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Study of Doppler reflectometry capability to determine the perpendicular velocity and the k-spectrum of the density fluctuations using a 2D full-wave code

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Abstract

The capability of Doppler reflectometry to determine the perpendicular velocity and the k-spectrum of the density fluctuations has been studied using two-dimensional full-wave codes in X and O mode. The numerical results show that the Doppler frequency can be obtained with high accuracy for broad ranges of antenna tilt angles and turbulence levels. However, the efficiency of the backscattering process depends on the probed wave-number, which must be taken into account in the evaluation of the wave-number spectra.

I. Introduction

Doppler reflectometry measurements have been carried out in different fusion experiments in order to measure the perpendicular velocity [1-3] and the k-spectrum of the turbulence-like density fluctuations [3]. An important issue is the dependence of the reflectometer response on a finite level density turbulence as well as the antenna geometry. This requires the use of a full-wave code to solve Maxwell´s equations in the magnetized plasma. Previous numerical simulations performed using a two-dimensional full-wave code in X-mode [4] showed that Doppler measurements require an optimized antenna system to minimize the errors in the determination of the perpendicular velocity of the turbulence [5]. Those studies also showed that the amplitude of the Doppler spectra, related to the efficiency of the backscattering process, depends on the probed wave-number. In this work we present a systematic study carried out to determine the performance of the Doppler reflectometry efficiency on probed wave-numbers and turbulence levels.

II. Numerical simulations characteristics

In our simulations we consider a constant magnetic field ($B = 1$ T) and a plasma slab with a linear density profile ($\nabla n = 2.5 \cdot 10^{20}$ m^{-4}). The density distribution is:

$$\tilde{n}_e(x, y, t) = n_e(x, y) \cdot [1 + \delta n_e(x, y, t)] \quad (1)$$

$$\delta n_e(x, y, t) = \frac{\sigma}{\sigma_{SD}} \sum a(k_\perp) \sin(k_\perp (y - v_p t) + \varphi_{random}(k_\perp, t)) \quad (2)$$

where $n_e(x,y)$ is the averaged linear density profile and $\delta n_e(x,y,t)$ takes into account the turbulence. We consider 48 poloidal modes $k_\perp$ equally spaced within the wave-number range $0 < k_\perp / k_0 \le 1.2$. The $k_\perp$ -spectrum of the turbulence is essentially flat with coefficients $a(k_\perp)$ =1. The random phase terms $\varphi_{random}(k_\perp, t)$ are uniformly distributed between $\pm\pi$. The summation in (2) is normalized by the standard desviation σ_{SD} and the variation of σ/σ_{SD} results in rms values from $0.1\% \le \delta n_e / n_e \le 10\%$. To avoid the deleterious effects of the wave-front curvature [5] the antenna system is modelled by a monostatic high directivity Gaussian beam antenna at a tilt angle θ , which results in an essentially plane wave-front. In these simulations the beam waist is 4.8 cm, the vacuum wavelength is 7.5 mm (f = 40 GHz) and the nominal cut-off layer is at a distance of 8 cm from the beam waist position.

III. Numerical simulations results

Two separate sets of simulations were undertaken: First, the antenna tilt angle is kept constant and the turbulence level is varied from $0.1\% \le \delta n_e / n_e \le 10\%$; second, the turbulence level is kept constant and θ is varied from 8^o to 30^o .

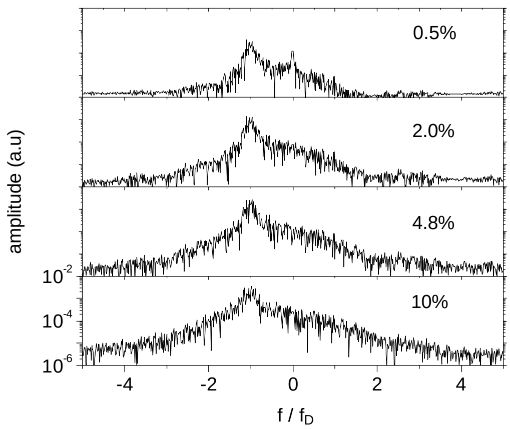

Figure 1. Complex amplitude spectra obtained with $\theta = 18^o$ and $k_\perp / k_0 = 0.618$ for different rms values of the turbulence from 0.5% to 10%. The four spectra have the same vertical scale.

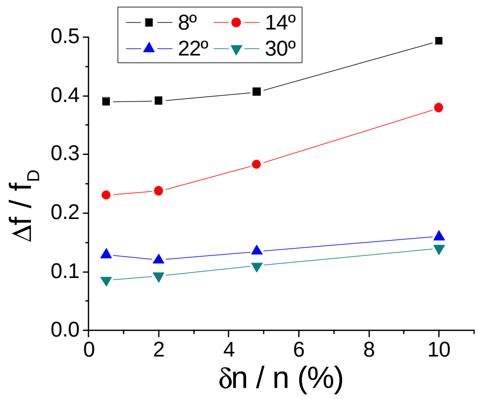

Figure 2. Normalised spectral width as a function of the rms level for 4 tilt angles.

