

PROGRESS WITH COMMISSIONING THE ICRH SYSTEM FOR THE LARGE OPTIMIZED STELLARATOR WENDELSTEIN 7-X

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Abstract

An important objective of W7-X is to demonstrate fast-ion confinement at volume-averaged beta values of up to 5%, corresponding to plasma densities exceeding 10^{20} m^{-3} . To achieve this, an ICRH system has been installed at W7-X, capable of delivering up to ~ 1.5 MW of RF power (depending on the coupling) in the frequency range of 25–38 MHz, with pulse lengths of up to 10 s. Energetic ions in the 50–100 keV range, characterized by a significant velocity component perpendicular to the magnetic field lines, generated through ICRH, are crucial for testing the confinement properties of W7-X. However, producing such a population in high-density plasmas is challenging when relying on conventional ICRH heating scenarios or other auxiliary heating methods. A promising option is the ^4He -(^3He)-H three-ion heating scenario at 25 MHz in W7-X, which can efficiently generate fast particles under these demanding conditions. In future D operations on W7-X, the equivalent D-(^3He)-H scenario can also be used. A two-strap ICRH antenna was developed in a collaboration between the TEC partners in Belgium, LPP-ERM/KMS and the institutes in Germany IFN-1, and ITE of the Research Centre in Jülich and was installed in W7-X during 2021–2022. This paper reports on the experimental results obtained with this system during the experimental campaigns OP2.2 (2024) and OP2.3 (2025) on W7-X.

1. INTRODUCTION

The superconducting stellarator Wendelstein 7-X (W7-X), located at the Max Planck Institute for Plasma Physics in Greifswald, entered operation in 2015 and is the world's largest advanced stellarator. One of its central goals is to demonstrate the confinement of fast ions at volume-averaged beta values of up to 5% - a key optimization criterion during its design [1]. This corresponds to plasma densities exceeding 10^{20} m^{-3} .

In its final stage, W7-X is designed to sustain plasma discharges lasting up to 30 minutes, enabled by steady-state superconducting magnets and an advanced heating system. The main heating method is electron cyclotron resonance heating (ECRH), currently installed with 10 MW of power at 140 GHz, capable of operation for the full 30 minutes. Complementing this, a neutral beam injection (NBI) system provides up to 7 MW of heating in hydrogen, with acceleration voltages up to 55 kV and pulse durations of up to 5 s. W7-X operates at a nominal magnetic field strength of 2.5 T.

Since its first plasma in 2015, W7-X has carried out a series of experimental campaigns that have progressively expanded its operational envelope and physics achievements. Important results have been obtained in OP1.1 [1], OP1.2a [2], and OP2.1 [3], laying the foundation for more advanced studies. The more recent campaigns, OP2.2 and OP2.3 [4], have built on this progress, demonstrating the capability of W7-X to explore high-performance plasma scenarios.

To replicate the behaviour of alpha particles in a future stellarator reactor, it is necessary to create a population of fast ions with energies with a large perpendicular velocity component to the main magnetic field in the range of 80–100 keV in the core of high-density W7-X plasmas [5]. Generating such a population is challenging, but it can be achieved with ion cyclotron resonance heating (ICRH). This can be achieved using 37.5 MHz fundamental heating of hydrogen, second-harmonic heating of deuterium, or the three-ion heating scheme ^4He -(^3He)-H (or equivalently D-(^3He)-H in future campaigns with deuterium [6]) at MHz. A key advantage of ICRH is its insensitivity to high-density cutoffs, a property that allows to deposit RF power directly in the plasma core, even at the highest densities foreseen for W7-X. Other aims of the ICRH system are ICRH wall conditioning and plasma startup at low magnetic field. In recent campaigns we demonstrated the principal possibility of those aims and we will document these below.

