

Frequency modulated continuous wave reflectometry for density profile measurement in front of ICRH antenna in Wendelstein 7-X

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Abstract

A Frequency Modulated Continuous Wave (FMCW) reflectometry with heterodyne detection regime is developed for measuring the electron density profile in front of the ICRH antenna in Wendelstein 7-X (W7-X). The dual-band set up consists of the one at E-band (60GHz-90GHz) and another at W-band (75GHz-110GHz), enabling to measure the local density at two different poloidal positions. The system is polarized in extraordinary mode (X-mode), corresponding to a measurable density of $n_e \leq 6.0 \times 10^{19} \text{m}^{-3}$ at a central magnetic field of $B_0 = 2.5 \text{T}$. The transmission line consists of an oversized wave guide in Ka-band (WR-28) in the vacuum, and is tapered to the fundamental wave guide, respectively. Two pairs of sectoral horn antenna are mounted between the ICRH antenna straps. The horn mouth is designed to keep the E-plane at the Ka-band dimension whereas the elongated H-plane is customized for a sufficient gain and directivity. In this paper the layout of the front-end and the design of electronic module are presented. Furthermore, the evaluated density profiles from the experiments demonstrate a good agreement with profiles measured by other diagnostic, e.g. Alkali metal beam. And the density profile inside the magnetic island is presented as well. The diagnostic will be operated routinely for density profile measurement and will contribute to related physical study on W7-X.

Full Text

Preamble

Frequency modulated continuous wave reflectometry for density profile measurement in front of ICRH antenna in Wendelstein 7-X

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Abstract

A Frequency Modulated Continuous Wave (FMCW) reflectometry system with heterodyne detection has been developed for measuring the electron density profile in front of the ICRH antenna in Wendelstein 7-X (W7-X). The dual-band setup consists of one system operating in the E-band (60 GHz–90 GHz) and another in the W-band (75 GHz–110 GHz), enabling simultaneous measurement of local density at two different poloidal positions. The system is polarized in extraordinary mode (X-mode), corresponding to a measurable density of $n_e \leq 6.0 \times 10^{19} \text{ m}^{-3}$ at a central magnetic field of $B_0 = 2.5 \text{ T}$. The transmission line comprises an oversized waveguide in Ka-band (WR-28) in vacuum, which is tapered to the fundamental waveguide for each band. Two pairs of sectoral horn antennas are mounted between the ICRH antenna straps. The horn mouth is designed to maintain the E-plane at Ka-band dimensions while the elongated H-plane is customized for sufficient gain and directivity. This paper presents the layout of the front-end and the design of the electronic module. Furthermore, density profiles evaluated from experiments demonstrate good agreement with

measurements from other diagnostics, such as the alkali metal beam diagnostic. The density profile inside the magnetic island is also presented. The diagnostic will be operated routinely for density profile measurement and will contribute to related physical studies on W7-X.

Keywords: Microwave reflectometry; ICRH antenna; density profile; magnetic island; W7-X stellarator

Introduction

The stellarator, with its intrinsic advantages of steady-state operation and absence of disruptions, has attracted considerable attention in magnetic confinement fusion research [?]. W7-X is the largest stellarator in the world and is highly optimized regarding neoclassical transport. One of the principal objectives of W7-X is to demonstrate the confinement of fast ions at finite plasma beta [?]. For the generation of fast particles, an ion cyclotron resonance heating (ICRH) system has been designed and implemented [?]. The heating efficiency depends on the distance of the ICRH antenna to the plasma. The ICRH antenna module consists of two parallel straps, whose surfaces are slightly shifted relative to each other to adapt to the 3D shape of the Last Closed Flux Surface (LCFS) of the standard magnetic configuration [?], allowing RF power up to 2 MW to be delivered to a resonant ion population at frequencies of 25 MHz or 37.5 MHz for pulses with a maximum duration of 10 s every 5 min [?].

