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High-performance ecrh at w7-x: experience and perspectives

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Abstract

The second operation phase of W7-X (OP1.2) showed the potential of exclusively electron cyclotron resonance heating (ECRH)-sustained plasma operations in stellarators. Employing multi-pass ECRH scenario in the second harmonic O-mode (O2-ECRH), stationary densities of up to 1.4×10^{20} m^{-3} could be achieved. This scenario also made stationary divertor detachment possible, which is a reactor-relevant scenario for power and particle exhaust. At high densities and with sufficiently high density gradients for an improved ion confinement, the coupling between the electrons and ions was strong enough to bring the ion temperature to values above 3 keV and to the neoclassical limit for some magnetic configurations, thus enabling to test the W7-X neoclassical optimization. The planned enhancement of the ECRH performance will enable to advance towards reactor-relevant beta values and to investigate their stability and confinement of fast particles, which is a priority goal of W7-X.

Keywords: ECRH, W7-X, stellarator, high performance, high density, detachment

(Some figures may appear in colour only in the online journal)

1. Introduction

W7-X is an optimized stellarator in which the otherwise strong neoclassical transport is reduced so that high confinement time values can be achieved. In particular this can be done with electron cyclotron resonance heating (ECRH) only, whereby only the electrons are heated directly, while the ion temperature is increased by electron ion collisions. Although it is expected that high ion temperatures will also be achieved by direct ion heating with NBI or ICRH, pure electron heating is a situation similar to that expected in a fusion reactor, where in a reactor it is the fusion alpha particles that transfer their energy to the electrons by slowing down collisions. This scenario can be simulated in W7-X with microwave heating of the electrons. However, it should be noted that although the fast alpha particles do not significantly interact with the thermic ions, they can have an influence on the ion confinement [1].

The superconducting coil system of W7-X generates a magnetic field strength of 2.5 T. This requires an ECRH frequency of 140 GHz, which corresponds to the second harmonic resonance of the electrons. Unfortunately, only the X2 mode is completely absorbed in the plasma at the resonance surface. However, the X2-mode can only propagate up to 1.2×10^{20} m^{-3}. The second harmonic O-mode, which has a cut-off density of 2.4×10^{20} m^{-3}, is incompletely absorbed in the single pass. On the other hand, the highest performance is expected at densities above 1×10^{20} m^{-3}, because of the

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[a] See Klinger *et al* 2019 (https://doi.org/10.1088/1741-4326/ab03a7) for the W7-X Team.

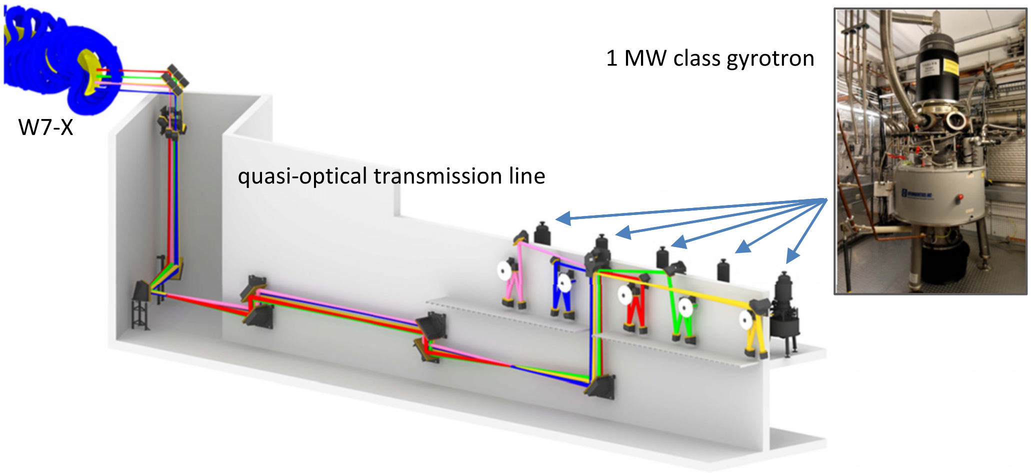

Figure 1. W7-X ECRH system. Here, one out of two models with five gyrotrons/beams is shown. The individual gyrotron beams, marked by different colours, are combined into a bundle and sent over a long distance with large common mirrors, the so called multi-beam section. They are divided into individual beams close to the vacuum vessel. Inside the vacuum vessel the beams are launched into the plasma by steerable mirrors.