In figure 1 we show the complex amplitude spectra of the simulated signals obtained for $\theta = 18^o$ and different turbulence levels. The Doppler shifted structure characteristics are obtained by fitting the non-symmetric part of the spectra with a Gaussian function $A_p \exp(-(f - f_p)^2 / \Delta f^2)$ where A_p is the amplitude of the Doppler peak, f_p is the Doppler peak frequency, and Δf is the spectral width. The Doppler shifted peak is located close to the expected position $f_p = f_D = k_\perp v_p / 2\pi$ irrespective of the turbulence level. This result holds when the tilt angle is varied from 8º to 30º. The important result is that over the range of turbulence levels and antenna tilt angles studied, the error in determining the perpendicular velocity of density fluctuations is lower than 5%. Figure 2 shows the normalized spectral width $\Delta f / f_D$ obtained from the Gaussian fits of the spectra. This figure shows that the spectrum broadening is influenced by the turbulence amplitude. Similar results were obtained with an analytical model in [6]. Two possible mechanisms may be responsible for the deterioration of the spectral resolution with increasing turbulence level: the broadening of the microwave beam due to high turbulence and the temporal modulation of the microwave beam, which also broadens the frequency spectrum. Figure 3 shows the Doppler peak amplitude of the spectra for different turbulence levels in the range $0.1\% \le \delta n_e / n_e \le 10\%$ ($\theta = 8^o$, i.e. $k_\perp / k_0 = 0.28$).

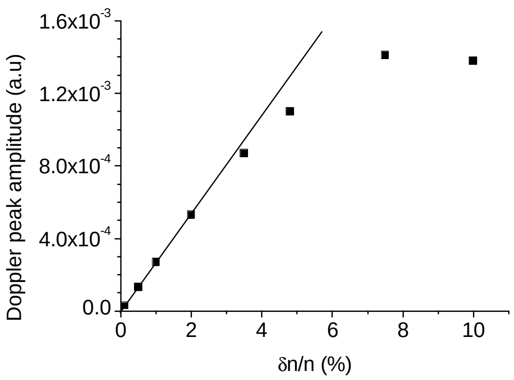

Figure 3. Doppler peak amplitude versus the rms value of the turbulence. The antenna tilt angle is 8º and $k_\perp / k_0 = 0.28$

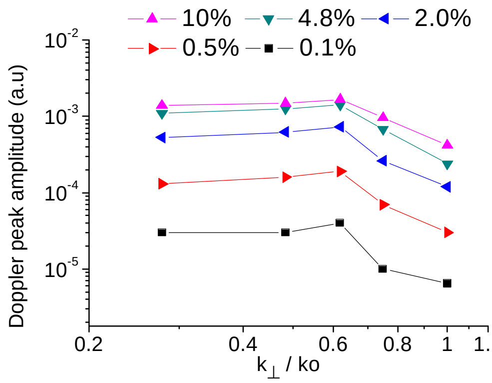

Figure 4. Log-Log plot of Dopper peak amplitude as a function of $k_\perp / k_0$ for different turbulence levels.

One observes a linear dependence between the Doppler peak amplitude and the turbulence level if the ratio $\delta n_e / n_e$ is below 2 %. In this regime, the Doppler peak amplitude can be used as a monitor of the turbulence level. Above this value, the dependence is not longer linear and the Doppler peak amplitude saturates when $\delta n_e / n_e$ is above 7%. In this regime, the Doppler peak amplitude does not reflect the changes in the turbulence level. The same result holds for the squared root of the frequency integrated power spectra. The saturation is due to multiple scattering of the microwave beam from the density fluctuations and (as a result) partial screening of the region close to the cut-off layer. Figure 4 shows a Log-Log plot of the Doppler peak amplitude of the spectra versus the normalised wave-number for five values of the turbulence level ($\delta n_e / n_e = 0.1$, 0.5, 2, 4.8 and 10 %). It shows that the backscattered power depends not only on the rms value of the turbulence but also on the probed wavenumber. Figure 4 shows a slight increase at low wave-numbers ($k_\perp / k_0 \leq 0.6$) and then a decrease at large wave numbers ($k_\perp / k_0 \geq 0.6$). The same trend is observed for the squared root of the frequency integrated power spectra. The results appear to be independent of the turbulence level. We have done additional simulations including a radial wave-number spectrum to the density fluctuations. First, we added 6 radial modes equally spaced within the range $-0.36 < k_r / k_0 \leq 0.36$, then we added 48 radial wave-numbers equally spaced within the range $-1.2 < k_r / k_0 \leq 1.2$. In both cases, the results do not change significantly and the same dependence of Doppler peak amplitude on $k_\perp / k_0$ is observed.

IV. Conclusions

An important result of the numerical simulations is that using Gaussian beams with optimized spot size the frequency of the Doppler shifted structure is in good agreement with the Doppler shift given by $f_D = k_\perp v_p / 2\pi$ irrespective of the turbulence level. Therefore, the perpendicular rotation velocity of the density fluctuations can be measured with high accuracy using Doppler reflectometry. Care must be taken in determining the level of density fluctuations from measured power spectra. The decreasing of the Doppler peak amplitude at large probed wave-numbers must be taken into account in the evaluation of the wave-number spectrum of the density fluctuations.

References

[1] M. Hirsch, E. Holzhauer, J. Baldzuhn et al. Plasma Phys. Control. Fusion 43 (2001) 1641

[2] G. Conway, J. Schirmer, S. Klenge et al Plasma Phys. Control. Fusion 46 (2004) 951

[3] P. Hennequin, C. Honoré, A. Truc, A. Quéméneur. Proc. 7th Intl. Reflectometry Workshop for Fusion Plasmas - IRW7 (Garching, May 2005), IPP Report 2/9, (2005) p74.
URL: http://www.aug.ipp.mpg.de/IRW/IRW7/proceedings.html

[4] E. Blanco, S. Heuraux, T. Estrada, J. Sánchez et al. Rev. Sci. Intrum 75 (2004) 3822

[5] E. Blanco, T. Estrada and J. Sánchez. Plasma Phys. Control. Fusion 48 (2006) 699

[6] E. Z. Gusakov, A. V. Surkov, and A. Yu Popov. Plasma Phys. Control. Fusion 47 (2005) 959