2. ICRH FOR WENDELSTEIN 7-X

2.1. Overview of the ICRH Antenna system

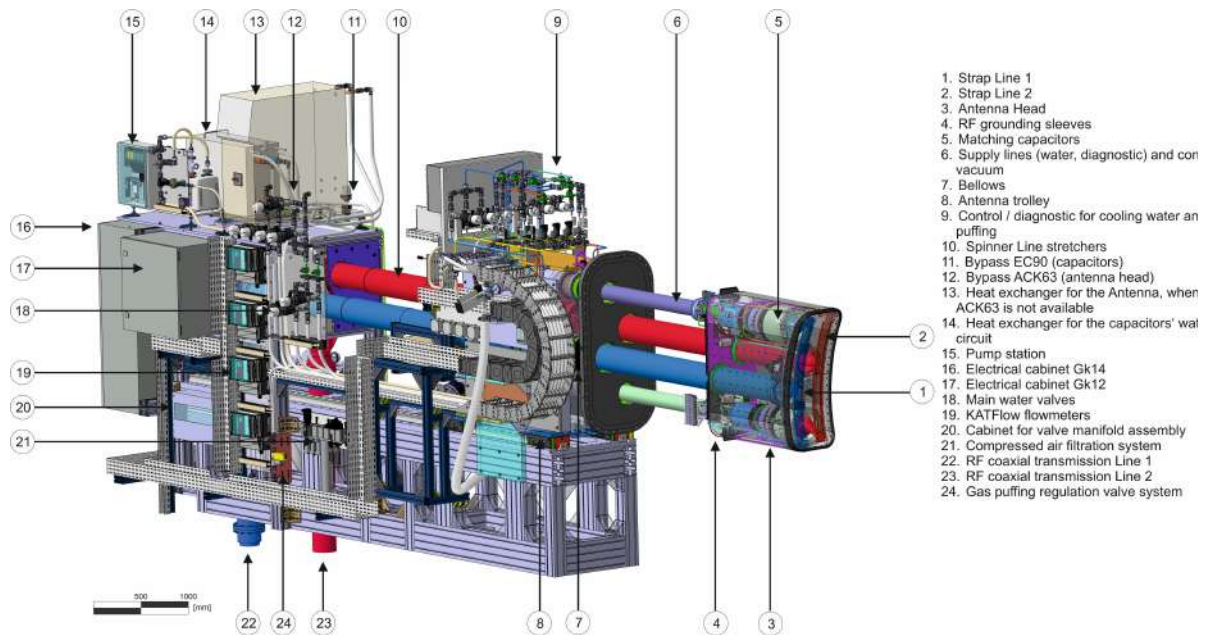


Fig. 1: Overview of the ICRH antenna system for W7-X with its main components.

The ICRH system for W7-X has been designed and constructed during the past years in an intense collaboration between the Laboratory for Plasma Physics of the Royal Military Academy (LPP-ERM/KMS), the Institute for Nuclear Fusion and Nuclear Waste Management (INF-1) under the Trilateral Euregio Cluster (TEC) umbrella, the Central Institute for Technology and Engineering (ITE) of the Research Centre in Jülich, Germany together with the Max Planck Institute for Plasma Physics in Greifswald, Germany [7, 8]. The final ICRH system is designed to deliver up to about 1.5 MW of RF power (depending on the density profile in front of the antenna) with pulse lengths up to 10 s [9] in the frequency range 25-38 MHz.

The system was first commissioned on W7-X plasmas in operational campaign OP2.1, where we demonstrated successfully the two main milestones: launching over 500 kW of RF power and assisted plasma breakdown using ICRH only. In the following campaigns OP2.2 and OP2.3 we also demonstrated for the first time fast particle generation using the ^4He -(^3He)-H 3-ion scenario [6].

The complete ICRH system consists of the antenna head mounted on a moveable trolley in the torus hall (Fig. 1), the two RF generators outside the torus hall, and the 96 m long transmission lines together with the matching system that connects the RF generators to the equipment in the torus hall. The antenna consists of two poloidal current straps, each connected to a tuning capacitor on one side, grounded to the antenna box at the other end, and fed near the centre, allowing a prematching of the antenna. Strap width and length and the antenna box depth have been optimized to maximise the power delivered to the plasma.

The shape of the antenna is carefully matched to the 3D shape of the Last Closed Magnetic Surface (LCMS) of the standard magnetic field configuration on W7-X [10], resulting in a variable curvature in toroidal and poloidal direction over the surface of the antenna. The antenna can be moved radially over max. 35 cm (with a speed ≤ 4 mm/s), to be able to position it as close as possible to various possible magnetic configurations in W7-X. In addition, to optimize coupling over the strap surface to magnetic scenarios where the LCMS has a different shape than that of the standard configuration, gas can be puffed through outlets in the limiter of the antenna. A reflectometer system with two horn antennas is included in the antenna head to measure the density profile in front of the antenna, and has been used to successfully monitor the shape of the plasma density profile in front of the antenna, as will also be shown below.