Knowledge of the density profile (n_e) in front of the ICRH antenna is critical for evaluating and optimizing the RF power coupling of the antenna to the plasma. The reflectometer diagnostic is advantageous due to its non-invasive approach and flexible access footprint for horn and waveguide routing, and has been applied for n_e profile and associated fluctuation measurements in many tokamaks [?, ?, ?, ?] and stellarators [?, ?].

In ASDEX Upgrade, a multichannel reflectometer has been successfully installed at different poloidal locations on the ICRH antenna [?]. By means of this system, ICRH power coupling and edge density profile evolution in front of the ICRH antenna have been studied [?]. In the ICRH system of ITER, a frequency-sweeping X-mode bistatic reflectometry system is designed for four positions on the ICRH antenna, with a 50 GHz to 150 GHz cutoff frequency range calculated to cover full and half magnetic field tokamak operation [?]. On W7-X, considering the accessibility within the ICRH antenna module, a reflectometer system has been designed for n_e profile measurement in front of the ICRH antenna, as it requires only minimal space for embedding the transmission line (TL) and front-end module. Furthermore, due to the 3D structure of the magnetic topology, density measurements from multiple sight lines are preferable to reveal the 3D geometry of the density profile in the edge region, especially when configured with an island chain in the plasma edge. Therefore, two poloidally separated antenna pairs are mounted on the ICRH antenna to enable simultaneous measurement through different views of the plasma boundary. This paper presents

the reflectometer setup in Section II, including the design of the front-end, the TL module, and the electronic schematic. Experimental results concerning the evaluated density profiles during plasma operation are illustrated in Section III, followed by a summary and future plans in Section IV.

2.1 Requirement of Reflectometer Measurement

An electromagnetic wave with a specific frequency is reflected by the plasma when the refractive index goes to zero. A complete density profile starting at zero density requires the reflectometer system to be designed with X-mode polarization. Here, the X-mode cutoff frequency is calculated as:

$$f_{\text{cutoff}} = \sqrt{f_{pe}^2 + f_{ce}^2/4} \pm f_{ce}/2$$

where the \pm indicates the upper (+) and lower (-) cutoff frequencies, respectively, $f_{ce} = eB/m_e$ is the electron cyclotron frequency, and $f_{pe} = \sqrt{ne^2/(m_e\epsilon_0)}$ is the plasma frequency. In addition to X-mode, it has an advantage for non-monotonic ne profiles since the cutoff frequency of X-mode is related to both the local density and the magnetic field B . In former W7-X experiments, it was observed that the ne profile tends to flatten throughout the island width when the line of sight (LoS) passes through the magnetic island [?], resulting in a weak density gradient. Therefore, a reflectometer with X-mode polarization is preferable for W7-X to achieve reasonable density profile measurement in the plasma edge with an intrinsic magnetic island chain.

In Fig. 1, the measurable density range for the X-mode cutoff frequency is estimated by varying the local magnetic field from 1.4 T to 3.0 T. The zero-density ($ne = 0$) cutoff frequency follows the line of f_{ce} , which separates the lower and upper cutoff regions in the B and probing frequency ranges. The determination of n_{e0} is critical since it determines the initial frequency of the transmitted wave to be reflected from the corresponding cutoff layer. The upper cutoff region, where the useful probing frequency is on the right side of the n_{e0} line, has the advantage that n_{e0} can be detected at relatively low probing frequency. In Fig. 1, it is found that the upper cutoff frequencies of the E-band (60 GHz to 90 GHz) and W-band (75 GHz to 110 GHz) cover n_{e0} and the plasma edge region when a typical edge magnetic field is set to 2.3 T ($B_0 = 2.5$ T at core). The probing frequencies of the E- and W-bands correspond to a cutoff density up to $6.0 \times 10^{19} \text{ m}^{-3}$. An overlap range of 75 GHz to 90 GHz can benchmark the signal between the two transmitter branches and allows comparison of ne information in the island region.

