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Effect of the k-spectrum and the poloidal rotation of turbulence in reflectometry measurements

S. Hacquin, S. Heuraux[†], F. Silva, G. Leclert[††], M. Manso and F. Serra

Centro de Fusão Nuclear – Associação EURATOM / IST, Instituto Superior Técnico, Av. Rovisco Pais, 1049-001 Lisboa, Portugal

[†] *Laboratoire de Physique des Milieux Ionisés et Applications, UMR 7040 CNRS, Université Henri Poincaré, Nancy 1, BP 239, 54506 Vandœuvre Cedex, France*

[††] *Laboratoire PIIM, UMR 6633 CNRS, Univ. de Provence, Faculté de St Jérôme, Case 321, 13397 Marseille Cedex 20 France*

I. Introduction

The knowledge of density fluctuation characteristics (amplitude, *k*-spectrum, …) is crucial for a better understanding of turbulent phenomena in fusion plasmas. Combining high spatial and temporal resolutions, reflectometry can provide some interesting information on density fluctuations [1]. However, additional analytical and numerical work has still to be done in order to help to the interpretation of reflectometry measurements (still incomplete due to the complex phenomenon affecting the microwave beam in a fusion plasma). In particular, reflectometry measurements do not give yet in very convincing way an accurate quantitative information on density fluctuations. From full-wave simulations of reflectometry experiments, we show in this paper that the *k*-spectrum of density fluctuations can be deduced from the spectrum of probing wave phase variations. Including 2D simulations, this work proposes an extension of the 1D study presented in [2].

II. Simulation of fluctuation reflectometry experiments

Simulations of reflectometry experiments are computed from 1D and 2D full-wave codes solving the wave equation for the O-mode polarisation and assuming the cold plasma approximation. To simulate the turbulence, we use a multi-modal model of density fluctuations [3]:

$$\delta n_e(x,y) = \sum_{k_x=-n}^{+n} \sum_{k_y=-m}^{+m} a(k_x,k_y)\cos\big(k_x x + k_y y + \varphi(k_x,k_y)\big)$$

This model allows to create density fluctuations in both radial and poloidal directions (respectively x and y) with a given 2D *k*-spectrum. As the coefficients $a(k_x,k_y)$ fix the spectrum amplitude $S(k_x,k_y)$ of the density fluctuations, the random choice of the phases $\varphi(k_x,k_y)$ insures the non-coherent property. The "turbulent" fluctuations are then superimposed to the average density profile:

$$n_e(x,y) = \langle n_e(x,y) \rangle + \delta n_e(x,y)$$

A linear average density profile and fluctuations with an experimental-like spectrum [4] (i.e. plateau for $k < k_{lim}$ and k^{-3} decreasing for $k_{lim} < k < 15$ cm^{-1}) has been input in our code. An amplitude of density fluctuations of 1% (RMS value) has been considered in all the results presented here. To evaluate the phase variations induced by the density fluctuations, a I/Q detection technique is used by computing two signals in phase quadrature (phase and amplitude can be then separately inferred) [5].

III. Effect of turbulence radial displacement

In this part, we propose to show the link between the density fluctuation spectrum and the phase variation spectrum. By comparison with 1D results [2], we investigate the respective contributions of radial and poloidal density fluctuations on the phase variations. The simulations are computed for a fixed-frequency probing wave and the density fluctuations are moved in the radial direction during the time. This approach gives analogous results to the case of a swept-frequency probing wave propagating in a plasma with frozen density fluctuations [2]. The phase variations of the fixed-frequency probing wave are then evaluated using the I/Q detector technique presented in the previous section. Typical frequency sweeping time (≥ 20 µs) for broadband reflectometry or typical turbulence time scales for fixed-frequency reflectometry correspond to a large number of iterations resulting in long computing times for 2D codes. From 1D simulations we show that within a certain limit (as long as there is no significant temporal effect as trapping wave) the phase variations remain almost identical whatever the time scale of turbulence radial displacement.