2. FIRST EXPERIMENTAL RESULTS WITH THE ICRH ANTENNA ON W7-X PLASMAS

The ICRH antenna system was installed in W7-X in August 2021, and commissioning of the full system, including safety tests, was successfully completed in time for operation during OP2.1. First experiments were conducted in February and March 2023. Due to a fault in one of the pre-matching capacitors, which developed during transport between FZ-Jülich and IPP-Greifswald, only one of the two antenna straps could be powered. In these campaigns, the antenna was operated exclusively at 37.5 MHz.

Remarkably, despite the limitations of single-strap operation ($k_{\parallel} \approx 0$), high-power performance of up to 500 kW was achieved within just the first hours of operation. This set a world record for the shortest time to deliver high ICRH power from a newly installed antenna—and notably, in a stellarator—without encountering limits on RF voltages or currents.

Furthermore, although the antenna was operated without a Faraday screen (following extensive TEXTOR experience [11]), operations were smooth and impurity levels remained low. After this campaign, the antenna was removed from the W7-X vessel with minimal wear or impact to auxiliary components.

The faulty capacitor was repaired during the shutdown preceding OP2.2 and OP2.3, enabling full two-strap operation for the first time. This allowed experimental studies with both dipole and monopole configurations, with the antenna powered up to ~ 0.5 MW in ~ 2 s pulses and up to 450 kW in pulses up to 6 s. Large outgassing was initially observed at the start of the campaign; to prevent deconditioning between operational days, the antenna was maintained at ~ 80 °C. This avoided further outgassing effects, resulting in a reliable operation on W7-X plasmas of the two-strap antenna. Following an event now attributed to an arc or glow discharge between the high-voltage side of Strap 1 and the (grounded) antenna box, Strap 1 was excluded from further operations, and the antenna was subsequently operated in a monopole configuration using Strap 2 for the remainder of campaign

OP2.3. The damage caused by this event is now under repair, and both straps will be slightly shortened on the high-voltage side to prevent a recurrence of similar issues. The reflectometer integrated into the antenna box was successfully commissioned and now routinely provides plasma density profiles in front of the antenna, needed for detailed studies of coupling and power deposition characteristics.

2.2.1 DEMONSTRATION OF HIGH-POWER ICRH OPERATION UNDER LONG-PULSE AND MODULATED CONDITIONS

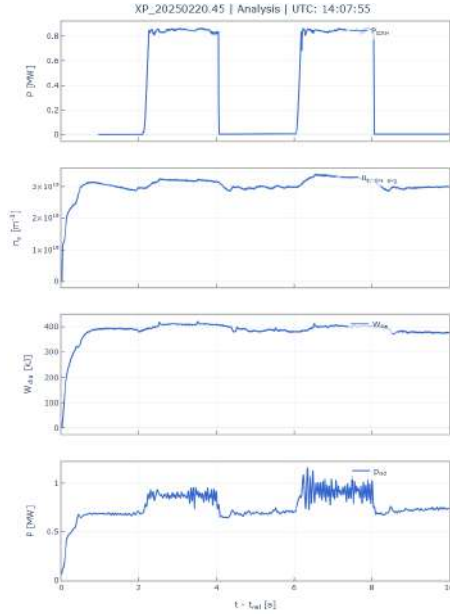


Fig 2a : Example of a modulated 800 kW ICRH discharge (W7-X #20250220.45) with the two strap antenna at 25 MHz in monopole phasing in a ^4He plasma with a few % of ^3He . Shown are as a function of time from top to bottom: ICRH power, line averaged density, stored plasma energy and total radiated power.

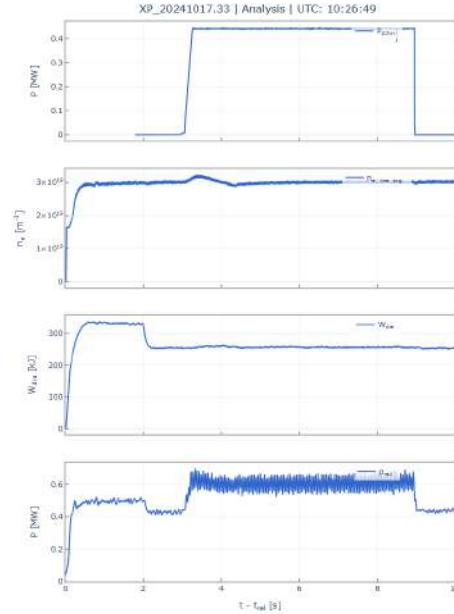


Fig 2b : Example of a long pulse high power ICRH discharge (W7-X #20241017.33) with the two strap antenna at 25 MHz in dipole phasing in a H plasma with $\sim 2\%$ of ^3He . Same set of signals shown as in Fig. 2a.