2.2 Transmission Line and Front-End Modules

The ICRH antenna is installed in the equatorial plane of module No. 3 at the AEE31 port on the low-field side of W7-X (toroidal angle $\phi = 12.8^\circ$). Two TLs are assigned for the reflectometer, as shown in Fig. 2, with the lower one

used for the E-band and the upper one for the W-band. The TL consists of an oversized waveguide in Ka-band (WR-28) in vacuum, which feeds through the ICRH brace along the path. The waveguide is inserted in the pipe used for electrical cables. Leaving the support pipe, the transition to air is accomplished with a 0.1 mm thick mica window. Outside this window, the waveguide is tapered to the fundamental waveguide (E-band or W-band) and connected to the reflectometer.

To avoid any conflict with the ICRH system, the routing of the waveguide in vacuum must bend four times. To minimize the excitation of higher-order modes in the waveguide and hence reduce transmission loss, the bends have been manufactured in a hyperbolic shape with increasing curvature to decrease mode conversion [?]. The vacuum window, a mica disk of 0.1 mm thickness, is sandwiched between the O-rings of two flanges on each TL branch to sustain the vacuum atmosphere. The fundamental waveguide connects the vacuum window to the reflectometer positioned on the trolley of the ICRH system. The total length of the TL is 4.7 m per path in the upper branch and 4.1 m per path in the lower one.

Two sectoral horn pairs are designed to realize multiple sight line measurements in front of the ICRH antenna. The location of the two antenna pairs represents a compromise between space availability within the ICRH antenna and the requirement to measure the density profile at the position of interest for the ICRH. The detailed structure and its location with respect to the ICRH straps are shown in Fig. 3. Each horn pair is mounted 117 mm behind the ICRH straps. The horn pair is made of stainless steel with an aperture dimension of $40.3 \times 3.6 \times 30$ mm. The antenna block is longer, with a length of 90.2 mm, because it contains part of the Ka-band waveguide as shown in Fig. 2. The beam width of the main lobe can penetrate between the ICRH straps, yet the side lobes are minimized to prevent reflection from the straps. The length of the E-plane is fixed at the Ka-band dimension, whereas the H-plane is elongated and tilted by 13° to match the magnetic field pitch angle of W7-X.

Fig. 3(d) shows the estimation of the radiation pattern angle at -3 dB power for the operational frequency range. Here, the pattern angle is empirically calculated to be $\phi = 68.2\lambda/a$, where a is the length of the H-plane and λ is the wavelength of the beam [?]. It is seen that the pattern angle decreases with increasing probing frequency. The opening angle of the horn is 18.25° , resulting in a beam angle for the -3 dB pattern well below the opening angle at $a = 40.3$ mm. With this horn geometry, the gain of the horn is estimated to increase linearly from 14.6 dBi at 65 GHz to 18.5 dBi at 110 GHz.

Fig. 4 depicts the Poincaré figure at the ICRH antenna cross-section in the so-called standard (EJM) and low-iota (DBM) configurations, where an island chain structure exists in the open field line region. The two red dashed lines indicate the lines of sight (LoS) of the reflectometer at the poloidally separated positions. In the EJM configuration, the upper LoS penetrates through the O-point of the island toward the plasma core, and the lower one passes through

the X-point of the island. In the DBM configuration, the lower LoS intersects with the O-point of the island. With the two LoS, radial coverage of density profile measurement spans from the scrape-off layer to the plasma edge region, including the island region in the EJM configuration. This enables measurement of the ne profile at the O- and X-points of the island simultaneously once the corresponding cutoff layer is located in the island region.

2.3 Reflectometer Architecture

The two subsystems are independently assembled but utilize a similar electronic design, employing a mature scheme developed for the EAST [?, ?] and Tore Supra [?] reflectometer systems. The schematic of the microwave reflectometer on W7-X can be seen in Fig. 5 [Figure 5: see original paper].