positive confinement scaling and the increasing coupling between the electrons and ions with density. Therefore, a multi-pass ECRH scenario was developed so that an absorption of the O2 mode of more than 90% could be achieved. It should be noted that in a stellarator reactor a magnetic field strength of above 5T is expected. In that case the well absorbed first harmonic O-mode (O1) will be used. Here the full flexibility of the ECRH with respect of current drive and off-axis heating will be achieved and further optimization of the electron temperature profile as well as the iota profile will be possible.

The high performance high density scenario must also be compatible with a technically reasonable particle and energy exhaust. For this purpose, W7-X is equipped with a so-called island divertor, which separates the core plasma from the plasma wall interaction.

2. Experimetal set-up

W7-X has the world's largest microwave heating system for plasma generation at the moment [2]. The ECRH works at a frequency of 140 GHz. That is twice the resonance frequency of the electrons at a magnetic field strength of 2.5 T, the nominal magnetic field of the superconducting coil system. The ECRH consists of 10 microwave sources, the so-called gyrotrons, with a unit power of up to 1 MW and an operating time of 30 min, which is also the targeted W7-X plasma duration of 30 min in the final completion phase. The maximum total port through power was about 8 MW, but for higher reliability in longer discharges the gyrotrons were detuned to a total port through power of 6 MW. The main reason for power limitation was arcing in the transmission line due to a high air humidity during the experimental campaign in summer 2018. The 10 microwave beams are transmitted with a purely quasi-optical transmission line from the gyrotrons into the plasma over a distance of about 40 m with an efficiency of 95% as shown in figure 1. The transmission takes place with cooled mirrors and at atmospheric pressure. A diamond disc forms the interface to the plasma vessel. Inside the plasma vessel, the individual rays are radiated flexibly in both toroidal and poloidal direction into the plasma with the help of movable mirrors. The 140 GHz EC-wave with ordinary (O2) polarization gives access to densities beyond the cut-off limit (1.2×10^{20} m^{-3}) of the commonly used extra-ordinary (X2) polarized waves, but to the expense of incomplete single pass absorption for the W7-X plasma parameters. This disadvantage could be compensated by a special multi-pass scenario, where the partially (60%–70%) absorbed ECRH-beams were reflected by specially shaped tiles and passed three times through the plasma core with an overall absorption of up to 90%. The O2-operation scenario has been also routinely used for plasma operation below the X2 cutoff at densities above 0.8×10^{20} m^{-3} prohibiting the otherwise high risk of uncontrolled beam deflection in the X2-mode ECRH case. In order to keep the absorption high, the density was feed-back controlled in such a way that a central T_e was always kept above 2 keV. It should be noted, however, that the O2 process comes at the price of flexibility. Ray trajectories are fixed by the reflector tile positions.

Three high performance scenarios are reported here. In the first scenario, a stationary plasma at a density of 1.4×10^{20} m^{-3} with only 6 MW O2-ECRH was achieved. The electron and ion temperatures almost equalized each other. In the second scenario, the density was built up with the help of pellet injection, which lead to a temporarily peaked density profile with a strongly improved ion heat confinement. This scenario could not be explored towards steady state due to the limited number of available hydrogen ice pellets of the existing blower gun pellet injector. In the third scenario, the so-called detachment was demonstrated, in which the power flux to the divertor is strongly reduced.