With both straps of the ICRH antenna operated at 25 MHz in monopole phasing applied to ^4He plasmas containing a few % of ^3He , modulated operation with up to 800 kW was demonstrated (Fig. 2a). In another experiment, up to 450 kW of ICRH was coupled (Fig. 2b) with both straps of the ICRH antenna operated at 25 MHz, in dipole phasing. Long-pulse operation up to 6 s was demonstrated in H plasmas containing a small amount ^3He . The coupled power remained highly stable throughout the pulse, with no indications of breakdowns. The impurity levels remained low. With the HEXOS spectrometer [21, 22] a small increase in the Cu and W radiation (from a W test tile in the edge of W7-X) was observed during ICRH operation. The C/O monitor diagnostic [12,13], located in port AEK30 in the same W7-X sector and close to the antenna, shows only a small increase in the intensity of O and a C impurities (illustrated for W7-X discharge #20250220.45 in Fig. 2c). Note that variations in intensity are also partly attributable to density fluctuations occurring during ICRH operation.



Fig. 2c : Intensity of C^{5+} (3.4nm) and O^{7+} (1.9nm) impurity lines as measured by the C/O monitor diagnostic for the discharge of Fig. 2a

The C/O Monitor is a high-throughput, high-time-resolution crystal spectrometer (~ 3 ms) based on Johann geometry with cylindrically curved dispersive elements. The system is designed to directly measure only the

intended lines together with their background. It consists of two vacuum chambers, each housing two independent measurement channels. The first chamber is dedicated to measuring C^{5+} (3.4 nm line) and O^{7+} (1.9 nm line), while the second, currently in the planning stage, is intended for boron B^{4+} (4.9 nm line) and nitrogen N^{6+} (2.5 nm line). The first chamber was successfully commissioned during the recent operational phase (OP2.3) at W7-X.

In both discharges the increase in the plasma stored energy is small. This can in part be attributed to the fact that in the discharge with 800 kW RF power the antenna was operated in monopole phasing; in the discharge with 6 s ICRH at 450 kW, ^3He minority heating in H was tested, and the efficiency of this scenario is known to depend crucially on the (small) ^3He concentration; a concentration scan is planned for upcoming campaigns. For estimating the ^3He concentration in these and the three ion experiments (see Subsection 2.2.4 below), a high resolution optical gas analysis technique was applied to the neutral gas exhaust, capable of resolving the ^3He and ^4He isotopic components, as originally demonstrated on JET ahead of the recent DT experimental campaigns [14].

2.2.2 RESULTS OBTAINED WITH ION CYCLOTRON WALL CONDITIONING

Long-pulse ion cyclotron wall conditioning (ICWC) was successfully demonstrated at 37.5 MHz in ^4He plasmas. To enable this, the ICRH local control system was adapted to produce extended pulse trains of ~ 100 s, consisting of 50 repetitions of 60 ms ICRH pulses at 50 kW followed by 140 ms interpulse intervals.

The experiments showed a marked reduction in nitrogen and hydrogen concentrations (Fig. 3). These results demonstrate the feasibility of ICRH-based wall conditioning and highlight its potential as an alternative to standard techniques. Future studies will focus on optimizing the technique and benchmarking its efficiency against electron cyclotron (EC) wall cleaning, which is routinely employed at W7-X.

