Fluctuation measurements in TJ-II using a broadband fast frequency hopping reflectometer

T. Estrada, E. Blanco, L. Cupido*, M.E. Manso* and J. Sánchez

Laboratorio Nacional de Fusión, Asociación Euratom-CIEMAT, Madrid, Spain

*Associação Euratom-IST, CFN, Instituto Superior Técnico, 1096 Lisboa, Portugal

A broadband fast frequency hopping reflectometer designed for measuring plasma turbulence has been recently installed at TJ-II. The main feature of the reflectometer is its possibility to be tuned, within a fraction of a millisecond, to any selected frequency while keeping synchronized the Local and Radiofrequency oscillators with the same stability as a fixed frequency system would do. The system includes heterodyne detection. Reflectometry measurements have permitted the characterization of the velocity shear layer that develops spontaneously in the edge of TJ-II plasmas above a certain critical density. Simultaneously, a second velocity shear layer develops at inner radial locations that moves radially inwards when the plasma density further increases. The interpretation of these experimental results has been crosschecked with results obtained using a 2-dimensional full-wave code. Changes the spectra shape linked to low order rational surfaces in the rotational transform profile are also reported.

Reflectometer description

A broadband fast hopping reflectometer designed for measuring the plasma turbulence is in operation at TJ-II. The system works in the frequency range 33-50 GHz with propagation in extraordinary mode and uses heterodyne detection. A detailed description of the system can be found in [1]. The antennas are standard gain horn type with a 3dB beamwidth of about 20°. The antenna arrangement was designed to view the plasma perpendicularly to the cut-off layers, however a small misalignment may exist as it is seen in the measurements. The reflectometer covers the density range from about 0.3 to 1.5 $10^{19}$ m$^{-3}$, almost the whole density range of the TJ-II plasmas heated by ECH ($B=1$ T, $f_{\text{ECH}}=53.2$ GHz, $n_{\text{cut-off}}=1.75$ $10^{19}$ m$^{-3}$). However, due to the shape of the ECH plasma density profiles (flat in the range $\rho < 0.6$) and to the low gradient of the magnetic field, the radial range covered by the reflectometer is limited in most cases to $\rho \geq 0.6$. Most of the experimental results discussed in the next sections refer to the spectra of the complex amplitude $Ae^{i\phi}$, but it is worth mentioning that the conclusions do not change when considering the complex phase $e^{i\phi}$.

Characterization of perpendicular velocity shear layers

As it has been recently reported [2] a perpendicular velocity shear layer develops spontaneously in the plasma edge of TJ-II above a certain plasma density. To study this phenomenon a set of experiments has been done modulating the plasma density around the critical value. In these experiments the plasma is created and heated by ECH with a total
power of about 400 kW. During the experiments the reflectometer is tuned to a low frequency (34 GHz) to probe a layer close to the Langmuir probe radial position ($\rho \geq 0.8$). The reversal in the perpendicular phase velocity measured by the Langmuir probes when the plasma density reaches the critical value is also seen in the reflectometer signal. Figure 1 shows the time evolution of the line density in a standard magnetic configuration discharge and the mean frequency of the complex amplitude spectra at $\rho \approx 0.8$. In this example, as the line density increases from 0.4 to 0.6 $10^{19}$ m$^{-3}$, the perpendicular phase velocity measured by Langmuir probes reverses from $+10^3$ to $-10^3$ m/s [3]. The comparison of the reflectometer measurements with Langmuir probes results gives us information about the direction of the reflectometer misalignment. The misalignment in the antennas is such that negative/positive mean frequencies stand for rotation in the electron/ion diamagnetic direction (negative/positive radial electric field).

