Optimization of ECRH operation at high densities in Wendelstein 7-X

S. Marsen[1], K. J. Brunner[1], H.P. Laqua[1], D. Moseev[1], T. Stange[1], W7-X Team

[1] *Max-Planck-Institut für Plasmaphysik, Wendelsteinstraße 1, 17491 Greifswald, Germany*

Introduction

One of the major goals of Wendelstein 7-X is to achieve steady state operation (up to 30 min.) at plasma parameters relevant for a future fusion reactor. This includes operation at plasma pressures requiring a density above $10^{20}\mathrm{m}^{-3}$. The only steady state capable heating currently available is ECRH using high power gyrotrons. Wendelstein 7-X is equipped with 10 gyrotrons operating at 140 GHz providing up to 7.5 MW to the plasma vessel. The power is transmitted to the machine using a quasi optical transmission line where the polarization and launching angle can be remotely controlled by the central W7-X control system. Using second harmonic X-mode polarization (X2-mode) break down can easily be achieved with $B = 2.52$ T on axis and the launched power is nearly perfectly absorbed (>99%) over a wide range of plasma parameters. Here, the achievable density is limited by the X2-mode cut-off at $n_e = 1.2 \cdot 10^{20}\mathrm{m}^{-3}$. For higher densities O2-mode polarization is necessary where the single path absorption depends more sensitively on the plasma parameters and is typically in the order of 50...80 %. The overall heating efficiency can be increased by reflecting the non-absorbed beam fraction back through the axis. Such a scenario using three paths through the axis was developed for W7-X. Figure 1 shows the predicted beam trajectory for one gyrotron. The first wall in the shine through area of the ECRH is equipped with carbon tiles. For the three path scenario special holographic reflector tiles were designed to redirect the beam through the magnetic axis after the first path. These are coated with tungsten in order to cope with the relatively high shine through power in steady state. The carbon tiles absorb ≈ 3 % of incoming ECRH power. A shine through of 20 % of a 600 kW beam would lead to a peak heat load of 2.7 MWm^{-2} which is incompatible with the design of the heat shield cooling system. The absorption coefficient of Tungsten is only ≈ 0.3 % leading to a significantly reduced heat load on the tiles. The in vessel components of W7-X were designed to withstand a microwave stray radiation level corresponding to a total amount of 1 MW of non-absorbed ECRH power, i.e. an

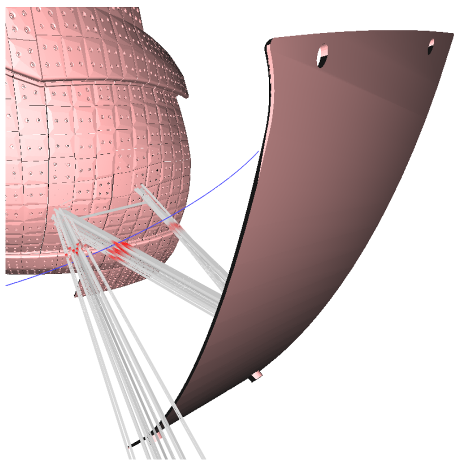


Figure 1: *Trajectory of an ECRH beam passing three times through the magnetic axis.*

overall absorption of > 90 % of the launched power by the plasma is requested. In a three path scenario this could be achieved with a single path absorption of 53 %. However, our aim for the first experimental campaigns of W7-X was to maximize the heating efficiency in O2-mode by optimizing the beam trajectories and polarization of each gyrotron.

O-mode heating scenarios

Plasma start-up in O2-mode is not possible because a target plasma with $T_e > 1$ keV is necessary to deposit enough energy to sustain a hot plasma. Therefore we use typically 3-4 gyrotrons in X2-mode to achieve break down and create a sufficiently hot and dense target plasma for O2-mode heating (① in fig. 2). O2-mode heating requires $B = 2.62$ T on axis in order to compensate a broadened absorption profile and the diamagnetic shift of the resonance at high β. 50 % more power is required for break down within the dead time of the plasma interlock system (50 ms) than at 2.52 T. After this start-up period the remaining gyrotrons in O2-mode take over the heating. While ramping up the density to the envisaged value, the polarization of the start up gyrotrons is changed to O2-mode ②. Eventually at maximum density the full power is available in O2-mode (③). Fig. 2 shows two O2-mode heated discharges from the last experimental campaign. These were He discharges with H2 pellet injection to reach densities close to or above the X2-mode cutoff. In the W7-X experiment No. 20171115.039 the X2-mode cutoff was exceeded as can be seen from the sudden drop of the ECE signal which measures X-mode radiation and is therefore blind for densities above the cutoff.