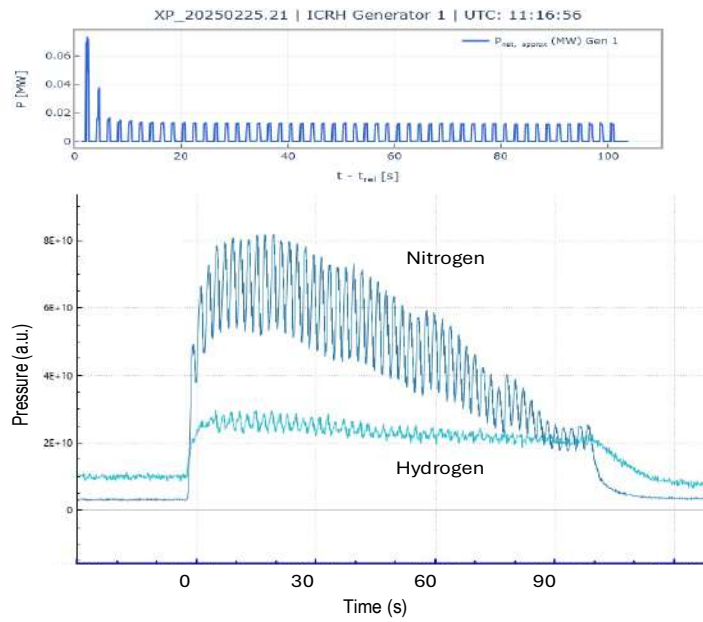


Fig 3: Illustration of a long pulse ICWC experiment in W7-X in a ^4He plasma (W7-X #20250225.21) with the antenna in dipole phasing at 37.5 MHz. Note the clear decrease in the signal for Nitrogen and Hydrogen.

2.2.3 DEMONSTRATION OF ICRH ASSISTED PLASMA STARTUP AT LOW MAGNETIC FIELD

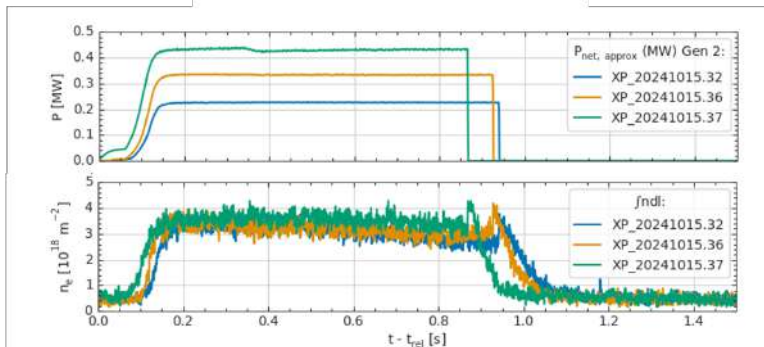


Fig. 4: Plasma startup using the ICRH antenna at various power levels. A saturation of the plasma density is observed with increasing ICRH power applied (W7-X #2024.1015.32,36,37).

Plasma startup at low magnetic field (1.7 T) was demonstrated in ^4He plasmas using the ICRH antenna operated with a single strap. Increasing the ICRH power beyond a certain level did not yield a further density rise, indicating saturation (Fig. 4). Under these conditions, a maximum line-integrated density of $\sim 4 \times 10^{18} \text{ m}^{-2}$ was achieved with up to 420 kW of ICRH power.

Startup can also be achieved with one W7-X ECRH gyrotron detuned to 110 GHz. However, further detuning to be resonant at fields below 1.7 T is technically challenging, making ICRH then the only viable method for startup under such conditions. This will be investigated in more detail in upcoming campaigns.

2.2.4 FAST PARTICLE GENERATION IN W7-X USING THE 3-ION SCHEME ^4He -(^3He)-H

We report the first observation of fast-particle generation in W7-X plasmas consisting of $\sim 17\%$ ^4He , $\leq 1\%$ ^3He , and $\sim 70\%$ H, a mixture predicted to enable resonant acceleration of ^3He ions to high energies via the 3-ion ICRH scenario [6]. A stable ^4He concentration was maintained using the main W7-X gas inlet in combination with localized ^4He puffing from the antenna system (see Fig. 5). Calibrated gas valves allowed to control the particle injection, enabling reproducible plasma conditions. Also in these experiments we used the residual gas analyzer for a first estimate of the ^3He content.