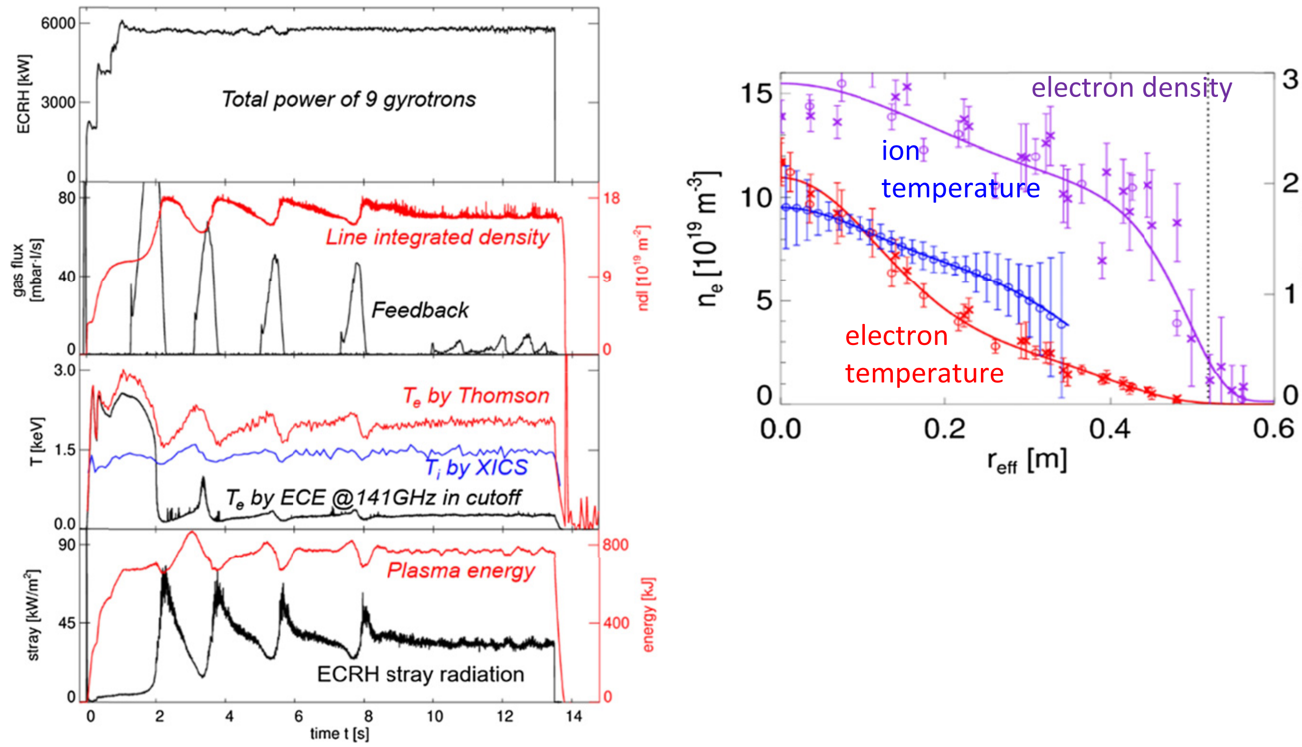

Figure 2. Left: time traces of a gas fuelled high density plasma with O2-ECRH only. Right: density and temperature profiles of the high density discharge.

3. Results

An outstanding result is the stationary operation with pure O2-ECRH at plasma densities of 1.4×10^{20} m^{-3}, which is clearly above the X2 cutoff density as shown in figure 2. Here the electron-ion coupling was so high that the ion temperature approached the values of the electrons. Unfortunately, the error bars of the x-ray spectroscopy were too high to carry out a precise profile analysis. The high density operation with the multi-pass O2-ECRH scenario showed an excellent plasma performance. However the maximum achieved temperature was limited the available heating power (6 MW for 15 s) and the respective transport parameters of the plasma scenarios. This scenario could be kept stationary and was only limited in time by of the maximum heating energy applicable to this W7-X operation phase with uncooled first wall elements.