An arbitrary waveform generator (AWG) based on the Mokulab platform [?] generates the VCO control signal with a voltage resolution of 100 μV . The generated signal is pre-calibrated to realize a linear frequency sweep after being linearly amplified to a range of 0 V to 15 V to meet the tuning voltage requirement of the VCO. The carrier output from the VCO is modulated by a 100 MHz signal from a quartz oscillator to achieve heterodyne detection. A single sideband modulator (SSBM) with a band suppression level better than 20 dB is applied to ensure a good signal-to-noise ratio. The modulated beam is amplified afterward and then fed into the $\times 8$ or $\times 6$ active multiplier to reach the E- or W-band frequency range. However, the minimum probing frequency of the E-band branch is 67.2 GHz instead of 60 GHz because the initial VCO frequency is 8.4 GHz for the E-band multiplier, while for the W-band the probing frequency starts from 81 GHz due to the initial VCO frequency being 13.5 GHz for the same reason.

The transmitted beam is fed through the TL to the plasma. A coaxial delay line with a transmission loss of 0.5 dB m^{-1} is used to compensate the time delay relative to the launching arm. After being multiplied, this reference signal is mixed with the received plasma signal in a balanced mixer to generate the intermediate frequency (IF) signal.

The I/Q demodulator separates the IF signal into the in-phase (I) and quadrature (Q) components via reference signals of 800 MHz and 600 MHz, respectively, which allows one to distinguish the absolute phase and amplitude of the beat signal required for the profile inversion process. To ensure a better input power level in the RF part of the I/Q detector, a Low Noise Amplifier (LNA) with a gain of 20 dB is used after the mixer. A low-pass filter at 110 GHz is installed in the receiver part to prevent stray radiation from the ECRH.

The microwave components, DC power module, and the Mokulab are integrated into a $40 \times 50 \times 20$ cm metallic case as shown in Fig. 2, excluding the coaxial delay lines and the data acquisition module (DAQ). Typically, the probing frequency is swept within 50 μs in both microwave bands. A total of 6 channels are fed into the DAQ, including both VCO voltages and two sets of I and Q signals.

The DAQ module has 8 channels with 14-bit resolution. A memory of 512 MB is insufficient to cope with normal plasma operation with a pulse length of 10 s on W7-X at a sampling rate of 50 MSamples/s. A digitization cycle with an interval of 100 ms is proposed for streaming data in real time for a measurement time window of 2.5 ms in normal operation, so as to cover long plasma pulses.

2.5 Commissioning of Reflectometer–Vacuum Test

After completing the installation of the reflectometer on W7-X, the system performance was assessed by monitoring the behavior of the beat frequency. The beat signal f_{beat} describes the phase variation and the corresponding group delay of the beam (τ_g) at the given sweep rate, given by $f_{\text{beat}} = \tau_g \cdot \frac{df}{dt}$ where τ_g is the group delay. The group delay consists of the delay time in the system, the delay time in the coaxial line, and the delay time that the beam needs to travel from the transmitter to the receiver after reflection. As deduced from equ.2, for a given constant sweep rate $\frac{df}{dt}$, f_{beat} can be modified by varying the distance between the transmitting and receiving antenna pairs. This distance variation is realized by moving the ICRH antenna trolley (flexible for moving backward or forward within 30 cm). The test is carried out in vacuum without plasma; during the test, the sweep rate of the VCO is set to 25 kHz and a delay time of 10 μs is applied between two consecutive voltage sweeps.

The E-band system is working properly and has been commissioned in experimental operation. In later sections of the paper, the test and experimental results focus on the E-band only. Figs. 6(a)-6(c) show the variation of the beat frequency spectrum of the E-band system when the ICRH antenna trolley moves backward toward the vessel wall, i.e., from a position of -293 mm to 0 mm; the color in each spectrum indicates the power of the beat frequency on a log scale. Two clear frequency strips are observed, whose values vary with the probing frequency in each figure. The bending of the beat frequency strips is attributed to the dispersion effect in the TL. Moreover, the beat frequency value of the lower branch remains constant as the ICRH antenna trolley moves backward, which means the beat frequency induced in this branch is due to a fixed reflection in front of the reflectometer antenna. This lower branch results from reflection at the ICRH antenna straps due to the side lobes of the antenna pattern. It is noted that the beat frequency of the upper branch increases with the ICRH antenna trolley moving backward, which fits well with the first-wall reflection when considering the group delay variation according to equ.2.