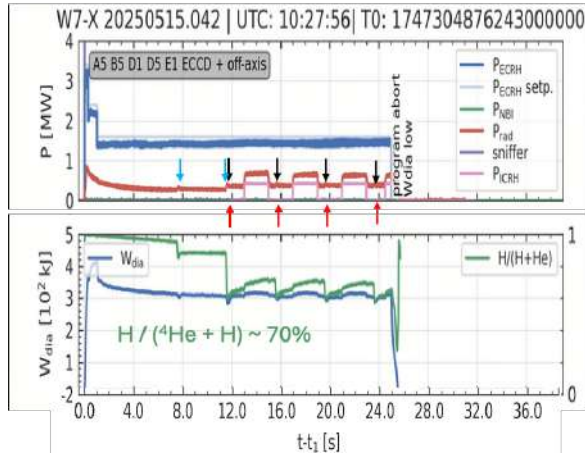


Fig 5: Operational scenario used for the first test of the 3-ion scenario ^4He -(^3He)-H to generate fast ^3He particles in W7-X (W7-X #20250515.42). Black arrows indicate ^4He puffing from the gas inlet at the antenna, blue arrows from the main ^4He gas inlet in W7-X. Red arrows indicate the timing of small ^3He puffs from one of the main gas inlets in W7-X.

Future planned hardware upgrades of this technique include (1) neutral gas recompression with a dual turbo-pump arrangement, similar to what is planned for ITER [15], and (2) development of a robust calibration method to extract ^3He concentration from the spectra of a novel, Time-of-Flight (TOF) mass spectrometer [16] that samples the same sub-divertor region as the optical gas analysis. A new optical gas analyzer, tested in OP2.3 for the first time [16], could in principle allow a reliable isotope separation at high time resolution, and might then even allow the real time control of ^3He in future 3-ion experiments on W7-X, in a way similar to the DT burn control studied in [15].

The Fast Ion Loss Detector (FILD) system [17] detected fast particles, with distinct signals in the high-energy R detector – an observation not previously achieved at W7-X (see Fig. 6). Control experiments confirmed the role of the three-ion ICRH scenario: excluding ^4He suppressed fast-ion generation, while closing the ^3He valve reduced the signal amplitude.

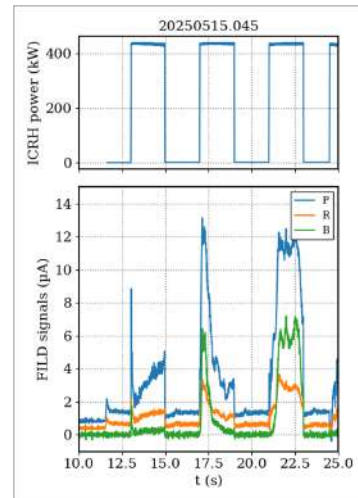
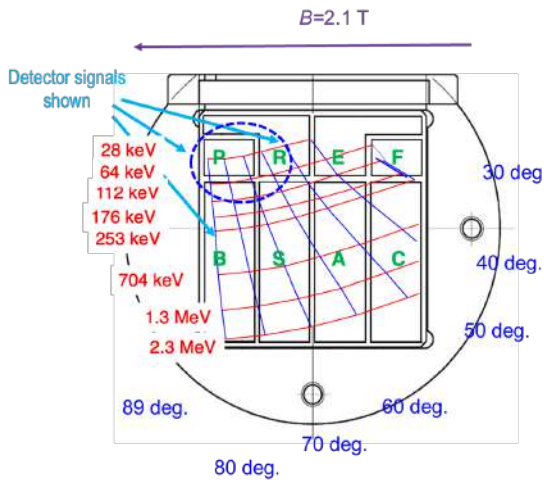


Fig 6 : Layout of the FILD detector for $^3\text{He}^{2+}$ ions (left) and signals detected (right) in plasmas with $\sim 17\%$ ^4He and $\leq 1\%$ ^3He in a plasma with H as main gas (W7-X #20250515.045)

Fast ions with energies exceeding 64 keV and pitch angles of 80° – 90° were observed. These measurements constitute the first demonstration of three-ion ICRH fast-particle production in a stellarator, establishing a new pathway for energetic-ion studies in W7-X. This achievement opens the door to systematic investigations of fast-particle physics and confinement in optimized stellarator configurations.

2.2.5 ROUTINE MEASUREMENT OF THE DENSITY PROFILES IN FRONT OF THE BUILT-IN REFLECTOMETER

To better understand the wave-particle coupling for plasma heating, the ICRH antenna is equipped with a microwave reflectometer capable of measuring the electron density profiles in front of the antenna. This diagnostic utilizes a frequency modulated continuous wave (FMCW) scheme with a heterodyne detection. The reflectometer has two frequency bands: E band (60 GHz – 90 GHz) and W band (75 GHz – 110 GHz), both operated in the extraordinary polarization (X-mode) regime, this corresponds to a measurable density of $n_e \leq 6.0 \times 10^{19} \text{ m}^{-3}$ at the central magnetic field of $B_0 = 2.5 \text{ T}$, with a radial resolution of approximately 0.01 m and a time resolution of 25 kHz [18].