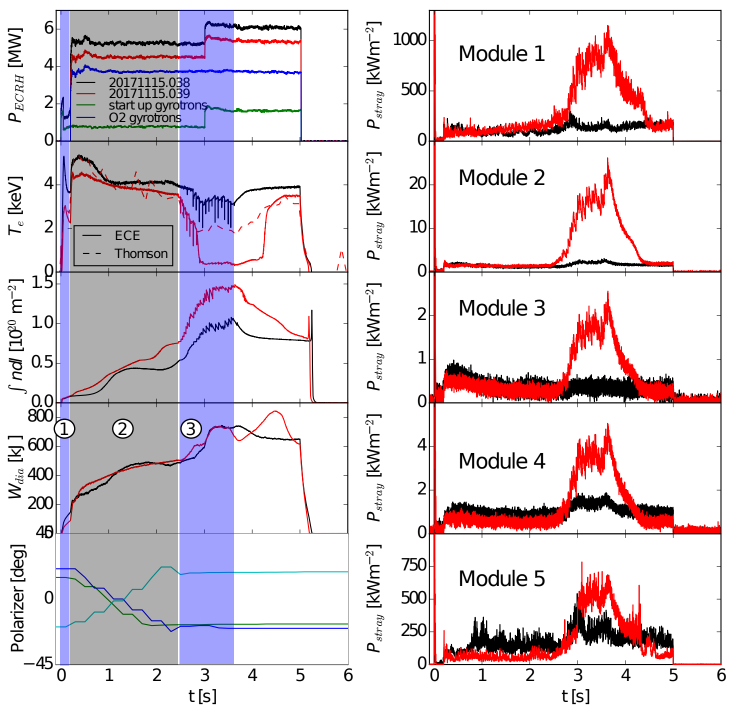


Figure 2: *Temporal evolution of O2-mode heated discharges with pellet injection. In # 20171115.039 the X2-mode cutoff density was exceeded.*

Stray radiation during high density O2-mode heating

One optimization criterion for the O2-mode heating scenario is the reduction of stray radiation to tolerable levels. The highest levels of stray radiation are expected in the proximity of the

ECRH launchers, gradually decreasing by more than an order of magnitude moving in toroidal direction to the most remote location. W7-X is build up of 5 modules in toroidal direction. The ECRH launchers are installed in module 1 and 5. Stray radiation is measured by so called sniffer probes which are installed in one port in each module. They provide a fast measurement of stray radiation.

The worst case in terms of stray radiation is operation above the X2-mode cutoff density where the X2-mode content of the stray radiation is not absorbed any more but only reflected back and forth between the plasma and the vessel. This can be clearly seen in fig. 2 where the cutoff was exceeded in exp. No. 20171115.039. During this phase a strong increase of stray radiation in all modules was observed as compared to # 20171115.038 where the cutoff was not reached. The max. stray radiation in modules 2,3 and 4, i.e. remote from the launchers, was 20 kWm^{-2} in module 2 at a heating power of 5.4 MW. Thus for the full available heating power of 7.5 MW a level safely below 50 kWm^{-2} is to be expected, which is the design criterion for all in vessel components in W7-X. Much higher levels up to 1000 kWm^{-2} were measured in modules 1 and 5. These values are unrealistically high to be interpreted as stray radiation. Due to the close proximity of the launchers the sniffer probes in modules 1 and 5 are affected by direct reflections of fractions of individual beams after a few reflections only. The impact of individual gyrotrons on P_{stray} in module 1 and 5 is shown in fig. 3 where during O2-mode heating at densities below the cutoff one gyrotron im module 5 tripped. P_{stray} in module 5 dropped by nearly a factor 3 in this case although the total heating power was only reduced by ≈ 10 %. The extremely high levels could also not be confirmed by independent measurements with ECRH bolometers measuring averaged stray radiation levels during a discharge. A bolometer in an empty diagnostic port in module 5 showed $< P_{stray} >= 22$ kWm^{-2} during over dense operation. Thus, the sniffer probe measurements are not representative for the stray radiation levels in module 1 and 5 but rather resemble local hot spots. Since the power densities measured by the sniffer probes are nevertheless real, the heating efficiency of each gyrotron needs to be optimized in the next experimental campaign OP1.2b. The single path absorption needs to be maximized by optimizing

