New X-mode reflectometry measurements of Alfvén Eigenmodes on JET

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I. Introduction

It was shown in recent works [1,2] that O-mode reflectometry is a powerful diagnostic to determine the time-frequency evolution of Alfvén Eigenmodes (AEs) on the JET tokamak. Due to the fact that the density profile is generally flat in the plasma core region where the AEs are localised, the best way of detecting these modes was to use a probing wave with frequency higher than the cut-off frequency (i.e. when the diagnostic acts as an interferometer). Although such line-integrated measurements exhibit an unprecedented time and frequency resolution, they cannot provide direct radial localisation of the AEs. To overcome this limitation, X-mode reflectometry is a promising option [3]. This paper reports on the first successful localised X-mode reflectometry measurements of AEs on JET, recently obtained with the benefit of new low-attenuation transmission lines installed under the EFDA enhancement project "Millimetre Wave Access" [4].

II. Principles of X-mode reflectometry measurements

An electromagnetic wave propagating in a magnetised plasma with X-mode polarisation (i.e. with its electric field perpendicular to the applied magnetic field) is affected by both the density and the magnetic field. Under the cold plasma approximation, the X-mode refractive index for a wave propagating along the direction r can be written as [5]:
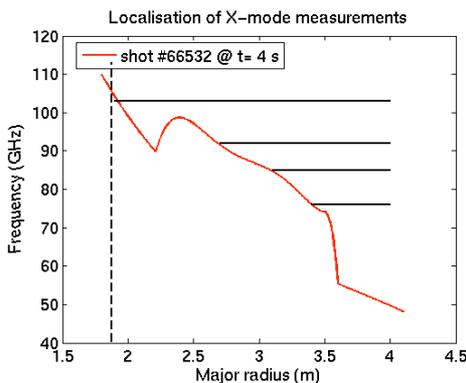

Figure 1: Example of radial profile of X-mode upper cut-off frequency (in red) for a JET discharge at 2.4 T. Four channels of the X-mode reflectometer are represented by the horizontal black lines.

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

where f, f_{pe} and f_{ce} represent the wave frequency, the electron plasma frequency and the electron cyclotron frequency respectively. In reflectometry experiments, the probing wave is reflected by the plasma at the cut-off position where the refractive index drops to zero. From equation (1), it can be deduced that the X-mode has two distinct cut-off frequencies:

$$f_{cut-off}(r) = \frac{1}{2}\left[\pm f_{ce}(r) + \sqrt{f_{ce}^2(r) + 4f_{pe}^2(r)}\right] \quad (2)$$
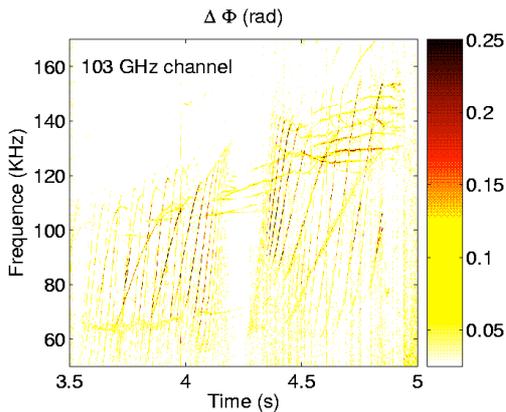
Figure 2: Spectrogram (sliding FFT) of the phase perturbations of the X-mode reflectometer 103 GHz channel working in the interferometry regime. Some Alfvén Cascades are clearly observed.

In practice, X-mode reflectometry usually relies on the use of the upper cut-off frequency (+ sign in (2)). Density fluctuations can then be inferred from the measurement of the phase perturbations of the reflected signal. The JET X-mode reflectometer system is dedicated to radial correlation measurements [6] but can be used as a fixed frequency multi-channel system (as done in this work). An example of the radial profile of the upper cut-off frequency for a typical magnetic reversed-shear JET discharge at 2.4 T is depicted in Figure 1, thus illustrating the localisation of the JET X-mode reflectometer measurements. In order to compute equation (2), the density profile inferred from the JET LIDAR Thomson scattering diagnostic and the magnetic field profile given by the EFIT equilibrium code were used as inputs. It is noticeable from Figure 1 that the channels of the X-mode reflectometer diagnostic (only channels at frequencies 78, 85, 92 and 103 GHz are represented in Figure 1) can be either in the reflectometry regime (reflected by the plasma) or in the interferometry regime (reflected by the inner wall). An illustration of the measurement of a particular type of AEs, so-called Alfvén Cascades (ACs), is shown on Figure 2. The time-frequency evolution of the ACs is observed in the spectrogram (sliding FFT) of the signal phase obtained from the 103 GHz channel (that works in the interferometry regime). This confirms the ability of reflectometry (in either O-mode or X-mode) to detect density fluctuations induced by AEs. In addition to the high time and frequency resolution of these measurements, which provides detailed information on the value of the safety factor at the shear reversal point, it is shown in the next section that radial localisation of the AEs is also possible from X-mode reflectometry.

