Measurement and analysis of density profiles in the island divertor region and in the plasma edge of W7-X

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Introduction

Microwave reflectometry is a non-intrusive plasma diagnostic tool which is widely applied in many fusion devices. The information of plasma electron density can be obtained by measures the round trip delays of transmitting microwave beams that are reflected at specific plasma cut-offs. One of the principal objective of optimized stellarator Wendelstein 7-X (W7-X) is to demonstrate the confinement of fast ions at finite plasma beta[1]. For the generation of fast particles an ion cyclotron resonance heating (ICRH) system is designed and implemented at W7-X [2]. For the coupling of the heating power into the plasma it is essential to know the density profile in front of the ICRH antenna. Therefore a density profile reflectometer is designed and installed in the ICRH antenna setup. The ICRH module as well as the density profile reflectometer have commissioned in the recent campaign (OP2.1, until end of Mar. 2023).

The reflectometer electronics utilize a frequency modulated continuous wave (FMCW) scheme with a heterodyne detection method to achieve a sub-millisecond $\mathrm{n_e}$ profile measurement. It consists of two sub-systems including the one at E-band (60 GHz - 90 GHz) and another at W-band (75 GHz - 110 GHz). The minimum probing frequency for E-band system is 67.2 GHz which is decided by the initial frequency of Voltage controlled Oscillator (VCO). The reflectometer polarized in extraordinary mode (X-mode), corresponding to a measurable upper cut-offs density of $\mathrm{n_e} \leq 6 \times 10^{19}\ \mathrm{m^{-3}}$ at the central magnetic field of $\mathrm{B_0} = 2.5\ \mathrm{T}$. While the capability of measurement can be extend if the lower X-mode cutoffs is observed. The detail description of the electronic diagram can be seen in [3, 4].

Localization of the reflectometer and its layout

Due to an intrinsic 3D structured magnetic topology for W7-X, the density measurement from multiple sight lines would be preferable to reveal the non-symmetry nature of profiles in particular around island structures in the plasma edge and outside the separatrix. Therefore two poloidally separated antenna pairs are mounted on the ICRH antenna to enable simultaneous measurement through different view of plasma boundary, as shown in fig 1. The left figure shows the Poincare plot at a toroidal angle of 12.8° (ICRH antenna module, AEE31) in the standard magnetic configuration, two red arrows present the Line of Sight (LoS) of two sub-systems. The upper one is the W-band system which LoS passes through the O-point of the magnetic island. While the lower one is the E-band system which the LoS passes through the X-point of magnetic island. The reflectometer is installed on the platform of ICRH antenna (configured with two straps) as dispatched in the right figure. Two pairs of transmission lines (TL) are assigned for the system. The TL consists of an oversized wave-guide in Ka-band (WR28) inside the vacuum, which

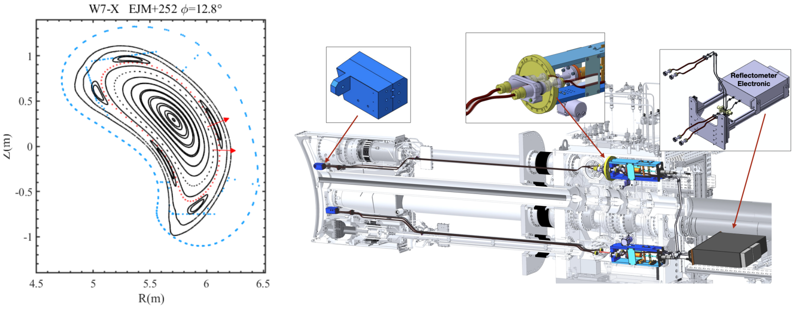

Figure. 1: Overview of diagnostic set up. Left figure shows the Poincare plot at toroidal angle of 12.8° the module AEE31, red arrows indicate light of sight for two subsystems respectively. Right figure shows the reflectometer layout emphasized by color, the ICRH transmission line id depicted in grey. The sectoral horn structure, vacuum window and electronic box of reflectometer is shown in detail in the individual figure.

