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RADIAL WAVE-NUMBER SPECTRUM DEDUCED FROM PHASE FLUCTUATION SPECTRUM GIVEN BY A REFLECTOMETER

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Introduction

Reflectometry is a useful tool to give the edge density profile and to provide information on the plasma fluctuations. Up to now the data on plasma fluctuations are rather qualitative information, We explore here the possibility to obtain quantitative information about the density fluctuations, either plasma turbulence, namely on the wavenumber spectrum (k_f-spectrum) of the density fluctuation. As it has been put forward in the paper of Y. Lin *et al*[1], 1D simulations still remain useful and necessary to understand the numerous physical processes involved in tokamak plasmas. The method relies upon between radial wave-number spectrum (k_f-spectrum) and phase fluctuation spectrum of the signal of a swept frequency reflectometer. Due to the Bragg selection rule $k_f = 2k(x)$ between the incident local wavenumber and the k_f-component of the fluctuation spectrum, every incident frequency *selects a wavenumber at a given radial position in the density gradient*. For O-mode reflectometry [2] analytical expressions of the phase variations induced by monochromatic density perturbations are then used to rely the phase spectrum to the density fluctuation spectrum. The phase perturbation varies as $\Delta\phi \propto k_f^{-1/2}$: as expected, the main contribution comes from the small k_f, i.e. the vicinity of the cut-off layer. The density gradient length L_n also renormalises the phase variation, $\Delta\phi \propto L_n^{1/2}$: For X-mode reflectometry, there is no simple dependence of the phase on the wavenumber or gradient length, and we establish empirical rules. For a wide k_f-spectrum of the density fluctuations, the present analysis shows as expected that all wave-numbers up to the Bragg detection limit ($k_f \leq 2k_o$ vacuum wave-number) contribute to the phase fluctuations.

Phase fluctuation spectrum versus density fluctuation k-spectrum.

For convenience, the simulations have been done at fixed frequency, density fluctuations with a given turbulent spectrum being moved down the density gradient to mock up the frequency sweep. We assume a linear density profile and density fluctuations with constant relative amplitude over the whole plasma. The results shown on figure 1 have been obtained after averaging over 50 fluctuation samples. As we use both O and X modes, the frequencies and plasma parameters have been chosen to probe the same zone that is to say the cut-off positions are the same for the ordinary (O) mode and the extraordinary (X) mode.

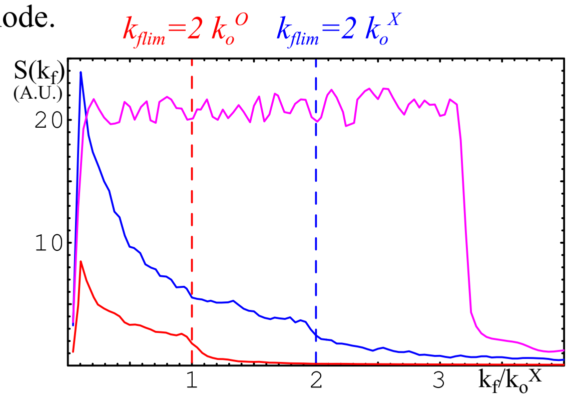

Figure 1: Phase fluctuation spectrum for O (red) and X (blue) modes on the same probed zone with the detection limits (dashed lines)

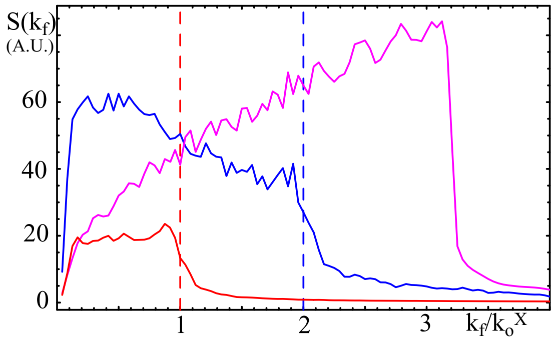

Figure 2: Phase fluctuation spectrum O and X modes induced by density fluctuation spectrum $S(k_f)\,\alpha\, k_f^{1/2}$.

