Performance of ECR heating during the first operational phase of W7-X

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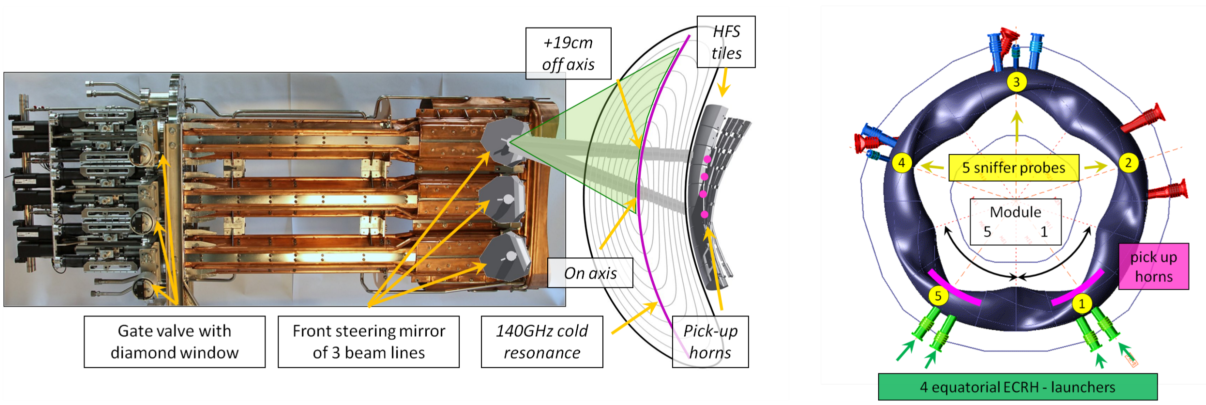
Wendelstein 7-X is an optimised stellarator designed for steady-state operation. The only steady-state capable heating system is electron cyclotron resonance heating (ECRH) launching microwaves at 140GHz into the vessel corresponding to the 2^{nd} harmonic of the electron cyclotron frequency at 2.5 T. A quasi optical transmission line is used to bring the power into the machine. The power is launched into the vessel by front steerable quasi-optical launchers from the low field side in X- or O-mode. Fig 1 (a) shows a photo of the launcher with respect to the vacuum flux surfaces. The launching angle can be varied both in toroidal as well as in poloidal direction allowing to run advanced heating scenarios like electron cyclotron current drive or off axis heating. During the first operational phase of W7-X (OP 1.1) 6 gyrotrons providing up to 4.3MW microwave power were available as the sole heating system. The total injected energy was limited to 4MJ in order to protect in vessel components, especially the five poloidal limiters, from overheating. For the next operational phases 4 additional gyrotrons will be brought into operation and the control system will be optimised aiming to provide 9MW port through heating power.

In this paper we present an overview of the plasma performance during OP 1.1 with respect to ECRH physics. A set of diagnostics is installed to characterise the efficiency of ECRH absorp-



(a) launcher (b) topview

Figure 1: (a) side view of the ECRH launcher with three beam lines with respect to the vacuum flux surfaces. (b) Top view of the plasma vessel showing the toroidal location of the launchers as well as the main ECRH related diagnostics.

tion. Small fundamental waveguide tubes embedded in the inner wall opposite the launchers directly pick up the unabsorbed power of individual gyrotrons after the first pass through the vessel (ECA diagnostic). Further on five stray radiation monitors, so called sniffer probes, are distributed toroidally around the vessel. The sniffer probes were absolutely calibrated before the start of OP 1.1 [1]. Fig 1 shows the toroidal location of the sniffer probes, the ECA diagnostic and the launchers.

Since ECRH was the only available heating system, it was also used to create the plasma. Start up times were analysed and optimised throughout the campaign in order to minimise the amount of unabsorbed energy. Both in He and H_2 typical start up times were $\approx$ 10ms or less when injecting a power of > 1MW, being somewhat lower in H_2 than in He. Fig. 2 shows an example of the start up phase in H_2 with $P = 1$MW. The stray radiation in all modules drops to a value corresponding to an absorption of $\eta_{pl}^{total} > 95\%$ within 10ms. Plasma build up, as seen from a measurable increase of the line integrated density as well as the central electron temperature, begins after $\approx$ 4ms. Increasing the power could not significantly decrease the start up time but would only increase the amount of unabsorbed energy.

