Density profile measurements with X-mode lower cut-off reflectometry in ASDEX Upgrade[a)]

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Despite the fact that density profile measurements using X-mode lower cut-off reflectometry are foreseen to be used on ITER, little or no experience is available within the reflectometry community and to our knowledge no results on this subject have been published so far. In ASDEX Upgrade the multichannel broadband reflectometer is equipped with both O- and X-mode channels. While X-mode operation was designed for upper cut-off reflection, it is observed that for high magnetic field high density discharges under favorable conditions of both the magnetic field and density the lower cut-off becomes accessible. Here we present reflectometry measurements obtained in ASDEX Upgrade using X-mode lower cut-off and compare both the resulting group delay and density profile with O-mode measurements performed simultaneously over the same plasma region. The possible use of this comparison to provide estimates of the magnetic field is briefly discussed.

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I. INTRODUCTION

X-mode lower cut-off probing will be used on ITER to measure the density profile from the plasma high-field side (HFS) as part of the reflectometry system for which the Russian Federation (RF) Domestic Agency (DA) is responsible[1–3]. However, except for experiments performed in the russian T-10 tokamak, little to no experience is available within the reflectometry community and to our knowledge no results obtained with lower cut-off probing have been published so far in the literature.

In ASDEX Upgrade, the Frequency Modulated Continuous Wave (FM-CW) broadband reflectometey system[4] is equipped with nine O- and two X-mode channels. The O-mode channels measure the density profile in the range 0.32 to $12.4 \times 10^{19}\,\mathrm{m}^{-3}$ while the X-mode channels are configured to probe the initial part of the profile, not covered by O-mode, for the range of magnetic fields used in ASDEX Upgrade typical operation regimes.

Although X-mode operation was designed for upper cut-off reflection, it is observed that for both high magnetic field and high density discharges the lower cut-off reflection layer becomes accessible. As the same plasma region is probed simultaneously with O-mode this opens a window of opportunity to estimate the performance of profile measurements with X-mode lower cut-off reflectometry through the comparison with O-mode measurements. In addition, the sensitivity of the X-mode profile to the magnetic field and the possibility to provide local estimates of the magnetic field can also be studied through this comparison.

II. X-MODE MEASUREMENTS

The refractive index N of an electromagnetic wave with frequency f propagating in a plasma with its electric field $\boldsymbol{E}$ perpendicular to the plasma magnetic field $\boldsymbol{B}$ (X-mode propagation) depends both on the local density and magnetic field and is given by:

$$N_X^2(r,f) = 1 - \frac{f_{pe}^2(r)(f^2 - f_{pe}^2(r))}{f^2(f^2 - f_{pe}^2(r) - f_{ce}^2(r))} \tag{1}$$

where r is the position along the propagation direction, $f_{pe} = [(n_e e^2)/(4\pi^2 \varepsilon_o m_e)]^{1/2}$ is the electron plasma frequency, and $f_{ce} = (eB)/(2\pi m_e)$ is the electron cyclotron frequency.

Wave reflection occurs for $N_X = 0$, which corresponds to the cut-off frequencies

$$f_{lc} = \sqrt{f^2/4 + f_{pe}^2(r)} - f_{ce}(r)/2 \tag{2a}$$

$$f_{uc} = \sqrt{f^2/4 + f_{pe}^2(r)} + f_{ce}(r)/2 \tag{2b}$$

known, respectively, as lower and upper cut-off. X-mode propagation is also limited by wave absorption occurring when the wave frequency is such that $N_X \to \infty$, known as upper hybrid resonance frequency and given by

$$f_{uh}^2(r) = f_{pe}^2(r) + f_{ce}^2(r). \tag{3}$$

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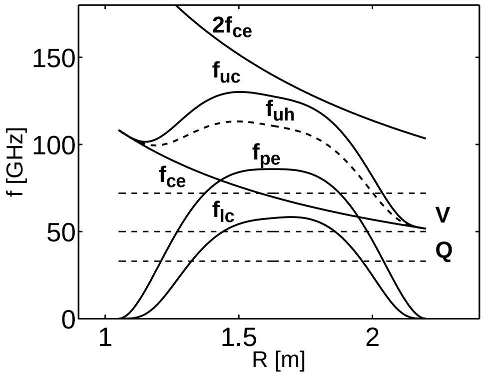

FIG. 1. Accessibility regions for a typical ASDEX Upgrade profile shape with high density and high magnetic field, showing that the X-mode lower cut-off becomes accessible in the Q and V bands.