III. Localised measurements of Alfvén Eigenmodes

Localised measurements of AEs were performed at magnetic field of 2.9 T, for which a good coverage of the JET plasma radius with the various X-mode reflectometer channels is achieved (as shown in Figure 3). The spectrograms of the phase perturbations from the 85 GHz and 103 GHz channels are represented in figure 4. Before t = 6.5 s, some Toroidal Alfvén Eigenmodes (TAEs) are observed around 180 kHz. After t = 6.5 s, some ACs appear on both channels, whose cut-off layers are localised at R ≅ 3.35 m and at R ≅ 2.6 m respectively. The ACs are not observed before t = 6.5 s, because the density is higher and the cut-off layers are localised outer in the plasma at R ≥ 3.35 m and R ≥ 2.8 m. This clearly indicates that the ACs are localised on two different radial locations. A cut at t = 6.87 s of the phase perturbations from all channels is shown in Figure 5. A strong peak with phase perturbations of almost 1 radian is observed in the two higher frequency signals, which are reflected in the high field side region at R ≅ 2.6 m. Another peak with smaller amplitude of 0.3 radian is observed on the 85 GHz signal, which is reflected in the low field side region at R ≅ 3.35 m. A statistical estimation of the level of phase perturbations induced by ACs have been carried out over a half a second time window. Since the respective cut-off layers of the various reflectometry channels move within this time window due to density profile changes, the distribution of phase perturbations as a function of the plasma major radius can be inferred (see in Figure 6). Two peaks of phase perturbations, one smaller in the low field side

region at R ≅ 3.35 m and another higher in the high field side region at R ≅ 2.6 m, are clearly noticeable. The position of these peaks is in good agreement with the position of the minima of the safety factor q_{min}, then confirming that the ACs are localised in these regions. These results also confirm theoretical estimations of the radial shape of the density fluctuations associated with Alfvén Cascades based on equilibrium reconstruction and MISHKA and NOVA-K simulations [1]. 1D simulations (using the WKB approximation [5]) were carried out to compute the phase perturbations of the reflected wave. The plasma parameters used in Figure 1 were used as inputs in these simulations. The parameters for the density fluctuations were set up in order to match the phase fluctuations obtained experimentally (see Figure 6). A level of density fluctuations in the order of magnitude of 5×10^{-4} was found.
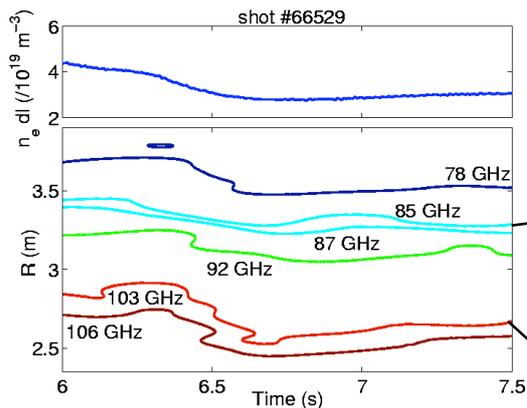

