 cut-off at the operating frequency f = 140 GHz. In the AUG case, O-2 mode single pass absorption is incomplete [4]. A second pass of the unabsorbed fraction, however, improves the situation significantly [5]. It is necessary to install reflectors into the heat shield on the central column inside the AUG vacuum vessel and to select a suitable beam dump.

Simulation set-up and scenario of the O-2 heating

An O-2 mode heating scheme exists for the two upper ECRH launchers (L5 and L6) in AUG segment no. 5, as described in [5]. There will be similar upgrades for the launchers L7 and L8 (figure 1). The simulation is based on the TORBEAM [6] beam tracing code and data from the AUG experiment #30505 at t= 3.3 sec with a total heating power of approx. 19.5 MW. This is considered a model high power discharge with partial detachment. In a similar process, an appropriate O-2 mode set-up will be added for the ECRH beamlines L1-L4, which are presently being upgraded towards higher power and longer pulse length [3].

In-vessel components

The plasma facing surface of the central column inside AUG is composed of tiles (figure 2) and the surface envelope is designed such, that leading edges are avoided. According to the simulation result, the reflector is large enough, if a double tile (approx. 210 x180 mm) is used.

It is possible to generate an efficient oblique reflection for a given wavelength and beam geometry, if an optimized grating [7] is machined into the mirror surface (figure 3). In addition, for each beamline a suitable beam dump has to be selected on the low field side. This is necessary in order to spread out the unabsorbed part of the beam after the second pass, which may typically contain 10% of the initial beam power. The cover plates of the lower PSL (figure 1) have a similar size as a double tile and they are considered robust enough.

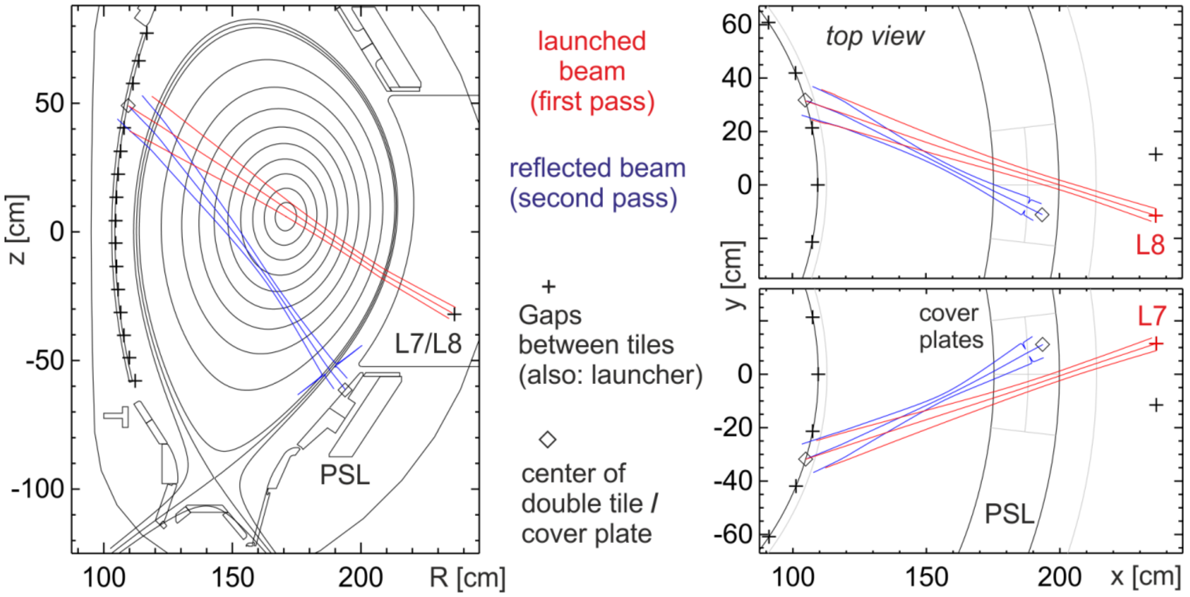


Fig 1: Simulation of O-2 mode heating via launcher L7 using a double pass. The cross section for L8 is similar, but slightly different. Solid cover plates mounted on the lower passive stabilisation loop (PSL) serve as beam dump. Model plasma is based on AUG #30505, t=3.3s. I_p= 1.2 MA, B_t= -2.48 T, central n_e= $1.15 \cdot 10^{20}$ m^{-3} and central T_e= 3.6 keV. Absorption estimates according to [6]: 1st pass 75%, 2nd pass 80%, giving a total of 95% of the launched power. The occurrence of a local peak in the simulated beam width is an artefact produced by insufficient smoothing in the experimental density profile, particularly in the pedestal region.

