Study of Doppler reflectometry viability in TJ-II stellarator using a two-dimensional full-wave code

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Abstract

A two-dimensional full-wave numerical code in the extraordinary mode of propagation has been developed to simulate reflectometry and in particular has been used to study the viability of the Doppler reflectometry technique in TJ-II. Two different antennas are used in the simulations: standard gain horns and gaussian antennas. The numerical results obtained modifying the plasma geometry allow us to conclude that the high curvature of the TJ-II plasmas demands a careful design of the antenna system for Doppler reflectometer optimization. Additionally, simulation results support the possibility to probe high wave-numbers keeping the spatial localization of the measurement.

Two-dimensional full-wave code

A two-dimensional full-wave code in X-mode has been developed to simulate the propagation of waves in turbulent and magnetized plasmas [1]. The Maxwell´s equations are solved using the Finite-Difference Time-Domain technique [2]. Two different antennas are used in the simulations: standard gain horns and gaussian antennas. The frequency of the wave is 40 GHz in all the simulations. The density distribution has been introduced adding a density perturbation to a steady density profile similar to the experimental one [3]. The density perturbation is given by the expression:

$$n_e(x,y,t) = <n_e(x,y)> + \delta n_e(x,y,t)$$

$$\delta n_e(x,y,t) = \sum \sum a(k_x,k_y) \sin(k_x x + k_y(y - v_p t) + \varphi_{random}(x,y,t))$$

The k-spectrum is fit by a gaussian function $\exp\left(-(k_x^2 + k_y^2)/k_w^2\right)$ with a spectral width $k_w =$ 540 m^{-1}. The plasma rotates in the perpendicular direction at $v_p = 3\,km/s$.

Numerical results

1. Standard Gain Horns

We have started out studies by using standard gain horns (with a 3 dB beam-width of 20º and a spot size close to 6 cm) and two plasmas with different geometry: TJ-II (cut-off layers with a curvature close to 20-25 cm) and slab plasma. The tilt angle of the antennas has been changed from a few degrees up to 30º. Figure 1 shows the spectra obtained at $\theta = 18º$ and

$\theta = 30^\circ$. At these angles, the frequency of the Doppler shifted structure should be 250 and 400 kHz respectively. To estimate the Doppler frequency and width of the simulated spectra, we fit the non-symmetric part of the spectra by the gaussian function $A\exp\left(-(f - f_D)^2/(\Delta f)^2\right)$. The result is shown in the figure. In the case of TJ-II plasmas (figure 1 top), there is no clear separation between the reflected and backscattered waves and the estimated Doppler frequency is erroneous. This result is a consequence of a poor spectral resolution $\Delta f / f_D$ of the system because different effects are contributing negatively to the results, mainly: the plasma and the beam curvature in the cut-off layer.
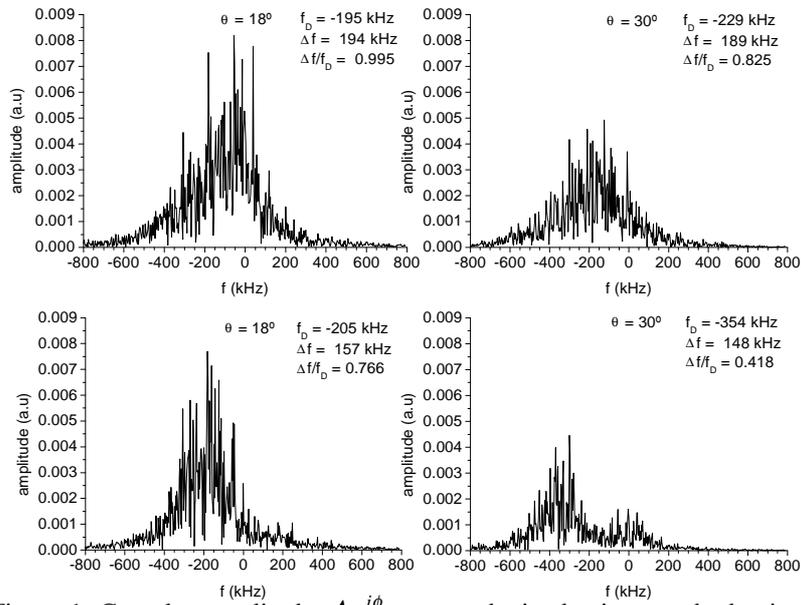

Figure 1: Complex amplitude $Ae^{i\phi}$ spectra obtained using standard gain antennas for TJ-II (top) and slab plasma (bottom) at tilt angles: 18º (left) and 30º (right).

To study the effect of the TJ-II curvature we consider a plasma slab (figure 1 bottom) with identical density profile and turbulence. The spectral resolution is better and at $\theta = 30^\circ$ it is possible to separate reflected and backscattered waves, however the perpendicular rotation velocity estimated from the Doppler frequency is lower than the real turbulence rotation for both tilt angles. This discrepancy can be partially explained in terms of the different amplitude of high and low fluctuation wave-numbers. To study this effect, we modify the spectral width of turbulence for the case of a plasma slab and 18 degrees. The shape of Doppler frequency structure changes to a more symmetric one (with respect to the expected value of the Doppler shift $f_D \approx 250\,kHz$) when the wave-number spectrum is broader, and the Doppler frequency obtained ($f_D = -226\,kHz$ and $\Delta f = 164\,kHz$) is closer to the theoretical value.