A further benefit of the O2-ECRH scenario was its compatibility with high neutral pressure at the plasma edge. Even though after boronization of the W7-X wall no glow discharge cleaning has been performed, the density control was never lost and the high density operation was very robust. But on the other hand in the presence of high neutral fluxes, plasma radiation and charge exchange losses pushed down the edge temperatures as shown in figure 2. The neoclassical impurity transport in stellarators predicts an inward pinch and thus an impurity accumulation. Temperature gradient driven turbulence is counteracting here and thus in ECRH-plasmas with gas fuelling no accumulation has been found [3]. In particular the laser blow off experiments estimated impurity confinement time of the order of 70–80 ms which is far below the neoclassical confinement times of 2–10 s [4]. Even more in cases, where impurity accumulation has been found, like in the exclusively NBI-heated high density plasmas, additional O2-ECRH significantly flattened the otherwise peaked impurity profiles and pushed the impurities towards the plasma edge.

The achievable large density range enabled a combined operation with pellet injection without the risk of approaching the cut-off condition for the here pellet-induced peaked density profiles. After the pellet injection phase, the transport properties were improved for both ions and electrons and thus high plasma performance with high triple product values has been achieved [5]. Here the ion power flux approached the neoclassical value enabling to test the neoclassical transport optimization of W7-X [6]. In figure 3, the time traces of the pellet-fueled plasma discharge is shown. First of all, the plasma start-up had to be performed with the well-absorbed X2 mode. While the plasma density was then built up with gas fuelling, the polarization of the ECRH beams was changed from X-mode to O-mode. It should be noted that the polarization change can be performed during gyrotron operation. As long as the plasma density is below the X2 cutoff density both ECRH modes will be absorbed. Then the density was further increased with the aid of pellet injection and further ECRH beams were switched on. After the pellet injection, a peaked density profile was established which improved the ion confinement and increased both the ion temperature and the plasma energy (diamagnetic energy). There reason for the confinement improvement is the simultaneous stabilization of the ion temperature gradient (ITG) turbulence and the trapped electron mode (TEM) turbulence. This is a unique feature of

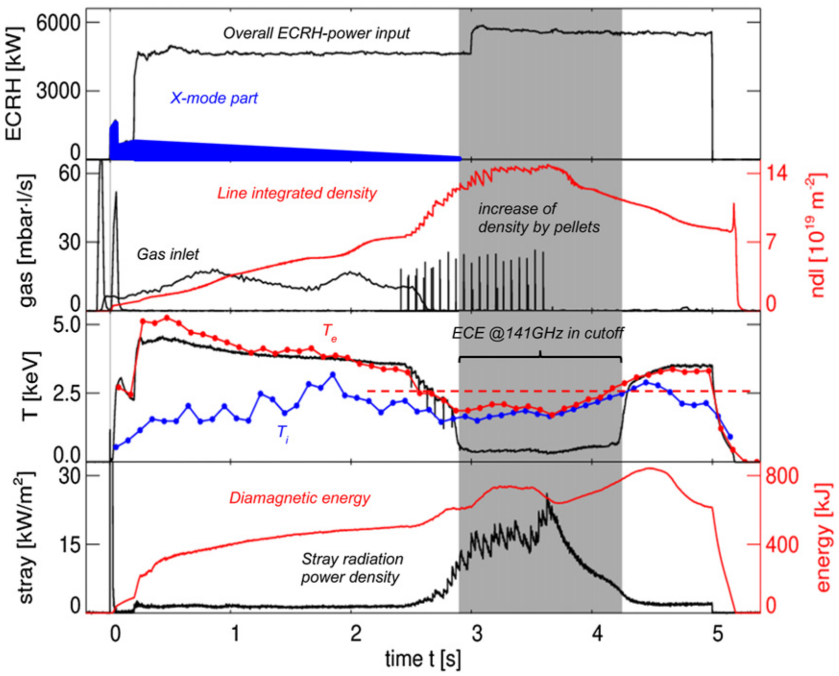

Figure 3. O2 ECRH scenario in combination with pellet injection (#20170904.015). For the plasma start-up three ECRH beams are polarized in X2-mode. During the density ramp their polarization is changed into O2-mode. The gray shaded area is the over-dense phase.

the W7-X configuration with a 'stability valley' for both ITGs and TEMs [7].