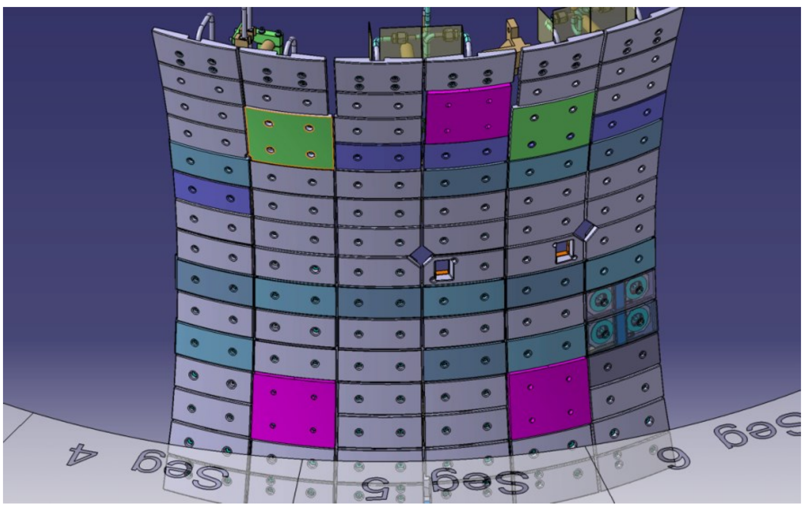


Fig 2: Heat shield tile structure in the AUG vessel segments 4-6, relevant for reflector mount. The lower double tiles in magenta are existing reflectors for launchers 5 and 6 [5]. The upper green double tiles are upgrades for launchers 7 and 8 and correspond to figure 1. The upper magenta tile is a reflector that was tested for measurement purposes.

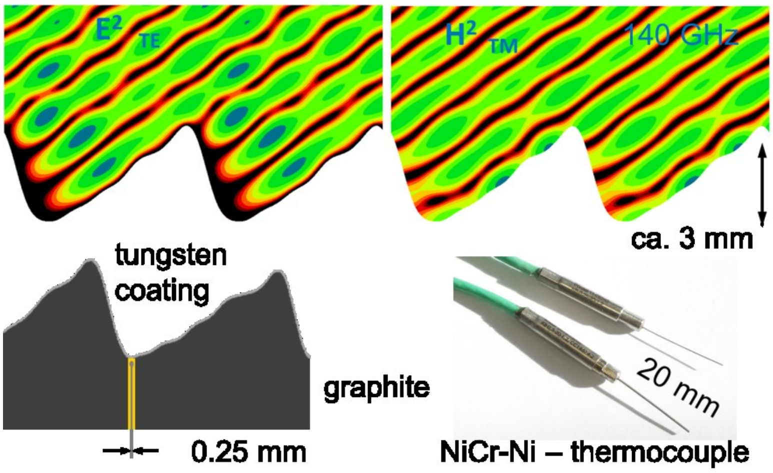


Fig 3: Exemplary mirror grating and contours of the millimetre wave amplitude squared [7]. This 3rd order grating (θ_{in} = 60°, θ_{out} = 50°) was optimised with respect to curvature and efficiency (TE/TM 0.89/0.969).

Fig 4: Thermocouple flush-mounted from the rear of the reflector tile.

Beam position control and machine protection

If the mm-wave beam overlaps with a gap between the tiles, part of it may penetrate and cause damage. The beam alignment on the reflector is, therefore, critical. Thermocouples built into the surface of the reflectors (figure 4) can be used to verify the beam position. In the past, pick-up waveguides were also tested. This was discontinued after the set-up was destroyed by the mechanical forces during a disruption. An overlapping design of the tile edges (figure 5) increases the shielding against mm-waves and reduces the risk of severe damage, if an error occurs. The shielding factor has been measured on a laboratory test mock-up and its worst-case value 0.036 or -14.4 dB (140 GHz) is considered sufficient for protection of vital parts.

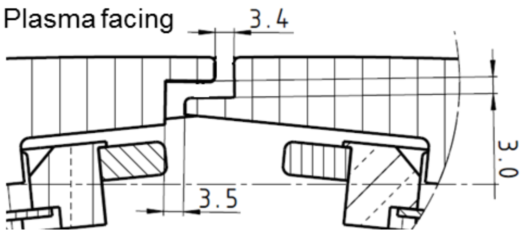


Fig 5: Edges of heat shield tiles have been redesigned with a labyrinth-like "dogleg" structure in order to increase the shielding against millimetre waves.