2. *Gaussian antenna*

To study the effect of the beam curvature, we use a mono-static gaussian antenna. The plasma is located inside the Rayleigh zone of the beam where nearly parallel wave-fronts exist.
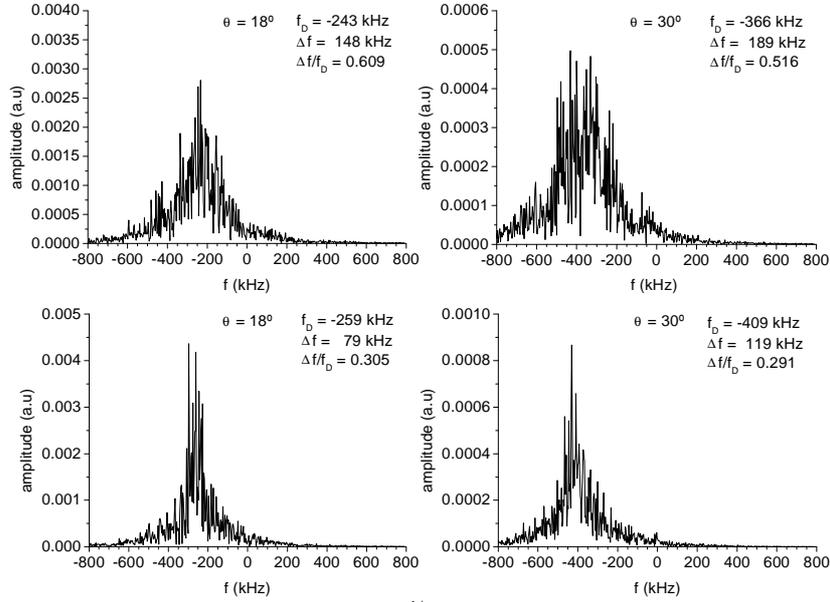
Figure 2: Complex amplitude $Ae^{i\phi}$ spectra obtained using a gaussian antenna for TJ-II (top) and slab plasma (bottom) at tilt angles: 18° (left) and 30° (right).

The beam waist is chosen to have a spot size close to that of the standard gain horns. With this antenna the backscattered and reflected waves are better separated (see figure 2) and the Doppler frequencies are closer to the theoretical ones. In the plasma slab cases (figure 2 bottom), the spectral resolution is very good ($\Delta f / f_D \approx 0.3$) and it is possible to recover the value of the perpendicular velocity of the plasma. For the TJ-II plasma geometry (figure 2 top) the spectral resolution ($\Delta f / f_D \approx 0.6$) is better than the obtained with the standard antennas and the Doppler frequency values are closer to the true ones. However, a further optimization is still desirable. Further simulations show that, as expected, the negative effect of the high curvature of the cut-off layers diminishes as the spot size is reduced and optimum values are obtained for a spot size close to 3.5 cm. This optimum value with the best resolution ($\Delta f / f_D \approx 0.5$) is shown in figure 3.
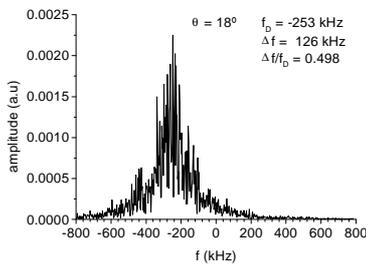
Figure 3: Complex amplitude $Ae^{i\phi}$ spectra obtained using a gaussian antenna with a half-power spot size of 3.5 cm for TJ-II at a tilt angle of 18°.

3. *Radial localization of the measurement at large tilt angles*

The code has been also used to study the contribution of the enhancement of the electric field to the radial localization of the measu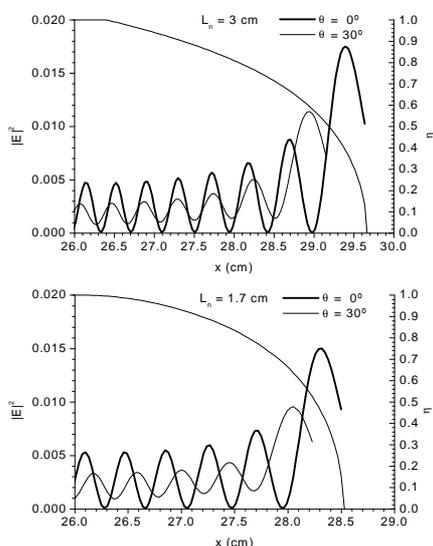rements at large tilt angles. We use the standard gain horns for these simulations. The enhancement of the electric field is estimated in two cases: $\theta = 0°$ and $\theta = 30°$ and for two different density gradient scale lengths at the cut-off layer $L_n \approx 3$ and 1.7 cm. Figure 4 shows the spatial variation of the electric field for these two angles and the refraction index η of the wave. The enhancement factor of the electric field depends on the density gradient scale length [4]; it changes from 4 to 3 when L_n decreases from 3 cm to 1.7 cm. However, it is almost unchanged when comparing $\theta = 0°$ and $\theta = 30°$ incidences; consequently its contribution to the spatial localization of the measurement remains.

Figure 4: Electric field for $\theta = 0°$ and $\theta = 30°$, and two density scale lengths. Also, it is shown the refraction index

Conclusions

The viability of Doppler reflectometry to measure the perpendicular rotation velocity of the turbulence has been studied using a two-dimensional full-wave code. To study the effect of the plasma and probing beam curvatures, we have considered plasmas with different geometry (TJ-II and slab plasmas) and beams emitted by standard and gaussian antennas. Standard gain antennas could be only used in slab plasmas, thought the spectral resolution is low and the estimated Doppler frequency depends on the turbulence wave-number spectrum shape. The plasma curvature of TJ-II demands the use of gaussian antennas with an optimized spot size while for slab plasmas gaussian antennas with broad spot sizes give good results.

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