Considering the variation of beat frequency value for the three different trolley positions of the ICRH antenna, the absolute distance difference Δd_{refl} measured by the reflectometer can be inferred from the equation $\Delta d_{\text{refl}} = \Delta\tau \times c$, where $\Delta\tau$ is the group delay difference between two movement cases and c is the speed of light. During the calculation, the sweep rate $\frac{df}{dt}$ of the E-band is constant at 0.6265 GHz/ns. It is seen in Fig. 2(d) that the distance difference deduced from the reflectometer matches well with the calculation of ICRH antenna trolley movement, which demonstrates that the system performs well.

2.7 Profile Verification

After commissioning the system, the reflectometer operated routinely during the recent experimental campaign. Since the whole reflectometer system is installed on the ICRH module, it is essential to determine the influence of ICRH application on the reflectometer measurements.

Fig. 7 [Figure 7: see original paper] shows a program from W7-X in standard magnetic configuration. Four time slices ($t = 1$ s, 2 s, 3.2 s, and 4 s, with the first two time slices without ICRH and the latter two with 0.6 MW ICRH power) corresponding to different density levels are selected for comparison. Fig. 8 shows the beat frequency spectrum calculated at these four time slices; the color in each spectrum indicates the power of the beat frequency on a log scale. The branches of interest for density profile evaluation are indicated by black points with dashed lines in each figure. It is clearly seen that the beat frequency value decreases compared to the case with back-wall reflection (the beat frequency with back wall is not shown here, and in this discharge its value is located around 0 MHz due to adjustment of the delay line length). Moreover, a weak indication of ICRH strap reflection is seen in each spectrum due to a relative increase in amplitude for the plasma reflection branch. It is seen in Figs. 8(c) and 8(d) that the main branches of interest for density profile evaluation are clearly detected, and no clear deformation of beat frequency or other interference is seen in the spectrum after applying ICRH power.

Furthermore, taking the $1/e$ power of the beat frequency spectrum and its error bar, Δf_{beat} is approximately valued at 11 MHz. Considering $\Delta r = c \times \Delta \tau_g$ and combining with equ.2, one can roughly estimate the spatial resolution of the reflectometer as $\Delta r = c \times \Delta f_{\text{beat}} / \frac{df}{dt}$. With $\frac{df}{dt}$ of the E-band constant at 0.6265 GHz/ns, this results in a spatial resolution of 0.526 cm.

However, there is no clear indication in any subfigure of Fig. 8 of a sudden drop in beat frequency value and a large increase in amplitude across the whole band (a well-accepted criterion for distinguishing the probing initial density where a transition from back-wall reflection to plasma reflection occurs). This is because the minimum probing frequency of the E-band is above the so-called initial density, and the whole band is reflected by the plasma. The minimum probing frequency (67.2 GHz) of the E-band system is very close to the zero-density probing frequency (64.8 GHz at an edge magnetic field of 2.28 T) for this case. The zero-density layer can be detected by the E-band system when the edge magnetic field is at 2.4 T, as seen from Fig. 1 in further W7-X experiments.

For density profile evaluation, the profile is recovered from the phase variation according to the Bottollier algorithm [?]. The initial point is fixed by taking the electron cyclotron frequency for each density construction. The radial position of this point is also taken from other edge profile diagnostics, such as Alkali Beam Emission Spectroscopy (ABES) [?, ?]. Fig. 9 shows the density profiles evaluated at four different time slices with the line-integrated density ramping

up. An outward shift of the profiles is clearly seen, which matches well with the increase in line-integrated density as indicated in Fig. 7(b). Furthermore, it is seen that the profile measurement is not perturbed by ICRH application (up to 0.6 MW), and reasonable profiles at $t = 3.2$ s and $t = 4$ s in Fig. 9 are obtained.