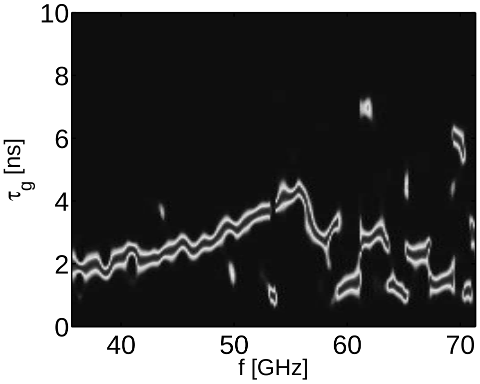

FIG. 2. Example spectrograms of X-mode Q (33–50 GHz) and V (50–72 GHz) bands signals obtained during discharge #23007. The transition between lower and upper cut-off can be observed in the V band around $f = 56$ GHz.

III. EXPERIMENTAL RESULTS

In ASDEX Upgrade, X-mode measurements are normally performed using the upper cut-off reflection in the frequency range 33–72 GHz. The main goal of this configuration is to provide measurements of the initial part of the density profile to initialize the O-mode measurements. Therefore, the lower cut-off is usually not accessible in typical operation regimes. However, for discharges with both high density and high magnetic field it is possible to access the profile with X-mode lower cut-off. Fig. 1 shows the estimated access regions in these conditions for a typical ASDEX Upgrade profile shape. As can be observed, the lower cut-off reflection becomes accessible for a frequency range corresponding to the full Q band and, depending on the actual discharge parameters, to the initial part of the V band.

In standard *H*-mode discharge #23007, with average density $n_e \approx 9.14 \times 10^{19}\,\mathrm{m}^{-3}$ and magnetic field $B = 2.5\,\mathrm{T}$, the accessibility conditions were met. Fig. 2 shows an example of the spectrogram of the Q (33–50 GHz) and V (50–72 GHz) X-mode signals obtained during the discharge. As can be observed, the Q band signal exhibits a clear group delay which corresponds to the distance between the antenna and the lower cut-off reflection layer.

The quality of the V band signal is not as good as that of the Q band, due to problems in the heterodyne detection hardware that limit the signal-to-noise ratio, in particular above 60 GHz. Nevertheless, the transition between lower and upper cut-off reflection can still be observed around $f = 56$ GHz. For $f > 56$ GHz the V band group delay exhibits the characteristic shape of upper cut-off measurements in the vacuum–plasma transition region.

IV. COMPARISON WITH O-MODE

In the ASDEX Upgrade broadband reflectometer all channels are operated synchronously, which makes it possible, in discharges where reflection from lower cut-off is accessible, to probe the density profile simultaneously in O- and X-mode. Therefore, the performance of the lower cut-off measurements can be assessed by cross-comparing the results with O-mode.

The comparison of the group delays measured in both modes is performed in two steps. First, the group delay measured with X-mode lower cut-off is extracted from the spectrograms shown in Fig. 2 using the best-path algorithm[5] and corrected for the microwave circuit and vacuum contributions. Like with O-mode, lower cut-off probing is unable to measure the density profile below a given density–a zero density location x_0 must be assumed and used in the calculation of the group delay correction due to the distance between the X-mode Q band antenna and the location where $n_e = 0$.

Second, an *equivalent* lower cut-off group delay is calculated from the O-mode density profile using the standard ASDEX Upgrade magnetic field profile and the same value of x_0. The obtained group delays are two independent measurements of the same plasma region and its comparison is a valuable tool to assert the performance of the lower cut-off measurements.