shares the pipe for the electrical cables. Leaving the supporting pipe, the transition between the vacuum and the air is sandwiched with a 0.1 thick Mica window. Outside this window the wave guide is tapered to the fundamental wave-guide (E-band/ W-band) and connected to the reflectometer. In order to avoid any conflict with the ICRH system, the routing of the wave-guide in the vacuum has to be bent by four times. To minimize the excitation of higher order modes in the wave-guide and hence to reduce the transmission loss, the bends have been manufactured in the hyperbolic shape with an increasing curvature to decrease mode conversion. The electronic box of reflectometer is located on top of the sliding carrier of the ICRH system. The total length for single path of the TL is 4.7 m/path in the upper branch and 4.1 m/path in the lower one. Two sectoral horn pairs have been designed to meet the requirements of the ICRH antenna setup. The locations of these antenna pairs are determined based on space availability within the ICRH antenna and the need to measure density profiles at specific positions of interest for the ICRH. The geometry of sectoral horns are customized in order to make sure the main lobe of microwave beam penetrate outside the ICRH straps and to minimum the side lube reflection as well.

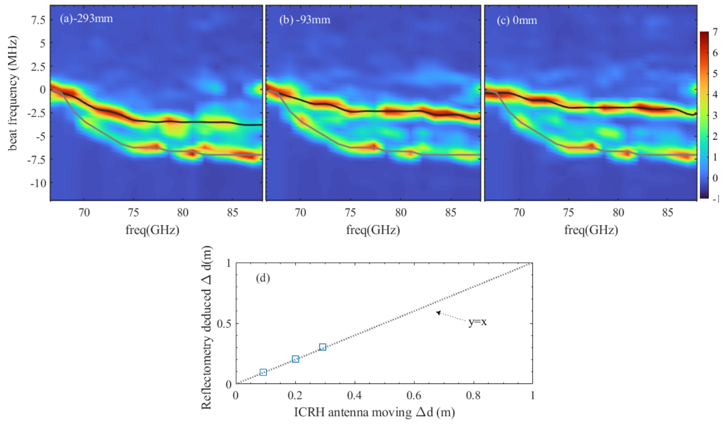

Figure. 2: System performance during the ICRH antenna trolley moving, (a)-(c) beat frequency f_{beat} variation and (d) the distance difference comparison between the result deduced from reflectometer measurement and the ICRH antenna trolley moving.

Commissioning of the reflectometer

After completed the installation of reflectometer on W7-X, the performance of the system is assessed by monitoring the behaviour of beat frequency. The beat signal $\mathrm{f_{beat}}$ describes the phase variation ($\mathrm{d}\phi/\mathrm{dt}$), and is corresponded to the group delay of the beam (τ_g) at the given sweep rate ($\mathrm{df/dt}$),

$$\mathrm{f_{beat}} = \frac{\mathrm{d}\phi}{\mathrm{dt}} = \frac{1}{2\pi}\frac{\mathrm{d}\phi}{\mathrm{df}}\frac{\mathrm{df}}{\mathrm{dt}} = \tau_\mathrm{g}\,\mathrm{df/dt} \tag{1}$$

where the τ_g is group delay. The system utilizes the coaxial cable to compensation of the group delay caused by the TL. In that case the τ_g contributed by the delay time in the system, the delay time in the coaxial line and the delay time that beam travels from the transmitter to the receiver after the reflection. It is deduced in the formula 1 that given a constant sweep rate $\mathrm{df/dt}$, the $\mathrm{f_{beat}}$ can be modified by varying the distance between the transmission and receiving antenna pairs. The distance variation is realized by moving the ICRH antenna trolley (flexible for moving backward or forward within $30\,\mathrm{cm}$). The test is carried out in the vacuum case without the plasma, during the test, the sweep rate of VCO is set in $25\,\mathrm{kHz}$ and a delay time of $10\,\mu\mathrm{s}$ is applied between two ramp up of the control voltage. Fig .2(a)-fig .2(c) shows the variation of beat frequency spectrum of E-band system when the ICRH antenna trolley moving backward towards the vessel wall. It is seen that the beat frequency varies with the probing frequency, which is attributed to the dispersion effect in the TL. Besides, two clear curved frequency strips can be seen in the spectrum of each figure. The beat frequency of lower branch keeps constant with the ICRH antenna trolley moving backward which is due to the side lobe reflection of ICRH antenna trolley. While the beat frequency of upper branch increase with the ICRH antenna trolley moving backward, which fits well with the first wall reflection when consider the group delay variation according to equa .1. Considering the variation of beat frequency with three cases of ICRH antenna trolley moving, the absolutely distance difference $\Delta\mathrm{d_{refl}}$ measured by reflectometer can be inferred from the equation of $\Delta\mathrm{d_{refl}} = \Delta\tau \times \mathrm{c}$, where $\Delta\tau$ is the group delay difference between two moving cases and c is the speed of light. It is seen in fig 1(d) that the distance difference deduced from reflectometer match well with the calculation of ICRH antenna trolley moving, which indicates that the system performers well.