Unfortunately, in this experimental campaign W7-X was insufficiently equipped to control the density gradient. This requires a controlled pellet injection for the central fuelling and a high neutral gas pumping capability for a low neutral gas pressure at the edge.

A general challenge of nuclear fusion with magnetic confinement is the power and particle exhaust. The advantage of the particle motion guided by field lines in magnetic confinement turns into a challenge when the power and the particles come into contact with the walls. Here the flux concentrated on the magnetic field lines leads to power densities that are technically difficult to control. The low shear concept of the W7-X has an advantage here, because it has long (>100 m) connection lengths between the last closed flux surface and the divertor target. Due to the different magnetic geometry and the much longer connection length compared to tokamak divertors, the W7-X stellerator detachment differs fundamentally from that in tokamaks. A detailed description can be found in [8]. Nevertheless, the detachment at the W7-X is also characterized by a strong reduction of the power flux on the divertor surface.

With its the help, steady state conditions could also be achieved for the uncooled test divertor of W7-X. Although the peak densities in the detachment experiments were just below the X2 cutoff density, the plasma had to be heated with the O2 mode in order to avoid the risk of uncontrolled ECRH X2 beam deflection so close to the X2-cutoff. In the experiment shown in figure 4 the transition to detachment was reached at 3 s and the radiated power approached the heating power. The power flux on the divertor was reduced from 3.5 MW m^{-2} to 0.4 MW m^{-2}. This state could be kept stable for 26 s [9]. The plasma was terminated regularly and no components had been at their power load limit.

4. Outlook

For the next operation campaign an upgrade of the available ECRH power to 10 MW and more efficient multi-pass reflector tiles are planned. In particular a new more powerful (1.5 MW) gyrotron is being developed now and an increase of the number of gyrotrons and beamlines from 10 to 12 is envisaged. The development strategy for the new gyrotron is to largely retain the successful basic W7-X gyrotron design and only to increase the operating mode from TE28.8 to TE28.10 in order to increase the cavity diameter and thus to keep the power load density at the cavity surface below the critical level of 20 MW m^{-2}. Keeping the azimuthal mode unchanged allowed to use the same electron optics as for the 1 MW class W7-X gyrotrons. Therefore the new 1.5 MW class gyrotron is fully compatible with the W7-X installation, in particular with the gyrotron magnet, and outdated gyrotrons can easily be replaced by new more powerful gyrotrons. Inside the new gyrotron only cavity and the microwave optics are adjusted accordingly. The beam current is increased from 40 to 60 A. In experiments at KIT with an uncooled short-pulse gyrotron with the same TE28.10 microwave system, 1.5 MW output power was achieved and thus the gyrotron concept has been successfully confirmed [10]. The 1.5 MW power cw gyrotron is currently being built by the Thales company and expected for November 2021 [11].

In addition the maximum power capability of the in-air quasi-optical transmission line is being enhanced with a powerful air drying system which brings down the relative

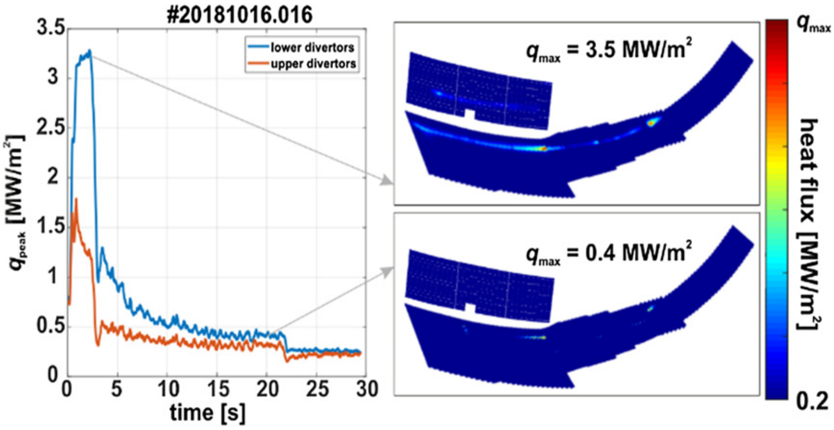

Figure 4. Left: time traces of the maximum heat flux at the divertor tile. Right: IR-picture of the divertor for attachment and detachment. Reproduced from [9].