In X2-mode a first pass absorption of more than $\eta_{pl}^{total} > 95\%$ was typically observed by the ECA diagnostic in agreement with the sniffer probes showing up to 98% overall absorbed power. Central power deposition was optimised by fine tuning of the magnetic field in order to achieve centrally peaked T_e profiles as measured by the Electron-Cyclotron-Emission (ECE) diagnostic [2]. The required magnetic field on the magnetic axis agreed with the theoretically predicted hot EC resonance by $\approx 99\%$. Fig. 2 shows plasma parameters for a pulse with optimum performance. Stationary conditions could be achieved in terms of density and temperature with central electron temperatures of $T_e = 7$keV at densities of $n_e \approx 4 \cdot 10^{19}\text{m}^{-3}$. The capability of ECRH to reach remarkable ion temperatures could already

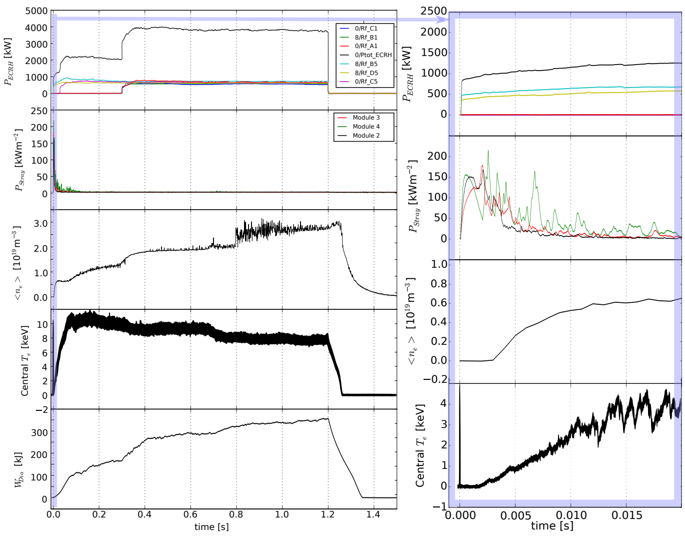


Figure 2: (left): Time traces of a high performance experiment in W7-X with 4MW heating power for 1s. Three density steps were achieved by puffing gas into the vessel during the discharge. (right) Zoom into the start up phase. Full absorption was achieved within $\approx$ 10ms

be demonstrated in OP 1.1. Using Ar as tracer impurity for X-ray measurements ion temperatures of up to $T_i \approx 2.1$keV were observed [3].

For these parameters ray tracing calculations predict a first pass absorption of ECRH in O2-mode of $\eta_{pl}^{1st} >\approx 70\%$. The predictions from ray tracing were experimentally confirmed using one gyrotron as low power diagnostic beam during an X2 heated plasma. The use of a low power beam was necessary in order to avoid arcing at the entrance of the ECA pickup antennas. Fig. 4 a shows the relative shine through of the O-mode power. The reference level of 100% shine through was determined by launching the beam before plasma breakdown where no absorption occurs. Throughout the pulse the shine through dropped to $< 50\%$ as predicted by ray tracing for the low T_e in this shot. The drop in T_e after $t = 60$ms was due a strong impurity influx and thus radiative losses which was regularly observed during OP 1.1 [4]. In order to achieve sufficient absorption ($\eta_{pl}^{total} > 90\%$) a multipath arrangement as shown in fig. 3 was chosen. Using plane graphite tiles on the high field side and curved stainless steel panels on the low field side as reflectors, the ECRH beam of 4 gyrotrons in O-mode could be directed through the plasma centre three times. In this scenario almost stationary plasma conditions with pure O2-mode heating could be achieved. As shown in fig. 4 b a target plasma was created using two gyrotrons in X-mode. After a short period of mixed O- and X-mode heating, the X-mode gyrotrons where switched off. In O-mode a central electron temperature of $T_e = 7$keV together with a line averaged density of $< n_e >= 2 \cdot 10^{19}\text{m}^{-3}$ was achieved. Although X-mode heating would still have been possible at this density (X2-cutoff density is $1.2 \cdot 10^{20}\text{m}^{-3}$), this experiment was an important proof of principle with respect to high density operation of W7-X in future campaigns. Apart from showing good plasma performance it could also be shown that safe long pulse operation is possible without the risk of overheating in vessel components by stray radiation. Stray radiation as measured by the sniffer probes in the neighbouring modules of launchers as well as by a microwave absorbing bolometer in an empty diagnostic port in module 5 showed levels of $P_{stray} < 10\text{kW/m}^{-2}$. The design value, which any in vessel component has to be designed for is $P_{stray} = 40\text{kW/m}^{-2}$. The multipath heating scenario will be optimised for the next campaigns by installing dedicated reflector