Fig. 3 shows the group delays obtained from lower cut-off (solid line) and from the O-mode profile (dashed line) by applying the above procedure. In this example only the Q band signal was considered, due to the mentioned hardware problems. As can be observed, the group delays show a very good match, which is a good indication that the X-mode lower cut-off is indeed performing very well. This is even more so since the Q channel was designed to measure the very edge of the plasma and is equipped with a small standard pyramidal horn, not optimized to measure the transport barrier pedestal located

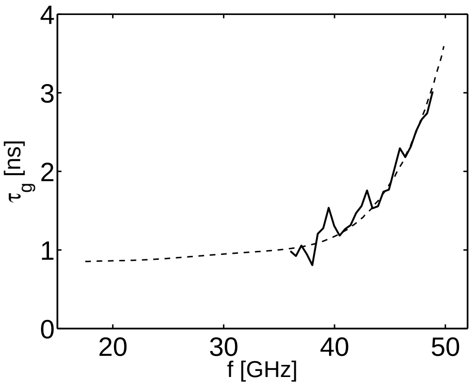

FIG. 3. X-mode lower cut-off group delay extracted from the spectrogram in Fig. 2 (solid line) and the *equivalent* group delay obtained from the O-mode profile (dashed line).

some 20 cm away.

One interesting possibility is to use this comparison to estimate the local magnetic field. While X-mode propagation depends on the plasma magnetic field, the group delay calculation itself is independent of $\boldsymbol{B}$. In principle, this would allow us to obtain information about the magnetic field profile by iteratively changing the magnetic field values until the *equivalent* and measured lower cut-off group delays match. In the example presented here such a procedure is not necessary since both group delays show a very good match for the standard ASDEX Upgrade magnetic field profile. A preliminary assessment of the effect of the magnetic field profile in the *equivalent* group delay curve has shown that within a ±1% error in $B(r)$ the group delays still match. A more detailed study including the sensitivity of lower cut-off measurements to the magnetic field profile is underway and will be the subject of a future paper.

Finally, we can compare the profile obtained from the lower cut-off group delay with the O-mode density profile. The X-mode profile is initialized using the *equivalent* group delay shown in Fig. 3 for frequencies below the first lower cut-off probing frequency f_1. The profile inversion is carried out using the Bottollier-Curtet algorithm[6]. Fig. 4 shows the density profiles obtained from O-mode (dashed line) and from lower cut-off (individual points) following the above steps. As expected the profiles match very well showing that X-mode lower cut-off probing is capable of measuring the density profile with good performance.

V. DISCUSSION

Density profile measurements using X-mode lower cut-off reflectometry is an important issue due to its application in ITER as part of the HFS reflectometry system. However, almost no knowledge is available about the performance of this type of measurements because the lower cut-off is not accessible in current ITER relevant machines. In ASDEX Upgrade a combination between the machine operation parameters and the reflectometry system setup made it possible to demonstrate the feasibility of lower cut-off profile measurements. In addition, the possibility to perform simultaneous O- and X-mode measurements makes it possible to validate those measurements by cross-comparison with O-mode measurements of the same plasma region. The results presented here clearly show that lower cut-off measurements exhibit very good performance when compared with their O-mode counterpart, even with a non-optimal antenna setup. Although in ITER the HFS system will certainly face other challenging issues, mainly due to the in-vessel space restrictions and harsh environment, these results represent a large step towards understanding the performance that can be expected from lower cut-off profile measurements.

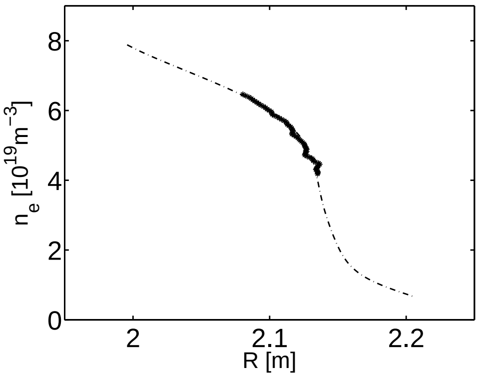

FIG. 4. Comparison between the density profiles obtained with O-mode (dashed line) and with X-mode lower cut-off (individual points).

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[1] G. Vayakis, *et al.*, Rev. Sci. Instrum. **68 (1)** (1997).
[2] V. Vershkov, S. V. Soldatov, D. A. Shelukhin, and A. O. Urazbaev, Instruments and Experimental Techniques **47 (2)** (2004).
[3] G. Vayakis, *et al.*, Nucl. Fusion **46** (2006).
[4] A. Silva, *et al.*, Rev. Sci. Instrum. **77** (2006).
[5] P. Varela, M. E. Manso, A. Silva, the CFN Team, and the ASDEX Upgrade Team, Nucl. Fusion **46** (2006).
[6] H. Bottollier-Curtet and G. Ichtchenko, Rev. Sci. Instrum. **58 (4)**, (1987).