The verification of the density profiles is based on a comparison between the evaluated density profile measured by the ABES diagnostic and the reflectometer. It is impossible to simply compare the profiles obtained by these two diagnostics because of the 3D structured magnetic topology on W7-X. A more efficient method is to trace the ABES n_e profile ($\phi = 72^\circ$, Module AEB21) from the equatorial plane to the reflectometer LoS ($\phi = 12.8^\circ$, Module AEE31) via the field line tracer (FLT) [?]. Fig. 10 explains the procedure of mapping the n_e profile via FLT in the EJM configuration. First, the ABES measurements are traced along magnetic field lines (pink lines, Fig. 10(a)) from the bean-shaped cross-section ($\phi = 331.72^\circ$, black points) to the reflectometer's cross-section ($\phi = 12.8^\circ$, Module AEB21, red points). Second, the FLT is performed to obtain a Poincaré figure using the line-traced positions (green points) as start points, as seen in the zoomed view of Fig. 10(c). Then the intersections along the reflectometer LoS can be collected on each flux surface of the Poincaré figure, which are indicated by the blue dots in Fig. 10(c). By assuming that the density level is constrained to the same flux surface in the Poincaré figure, one can obtain the mapped n_e profile along the reflectometer LoS, as shown in Fig. 11. It is noted that the obtained tracing points (red points) of ABES and the intersection points (blue points) in Fig. 10(c) are located in different phases of the 5/5 island chain; in that case, the mapped n_e profile does not include those measurements inside the island.

Fig. 11 shows the density profiles at two time slices of program 20230330.040. It is seen that inside the LCFS, well-matched density profiles between the two diagnostics demonstrate convincing and promising reflectometer measurements. The comparison of density profiles outside the LCFS is challenging in W7-X, and an advanced mapping method is required; this is planned for future work.

As illustrated in Fig. 4(a), the LoS of the E-band system passes across the X-point of the magnetic island. The LoS could intersect the magnetic island by applying control coils to adjust the island chain [?]. The island divertor and its properties are key issues for W7-X. The 5/5-island chain serves as the island divertor in this case, and it is of interest to examine the measurement inside the magnetic island. Fig. 12 shows such an example of a density profile measured by the reflectometer. Fig. 12(a) shows a Poincaré figure (obtained by FLT from ideal coils) and magnetic field line connection length contour (obtained by FLT including ideal coils, control coils, and trim coils). It is seen that the LoS of the reflectometer intersects the island indicated by the Poincaré figure. The beat frequency measured by the reflectometer shows a jump in its value when the cutoffs of those probing frequencies are located inside the magnetic island, as shown in Fig. 12(c). The beat frequency should show continuous evolution when probing a monotonic density profile, and an upward jump in beat

frequency means an abrupt decrease in density gradient; therefore, a flattened density profile is seen in Fig. 12(b). Furthermore, the width of the flattened region in the density profile corresponds well with the width of the magnetic island indicated by the Poincaré figure and connection length at the LoS of the reflectometer.

2.8 Summary and Outlook

A frequency-modulated continuous wave (FMCW) reflectometer with heterodyne detection has been developed for density profile measurement in front of the ICRH antenna in W7-X. Two subsystems share a similar electronic schematic covering the frequency ranges of E-band (60 GHz-90 GHz) and W-band (75 GHz-110 GHz), with an X-mode polarization scheme corresponding to measurable n_e coverage up to $6.0 \times 10^{19} \text{ m}^{-3}$. The E-band system provides convincing density profiles that are comparable with measurements of line-integrated density and ABES. The reflectometer measurement is not influenced by application of the ICRH system. Moreover, a flat density profile is obtained when the LoS of the reflectometer passes across the magnetic island. The high spatial (1 cm) and temporal resolution (normally 50 μs) allows tracking of fast events and plasma transport studies. The reflectometer will be operated routinely for density profile measurement and will contribute to physical studies in W7-X experiments. The W-band system will be commissioned in the upcoming experimental campaign. A combination of the two subsystems at one position (either at the X-point or O-point of the island) will be carried out in the near future as well. Cross-checking of density profiles with other edge diagnostics will be fulfilled.