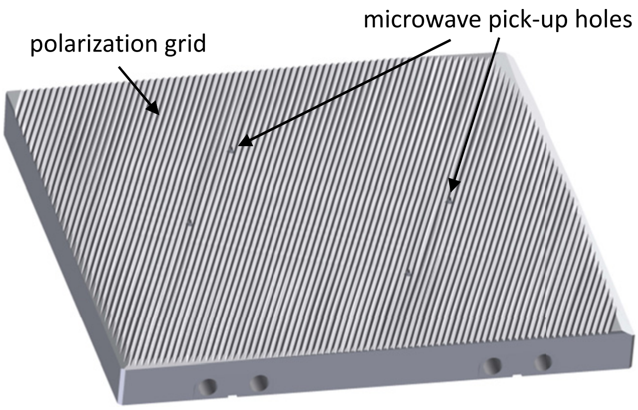

Figure 5. Tungsten covered TZM reflector tile with prolarization grating on top.

humidity below 20% at 20°c. Here a high microwave power transmission test has been performed in 2020 where the successful transmission of a 0.9 MW beam for 2 min through the whole in air section of the transmission line has been demonstrated. Since here the maximum power was limited by the maximum gyrotron out-put power only, we expect a further margin enabling the transmission of the 1.5 MW beam.

A detailed analyses of the absorption and losses with the O2-mode for all 10 ECRH beams in the experiments enabled further optimization of the reflector tiles. The new reflector will also correct the polarization of the reflected beam, such that the O-mode polarization is maintained as shown in figure 5. Thus in the next campaign an overall absorption of 95% is envisaged. This is at first glance a small improvement. But it will reduce the none-absorbed ECRH stray radiation by 50%, which is a remarkable step forward for prospective future steady state operation, since the microwave stray radiation gives an additional load to all W7-X components even if they are outside a line of sight to the plasma [12].

The multi-reflection system can also be used for efficient plasma heating with the third harmonic X-mode at the magnetic field strength of 1.7T, thus opening a new operation point for W7-X. In particular with reduced magnetic field a higher relative plasma pressure (beta) can be achieved with same heating power compared to the nominal operation at 2.5 T. Plasma performance enhancement is also expected by an improved edge neutral density control with powerful cryo pumps in the divertor pumping gap and gas valves in the divertor region. In addition a steady state pellet injector will be installed as a US contribution to W7-X. It will enable continuous core fuelling at low neutral edge density. This injector is a prototype of the US ITER pellet injector.

Four microwave pickup holes are connected to waveguides the back of the tile, which measure the position, power and polarization of the incoming beam.

5. Summary

In the W7-X operation phase 1.2, a routine high-density operation with O2 ECRH could be established. The O2-ECRH made it possible to achieve high performance plasma scenarios in various aspects. Stationary gas puff fuelled discharges of high densities were achieved, where the electron and ion temperatures were equalized due to the high collision frequency. The good heating efficiency at high densities also made it possible to use hydrogen ice pellet injection with which the density gradients were increased with a strongly beneficial effect on the confinement. Finally, the stationary high-density operation also enabled to reach the detachment at the plasma edge, which strongly reduced the thermal load on the divertor plates and thus represents a possible scenario for safe long-pulse operation. For the next phase of operation for W7-X (OP2), in addition to the installation of water-cooled first wall and divertor components, further upgrades of the active components are also planned. The ECRH power will be increased by two more gyrotron positions and new, more powerful gyrotrons. The continuous-wave pellet injector and the high-performance cryo-pumps should, among other things, enable the density profile control for scenario optimization.

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