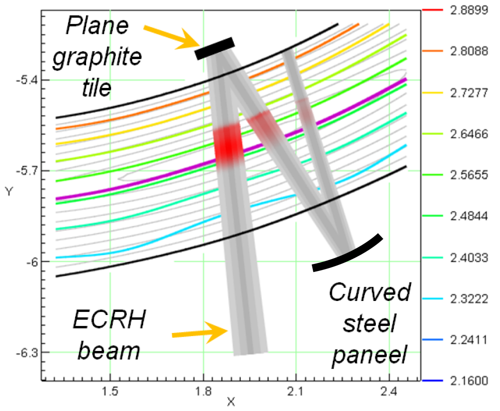
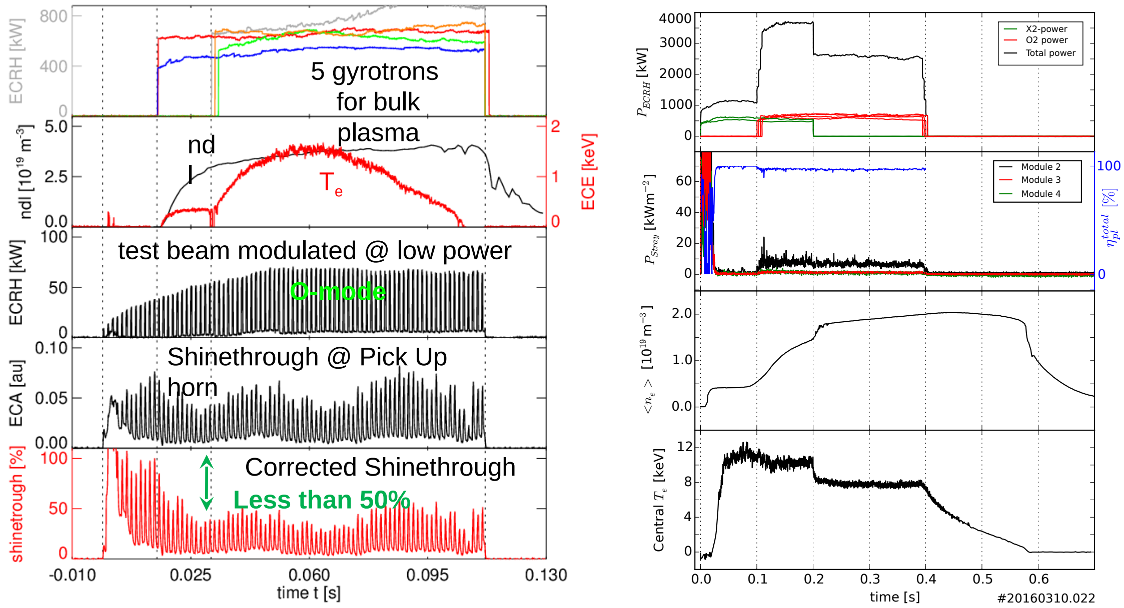


Figure 3: Cut through the equatorial plane at the ECRH launchers showing the arrangement of reflectors for a multipath heating scenario. The purple line indicates the resonance layer.



(a) First pass absorption

(b) O-mode heating

Figure 4: (a) Measurement of the direct shine through of a low power ECRH beam in O-mode on top of an X-mode heated plasma. (b) Performance of a pulse heated by O-mode only after creating a target plasma in X-mode

tiles made of a molybdenum alloy coated with Tungsten. In long pulse oparation graphite tiles in the shine through area of the first pass would likely overheat since graphite absorbs about $5\ldots10\%$ microwaves at 140GHz.

Summarizing the results from OP 1.1 ECRH proved to be a robust and reliable tool capable to produce and sustain high performance plasmas. The first results from O2-mode heating are promising with respect to the operation of Wendelstein 7-X at reactor relevant parameters, i.e. $n_e > 1\cdot10^{20}\mathrm{m}^{-3}$.

References

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