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Figure 1 [Figure 1: see original paper]: The cutoff density distribution at different probing frequencies with variation of magnetic field. The horizontal dashed line indicates a typical magnetic field at the magnetic axis of 2.5 T with edge magnetic field of 2.3 T on W7-X. The blue vertical dashed lines denote the initial probing frequencies for the E-band and W-band, respectively.

Figure 2 [Figure 2: see original paper]: The reflectometer layout is emphasized in color; the ICRH transmission line is depicted in grey. The sectoral horn structure, vacuum window, and electronic box of the reflectometer are shown in detail in individual figures. (a) Photo of the ICRH straps and the sectoral horn pairs of the reflectometer. (b) Dimensions of the horn, and (c) its internal cut shape. (d) Radiation pattern angle estimation for the -3 dB pattern. The colored lines indicate operational frequencies. The E-plane of the horn is fixed at 3.556 mm, the H-plane is scanned in the range of 25 mm to 50 mm. The red dashed line is the opening angle of the horn (18.25°) and the vertical black dashed line is $a = 40.3$ mm of the H-plane.

Figure 3 [Figure 3: see original paper]: (a) Poincaré figure (in grey) for a standard configuration with 5/5 island chains at toroidal angle $\phi = 18.25^\circ$. The launcher and receiver are labeled by red triangles, and the lines of sight are indicated by red lines. The vessel and divertor modules are presented in light blue. (b) Poincaré figure in the low-iota configuration (DBM).

Figure 4 [Figure 4: see original paper]: Schematic of the FMCW reflectometer.

Figure 5 [Figure 5: see original paper]: System performance during ICRH antenna trolley movement. (a)–(c) Beat frequency f_{beat} variation and (d) distance difference comparison between the result deduced from reflectometer measure-

ment and the ICRH antenna trolley movement.

Figure 6 [Figure 6: see original paper]: W7-X plasma experiment 20230330.040. Time traces showing (a) plasma heating with ECRH and ICRH, (b) diamagnetic energy, and (c) line-integrated density.

Figure 7 [Figure 7: see original paper]: Beat frequency comparison for four different time slices with line-integrated density ramp-up: $t = 1$ s, 2 s without ICRH and $t = 3.2$ s, 4 s with 0.6 MW ICRH power. The beat frequency branches reflected by the plasma and by the ICRH antenna straps are marked with black points and grey points, respectively.

Figure 8 [Figure 8: see original paper]: Density profiles evaluated at four different time slices with line-integrated density ramp-up: $t = 1$ s, 2 s without ICRH and $t = 3.2$ s, 4 s with 0.6 MW ICRH power.

Figure 9 [Figure 9: see original paper]: Mapping the profile measurement from ABES diagnostic cross-section to density profile reflectometer cross-section via magnetic field line tracing. (a) Shows the results of tracing. Details of the two cross-sections: (b) the Alkali beams (ABES) cross-section and (c) the profile reflectometer cross-section.

Figure 10 [Figure 10: see original paper]: Density profile comparison between ABES measurements and reflectometer measurements after mapping via FLT. (a) $t = 2$ s, (b) $t = 3.5$ s.

Figure 11 [Figure 11: see original paper]: Density profile inside the magnetic island. (a) Poincaré figure and connection length contour, with the reflectometer LoS indicated by blue points, (b) the density profile, and (c) the beat frequency.

Note: Figure translations are in progress. See original paper for figures.

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