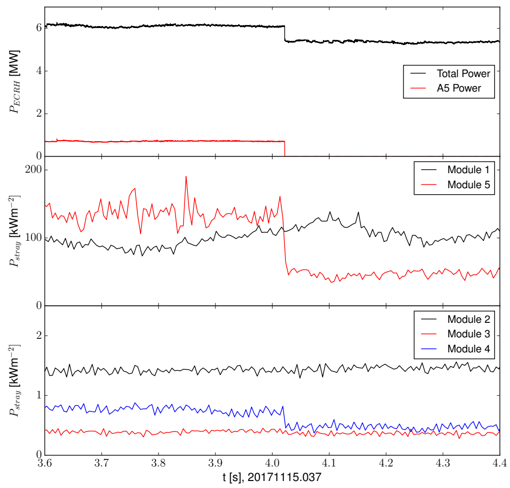
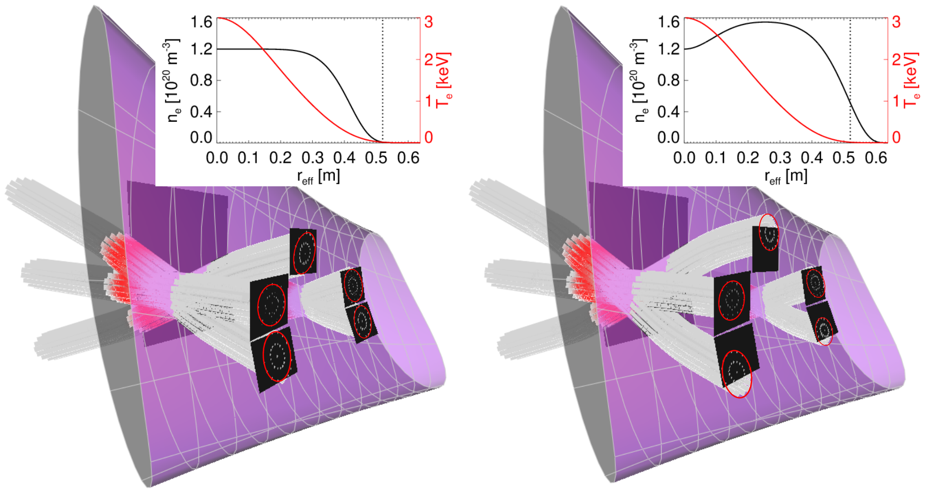


Figure 3: *Stray radiation in all modules during O2-mode heating at densities below the X-mode cutoff. At $t \approx 4s$ the gyrotron A5 tripped.*



(a) (b)

Figure 4: Beam trajectories from ray tracing calculations showing the intersection with the first wall for (a) a density profile just at and (b) a profile exceeding the X2-mode cutoff. Beam refraction at high densities is clearly visible.

the polarization of the launched beams. Also the beam trajectories need to be optimized for the first three paths to cross the magnetic axis.

Beam refraction at high densities

Operating at high densities causes a displacement of the shine through power on the first wall with respect to the target position in vacuum due to beam refraction. Fig. 4 shows beam trajectories predicted by ray tracing calculations assuming different density profiles. A displacement by about half a tile width ($\approx$ 5cm) is expected for these two cases. The optimized 3 path heating scenario in W7-X requires the beam to hit the reflector tiles centrally for optimum heating efficiency. Targeting at the reflector tiles during plasma start up causes the beams to hit the neighbouring carbon tiles at high densities. This was observed during the last campaign as shown in fig. 5. Since no feedback control of the ECRH launching angle is currently foreseen for steady state operation, the strategy to deal with beam refraction is to compensate the expected displacement by targeting at the neighbouring tiles during start up. Due to a lack of experimental time this optimization by feed forward compensation could only be exemplified during the last campaign, but will be done for all gyrotrons by measuring beam refraction for a wide parameter range.

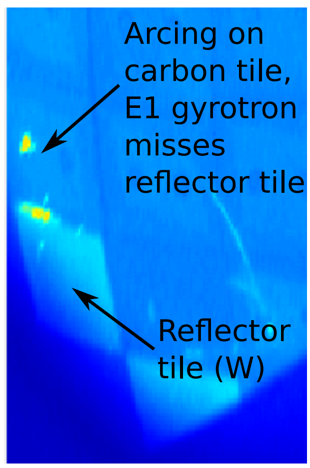


Figure 5: *Beam refraction observed during high density operation.*

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014 - 2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.