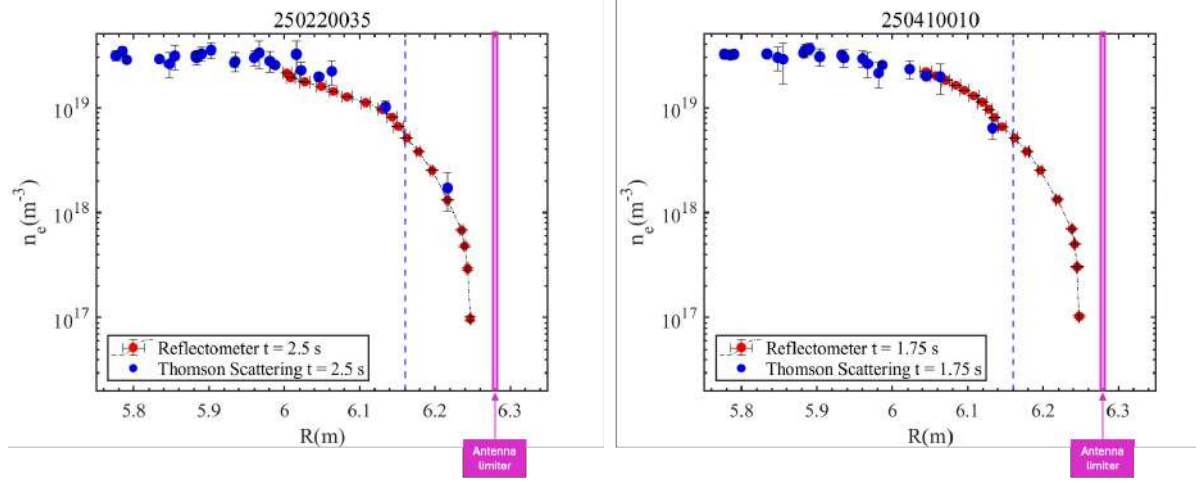


Fig. 6: Electron density profiles in front of the antenna measured with the built-in reflectometer in a He (W7-X #250220.035, left figure) and H (W7-X #250410.010, right figure) plasma for otherwise the same operational conditions and antenna position in W7-X. We also added the profiles obtained by the Thomson Scattering diagnostic on W7-X. Note the striking agreement between both sets of profiles, well within the error bars of both diagnostics.

The microwave frequency is swept at a constant rate, for each frequency the waves reach their respective cutoff and get reflected by the plasma. The electronic system distinguishes the absolute phase and amplitude of the reflected beat signal. To estimate the density profiles, the phase variation is inverted according to the Bottollier algorithm [19]. This algorithm inverts numerically the relation between the group delay and the refractive index, so it allows to obtain the density using the measured beat frequency and the magnetic field along the line of sight. The initial radial position is taken from the other edge profile diagnostic, such as Alkali beam emission spectroscopy (ABES) in W7-X [20].

Additionally, the density profiles estimated by the reflectometer are compared to the density profiles measured by Thomson scattering. A good agreement is found between the edge measurements of the reflectometer and the last points of the Thomson scattering profiles, well within the error bars of both diagnostics. This is illustrated in Fig. 6 for two density profiles, measured in ^4He and H plasmas under otherwise identical plasma conditions.

3. CONCLUSIONS

Over the last years, the ICRH system has demonstrated its principal use for W7-X. The antenna was installed in W7-X in August 2021, successfully commissioned in the first months of 2023, in the W7-X operational campaign OP2.1, and further explored in 2024 and 2025 in the operational campaigns OP2.2 and OP2.3.

We demonstrated its use for fast particle generation, plasma breakdown and wall conditioning. Various ICRH heating schemes for plasma heating have been tried for the first time and need further optimisation, foreseen in next campaigns. The three-ion heating scheme was used for the first time and fast particles were detected with energies above 64 keV.

A reflectometer built into the antenna now routinely delivers plasma density profiles in front of the antenna. The results obtained are confirmed, in the region of overlap, by the edge Thomson Scattering diagnostic. The availability of the edge density profile is important to understand the coupling and power deposition properties of the antenna.

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