Experimentally, the behaviour of the turbulence rotation for inner radial locations has been studied changing the reflectometer probing frequency in a staircase mode during the discharge and changing the plasma density in a shot to basis. For plasma densities below the critical value, the mean frequency of the reflectometer signal spectrum is positive independently on the probing frequency. When the plasma density is slightly above the critical value the reversal in the perpendicular velocity is only seen for the lowest probing frequencies while the mean frequency of the reflectometer signal spectrum stays positive for the high probing frequencies. In these conditions the radial position where the perpendicular velocity reverses, computed as the radial location where the asymmetry changes sign, is located at $\rho \approx 0.8$. Increasing the plasma density further, this velocity shear layer moves to inner radial locations. As an example figure 2.a shows the staircase variation of the reflectometer probing frequency and the evolution of the line-averaged plasma density in three discharges with densities below (#11289), close (#11291) and above (#11294) the critical density ($\langle n_e \rangle \approx 0.5 \times 10^{19}$ m$^{-3}$). The mean frequency of the reflectometer signal spectrum as a function of the radial cut-off location is displayed in figure 2.b for these three discharges; also a fourth discharge with higher line density ($\langle n_e \rangle \approx 0.9 \times 10^{19}$ m$^{-3}$) is included. These measurements show that when the
velocity shear layer develops at the plasma edge, simultaneously, a second velocity shear layer appears at \( \rho \approx 0.8 \) that moves to inner radial locations when the plasma density further increases. HIBP measurements show that the inversion in the perpendicular rotation measured with the reflectometer may be dominated by the radial electric field. These results draw attention to the capability of the reflectometer to measure the inversion of the perpendicular rotation of the turbulence in a rather narrow radial region. This observation has been analysed using a two-dimensional full-wave numerical code [4]. As it is explained in [5] the code works with propagation in x-mode and incorporates the antennas arrangement of the experimental system. Realistic plasma shape and magnetic field distribution are introduced in the code using the theoretical magnetic surfaces of TJ-II. First numerical simulations indicate that asymmetric spectra are obtained for a misalignment as small as two degrees. Considering this tilt angle, we have studied the behaviour of the reflectometer signals in plasmas with a velocity shear layer localized in a very narrow region. For this study we consider a perpendicular velocity \( v_p = -3000 \) m/s at the plasma edge that changes linearly to \( v_p = +3000 \) m/s within a narrow region \( \delta x \) and stays constant further inside. The reflectometer signals are simulated for different probing frequencies within the band 33-50 GHz. The result for \( \delta x = 4 \) mm is displayed in figure 3. This figure shows the perpendicular rotation velocity and the mean frequency of the simulated complex amplitude spectra as a function of the major and normalised radius. These simulation results demonstrate the capability of the reflectometer to

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Figure 2: (a) Three discharges with densities close to the critical \( (0.5 \times 10^{19} \text{m}^{-3}) \) and staircase variation of the probing frequency, (b) Mean frequency of the spectra vs. cut-off radius in these discharges and in a fourth one with higher density.

Figure 3: Perpendicular velocity and mean frequency of the simulated spectra as a function of the major and normalised radius.
measure the velocity shear layer with a spatial resolution of about 1 cm, better than twice the probing wavelengths in vacuum ($\lambda_e$: 0.7 – 0.8 cm).

**Modification of the reflectometry signals spectra linked to rational surfaces**

Modifications in the spectra have been observed in configurations having a low order rational surface in the rotational transform profile within the radial range covered by the reflectometer. An example is displayed in figure 4. The spectrum at the most internal radial location ($\rho = 0.55$) shows a coherent mode of about 10 kHz and the spectra modification appears for the adjacent probing frequencies (at $\rho = 0.65$ & 0.7). These measurements can be interpreted as a localized increased in the perpendicular rotation velocity of the fluctuations: due to the small misalignment of the antennas and to the long probing wavelengths, the perpendicular velocity should be as high as 15-20 km/s to reproduce the experimental spectra. This phenomenon could be explained if we consider that the magnetic island produce an enhancement in the electron diffusion higher than the ion diffusion and consequently the plasma reacts creating a positive radial electric field to preserve the ambipolarity. A similar phenomenon has been measured using the HIBP diagnostic during the formation of electron internal transport barriers triggered by low order rational surfaces [6]: the positive radial electric field increases in a factor of three in the central plasma region when the e-ITB forms.

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**References**