Operation experience

Launcher alignment can be accurately checked in vacuum, sweeping the beam over the thermocouple positions while the Gyrotron generates a pulse train with reduced microwave power (figure 6). During plasma operation it is found that the toroidal position of the beam on the reflector is very robust with respect to changes in the plasma configuration. The vertical position may change in particular with plasma density [5] and an automated feedback of the launch angle, depending on the thermocouple signals was tested successfully. In the harsh environment of high power plasma operation and under certain conditions, the thermocouple signals are, however, subject to cross-talk from the AUG ion cyclotron heating system. In this case video observation is helpful in order to detect arcs, which are ignited if the beam is crossing the tile edge (figure 7). Automated real-time video analysis is being developed and will be discussed elsewhere.

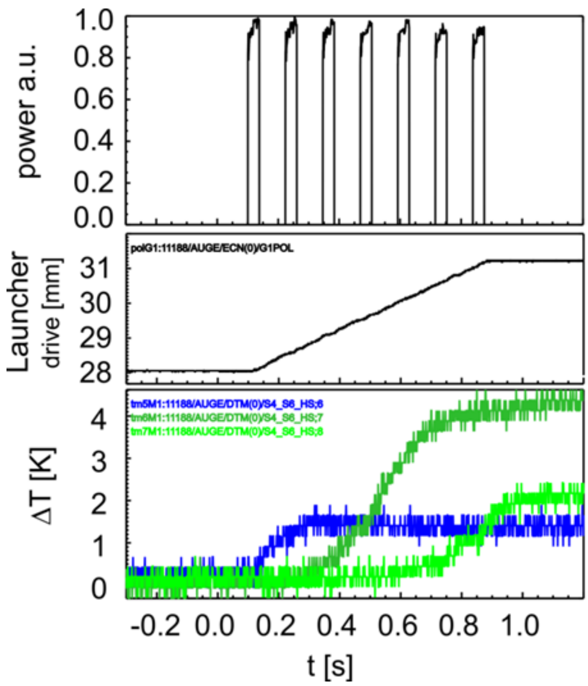


Fig 6: Beam alignment control, using a pulse train from the Gyrotron with reduced power (ca. 200 kW) and without plasma. The beam path is indicated on the photo inset below. The response of the thermocouples (lower left) follows the expectation

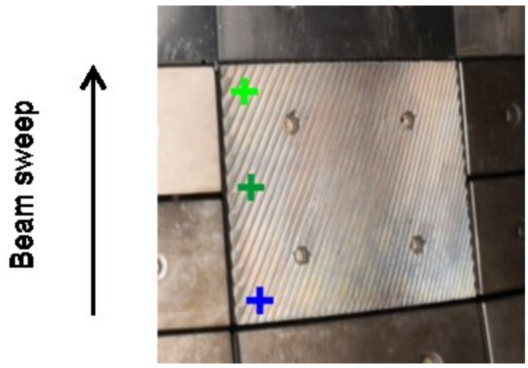
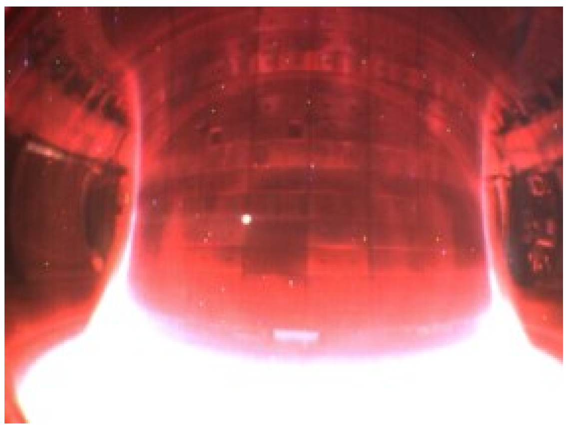


Fig 7 (right) Plasma operation with O-2 mode heating (AUG #32341 at t=2.579 s). One double tile reflector is visible in the center of this photo. For testing purposes, the beam launching angle was slowly swept during this experiment. At the time point where the photo is taken, the beam has an overlap with the upper left corner of the reflector. An arc is ignited at the tile gap, visible as a bright white spot.



Acknowledgement

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