Figure 3: Line-integrated density from Far Infra-Red interferometry and cut-off positions of the different X-mode reflectometer channels.
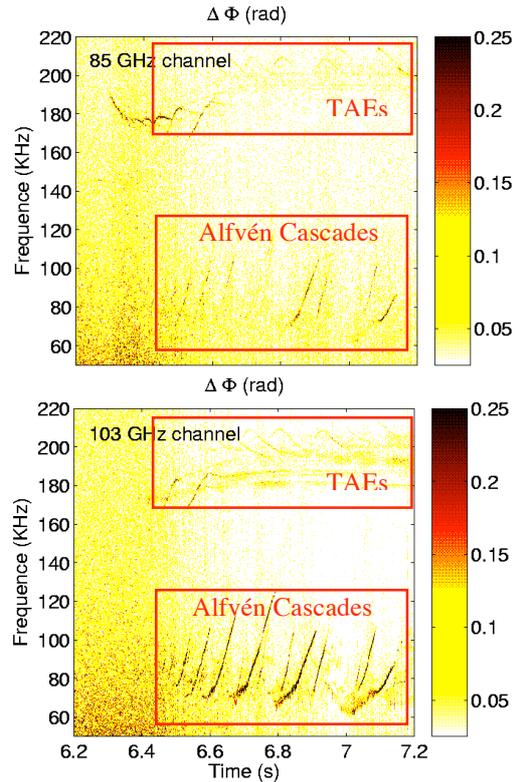
Figure 4: Spectrograms of the phase perturbations of the X-mode reflectometer 85 GHz and 103 GHz channels, probing the low field side and the high field side respectively.
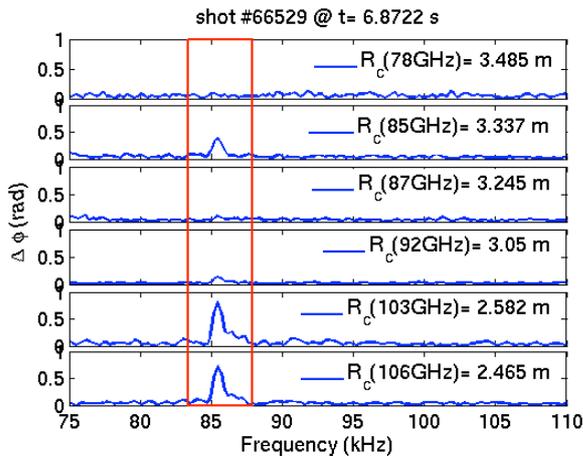

Figure 5: Phase perturbations from different X-mode reflectometry channels. The localisation of the AC with frequency of 85 kHz can be deduced from the corresponding cut-off layer positions.
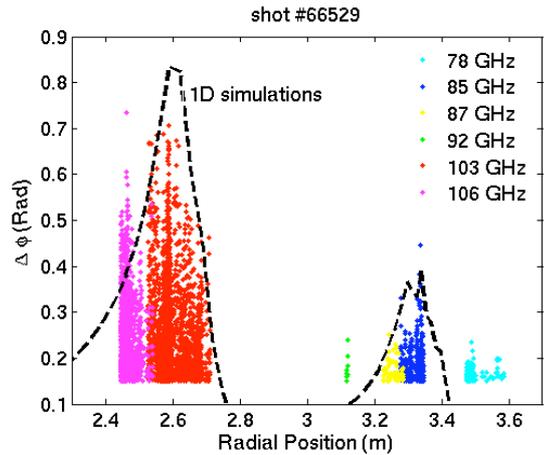
Figure 6: Statistical distribution of the phase perturbations induced by ACs, displaying two clear peaks - one at the low field side and another with higher amplitude at the high field side.

IV. Conclusion

Diagnosis based on the excitation and observation of Alfvén Eigenmodes (AEs) such as Alfvén Cascades (ACs) has proved to be very useful for study of advanced plasma scenarios. The detection of ACs is for instance used for the determination of the safety factor minimum q_{min}, which is of the great importance for the development of advanced scenarios with Internal Transport Barriers (ITBs). Therefore a strong demand has recently appeared for reliable diagnostics allowing measurement of ACs with good resolution. Although it does not provide localised measurements, O-mode reflectometry (used in the interferometry regime) has shown a particularly good potential, since it usually gives a better picture of the ACs than other diagnostics, such as the external magnetic pick-up coils. Thanks to X-mode reflectometry, the detection of ACs can now be used not only for the time determination of $q_{min}(t)$, but also for identifying the radial localisation $q_{min}(R)$. Finally, it should be pointed out that the challenging conditions in which the reflectometry measurements are performed on JET (with for instance the use of up to eighty metres of transmission lines) make them particularly relevant to ITER.

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