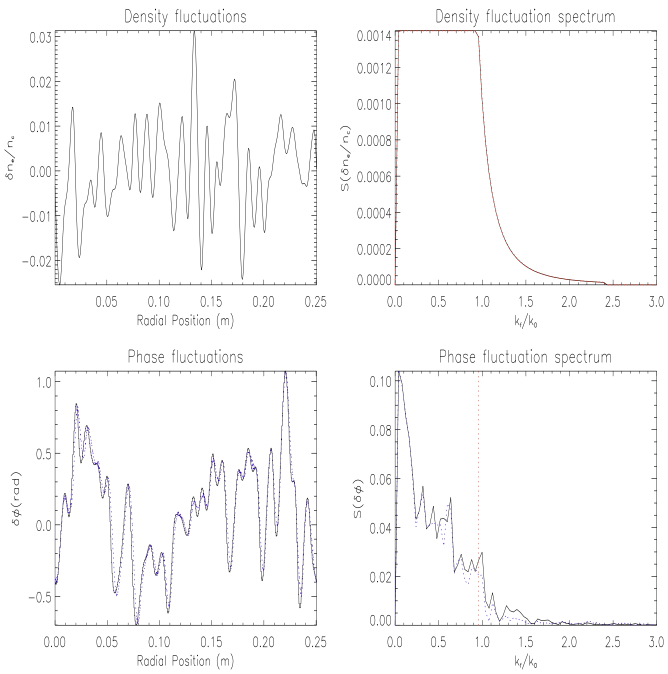

Figure 1: Density fluctuations and their spectrum (on top). Corresponding phase variations and their spectrum computed from 1D simulations for two time scales of turbulence movement (on bottom)

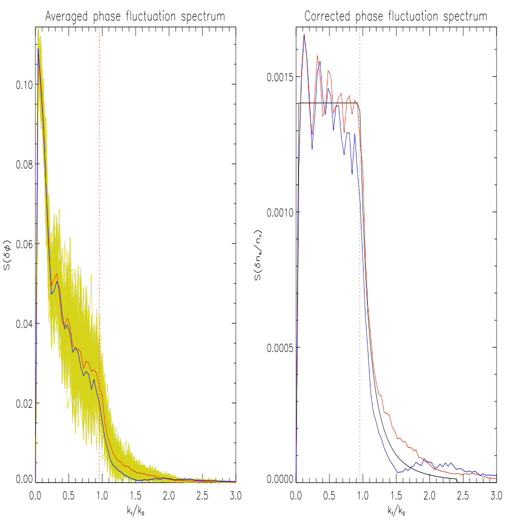

Figure 2: $\delta\varphi$ spectrum averaged using 100 samples (on left) and corrected $\delta\varphi$ spectrum fitting with δn_e spectrum (on right) for both time scales of turbulence movement in fig. 1

This is illustrated on figure 1 where the phase variations and its spectrum for two different time scales of turbulence movement (100 µs and 100 ns) are similar. Confirming previous results [3], this is used to reduce the computing time in the following 2D simulations. To get reliable information for a given spectrum, it is required to use a large number a phase set in our simulations. 1D simulations showed that 100 samples give a sufficient statistic to be representative of the chosen spectrum. However, to limit the computational time in 2D simulations, we only used 20 samples in this work. Figure 2 shows a comparison of phase variation spectrum reconstructed respectively from 20 and 100 samples (left picture). Although the accuracy for 20 samples can be too small to extract reliable quantitative information, no significant change is expected on the qualitative interpretation of the results. The right picture on figure 2 depicts the corrected phase variation spectrum fitting with the density fluctuation spectrum. More details on the procedure to recover the density fluctuation spectrum are given in [2].

We present now some results showing the contribution of poloidal density fluctuations on the phase variations. In the following cases, we have chosen the same radial spectrum of density fluctuations (k_{lim} = 6 cm^{-1}) and we compare the phase variations for three different poloidal spectra. The first example has been obtained without poloidal fluctuation (two left pictures on figure 3). Using the correction method to recover the density fluctuation spectrum, we can notice that both 1D and 2D results give the initial density spectrum. The discrepancies between 1D and 2D spectrum are probably due to a lack of statistic information (as only 20 samples have been considered). Both right pictures on figure 3 have been obtained in the presence of poloidal density fluctuations (spectra respectively with k_{lim} = 6 cm^{-1} and k_{lim} = 12 cm^{-1}). Whatever the poloidal fluctuation spectrum, the spectrum shape of phase variations remains the same and is imposed by the radial fluctuation spectrum for both 1D and 2D results. This confirms that the major contribution to the phase variations comes in this case from the radial fluctuations. We can also notice a significant decrease of the spectrum for the 2D simulations in the presence of poloidal fluctuations. This seems to indicate that the wider poloidal fluctuation spectrum, the smaller phase variations. Additional studies are carried out to investigate clearly the reason of this decrease.