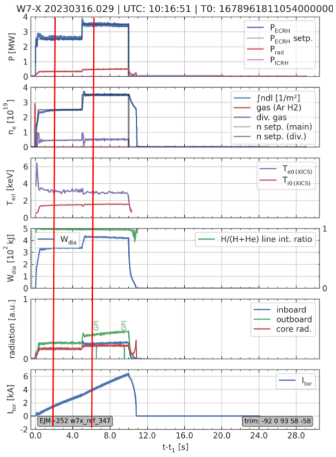

Figure. 3: W7-X plasma experiment of 20230316.029, time traces from (a)plasma heating and total radiation, (b) line-integrated density, (c) ion and electron temperature, (d) diamagnetic energy,(e) plasma current.

After the commissioning of the system, the reflectometer operates routinely during the recent experimental campaign. Fig 3 shows a program from W7-X in standard magnetic configuration. Two time slices (indicated in red, t=2s and 6s) corresponding to the different density lever are selected for comparison. Fig 4(a) and (b) show the beat frequency calculated at time slice of -0.1s and 2s, respectively. Which corresponding to the cases without plasma and with plasma. The branch which is interested for density profile evaluate are indicated in black in each figure. It is clearly seen that the beat frequency value decrease in fig 4(b) when reflected by the plasma compare with back wall reflection in fig 4(a). More, this is no clear indication of a sudden drop of beat frequency value and largely enhance of the amplitude in fig 4(b)(a well accepted judgement for the distinguish of initial density when reflection transited from back wall to plasma). This is due to the minimum probing frequency of E-band is above the so called initial density. Since the minimum probing frequency of E-band system very close to the zero probing frequency (64.8GHz at a edge magnetic field of 2.28T) for normal operation. The initial point is fixed by taken the electron cyclotron frequency for each density construction. And the radial position of this point also taken from the other edge profile diagnostic, such as ABES[5]. For the density profile evaluate, it is recovered from the phase variation according to the Bottollier algorithm[6]. Right figure in fig 4 shows the density profiles. It is clearly seen that at t=6s, a increase of density gradient and outer-shift of the reflectometer measurement, which is match well with the increase of line integrated density, as indicated in fig 3(b).

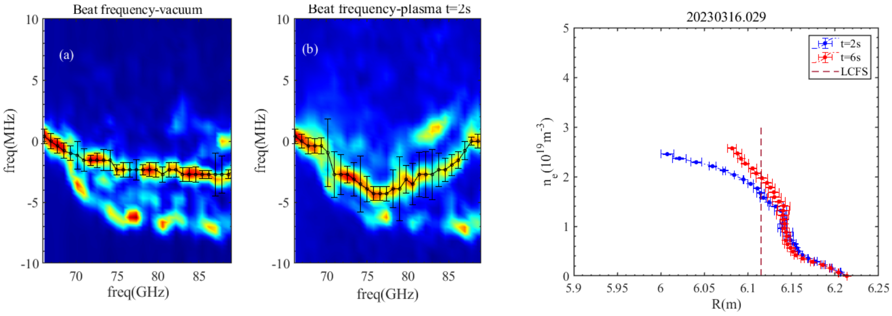

Figure. 4: Left figure, beat frequency comparison without plasma and with plasma. Right figure, density profile evaluated at two different time slices.

Summary and outlook

A frequency modulated continuous wave (FMCW) reflectometer with heterodyne detection has been developed for the density profile measurement in front of the ICRH antenna in W7-X. The E-band system offers a convinced density profile which is comparable considering the measurement of line integrated density. The W-band system will be commissioned in the upcoming experimental campaign. And a combination of two sub-system at one position (either at X-point or O-point of island) will be carried out in the near future as well. The cross check of density profile with other edge diagnostic will be fulfilled. And a promising of density profile at different sight view of island will be analysed. The reflectometer will be operated routinely and contribute to the physical study of W7-X experiments.

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Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No. 101052200 EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them. And this work was supported by the National Natural Science Foundation of China under Grant (No. 11605235, No. 12175277, No. 11975271, No 12075155, and the National Key R&D Program of China (No. 2022YFE03050003, No. 2022YFE03070004) as well.