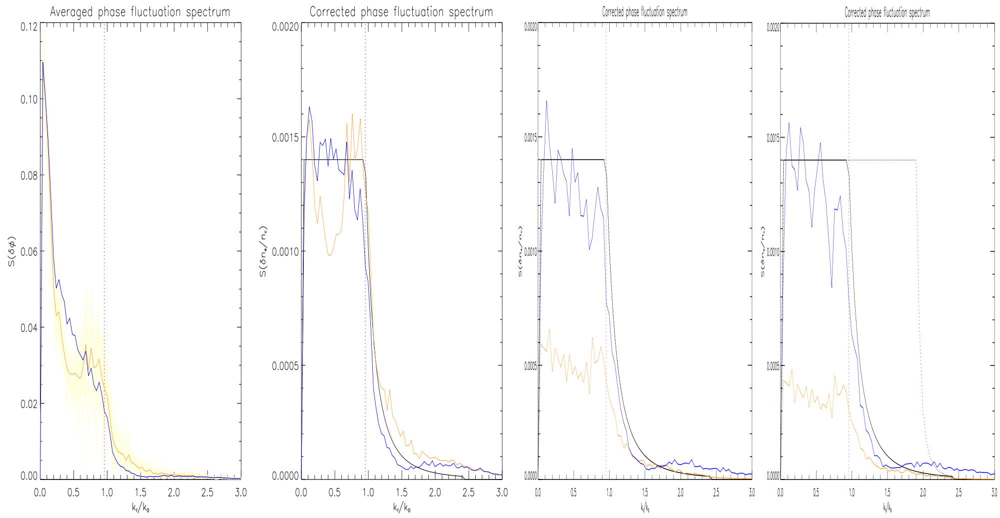

Figure 3: $\delta\varphi$ spectra from 1D and 2D simulations when only radial density fluctuations are present (two left pictures) and in the presence of poloidal density fluctuations with 2 different spectra (poloidal spectrum in dotted-line on two right pictures)

IV. Effect of turbulence poloidal rotation

In this section the effect of the poloidal rotation of turbulence in fixed-frequency reflectometry is studied. We first show a simulation in the presence of density fluctuations in both radial and poloidal directions (with identical spectra k_{lim} = 6 cm^{-1}). The spectrum of phase variations does no longer permit to recover the fluctuation spectrum (as shown on figure 4). It presents a detection limit quite smaller than in the case of turbulence radial movement. As expected the contribution on phase variations comes now from the poloidal fluctuations. Since the Bragg scattering by poloidal density flutuations correspond to small wave-numbers, the detection limit is small. This limit depends on the antenna characteristics as the poloidal wave-number range satisfying the Bragg rule is defined by the antenna radiation pattern. Another simulation with a poloidal spectrum of density fluctuations given by k_{lim} = 12 cm^{-1} is presented on figure 4 (two right pictures). The phase variation spectrum obtained in this case is quite similar from the previous one (with the same detection limit < k_{lim} = 6 cm^{-1}), except a reducing of spectrum amplitude (probably for the same reasons as in the previous section on figure 3). More simulations should be done in the future to get more quantitative information and could be used for instance to interpret Doppler reflectometry experiments in the case of an inclined antenna [6].

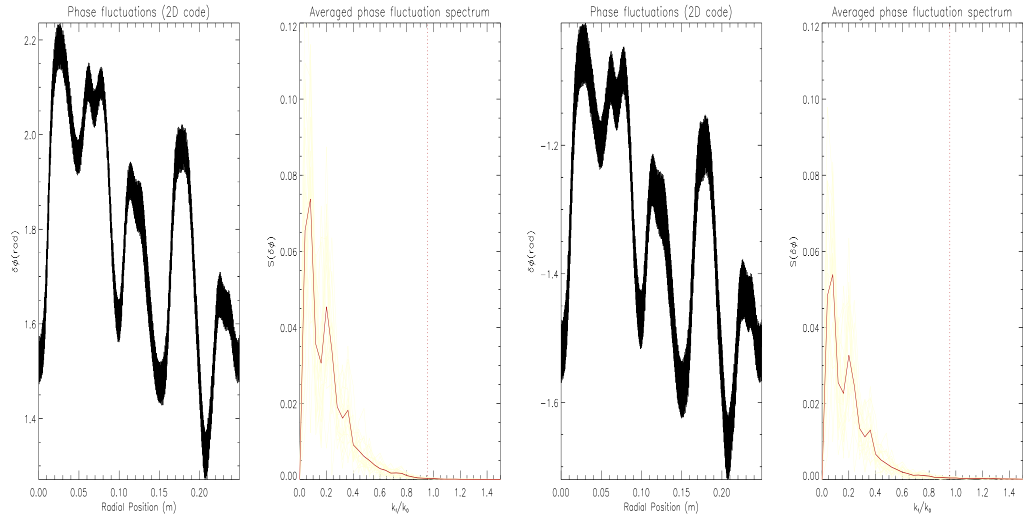

Figure 4: $\delta\varphi$ and $\delta\varphi$ spectrum due to turbulence poloidal rotation for a poloidal fluctuation spectrum with k_{lim} = 6 cm^{-1} (two left pictures) and with k_{lim} = 12 cm^{-1} (two right pictures)

V. Conclusion

Reflectometry simulations in the presence of large spectrum density fluctuations (in both radial and poloidal directions) are presented in this paper. It is first shown that the radial spectrum of density fluctuations can be inferred from the phase variations of the probing wave. By comparison with 1D simulations, we show that the major contribution to the phase variations comes from the radial fluctuations. We also put forward that the poloidal rotation of turbulence contributes (in a certain limit) to the phase variations. Additional studies are carried out to obtain more quantitative results.

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