The input density fluctuation spectrum has to be taken wide enough to reach the upper limits of the both modes.

To verify the wavenumber dependencies given in the Fanack's paper [2] for the O-mode, proportional to one over the square root of the fluctuation wavenumber, we choose an input density fluctuation spectrum proportional to the square root of the wavenumber. The phase fluctuations spectrum for the O-mode is then flat as expected (fig 2.) and exhibits clearly the detection limit at $k_f = 2k_o$. The X-mode phase fluctuation spectrum shows different dependencies for high k_f values in the Bragg backscattering resonant zone. For a linear density profile and low constant magnetic field the high k_f part behaves roughly as $k_f^{-3/4}$. Near the cut-off layer, the low k_f part behaves like the O-mode namely proportional to $k_f^{-1/2}$. In the case of the X-mode, the index is never linear in realistic cases and the correction to reconstruct the density fluctuation k_f-spectrum has to take into account the dependencies in k_f and the index gradient length at the same time.

Method to reconstruct density fluctuation wavenumber spectrum (k_f-spectrum).

To recover the density fluctuation k-spectrum from the phase fluctuation spectrum in the case of the O-mode reflectometry, the above mentioned corrections of the phase response with k_f and L_n are applied. To compensate these dependencies, the phase fluctuation spectrum is multiplied by the square root of k_f. It is further divided by the square root of the local value of the density gradient length, taken at the Bragg resonant position corresponding to the selected value of k_f. To illustrate the efficiency of this method, we have compared the reconstructed density fluctuation k_f-spectrum and the input spectrum on figure 3. The upper detection limit $k_f = 2k_o$ is clearly seen. At low k_f values the reconstructed k_f-spectrum differs slightly from the input one, this situation corresponds to the case where the probing zone length is of the order of the density fluctuation wavelength. Other situations have been simulated with different shapes for the input k_f-spectrum (gaussian, experiment like [3], ...) and have been recovered by this method. The procedure can also be used in the case of X-mode reflectometry with the appropriate parameters.

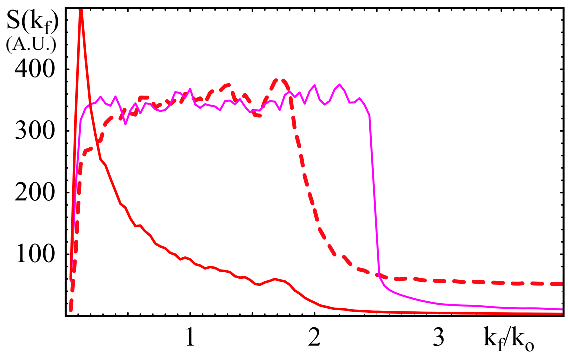

Figure 3: Phase fluctuation spectrum for O-mode for parabolic density profile (red line), reconstructed density fluctuation spectrum (red dashed line) and the input (magenta).

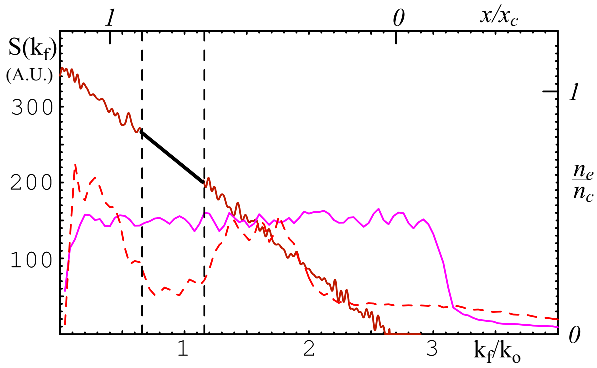

Figure 4: Reconstructed density fluctuation spectrum (dashed) induced by the input density fluctuation profile (brown) and the input spectrum (magenta).

Spatial localisation

As shown on figure 4 we have removed the density fluctuations in one part of the density profile. Due to the localisation of the Bragg back-scattering, it is possible to associated a range of density fluctuation wavenumbers which is then removed from the reconstructed k_f-spectrum corresponding to the hole in the k_f-spectrum on figure 4.

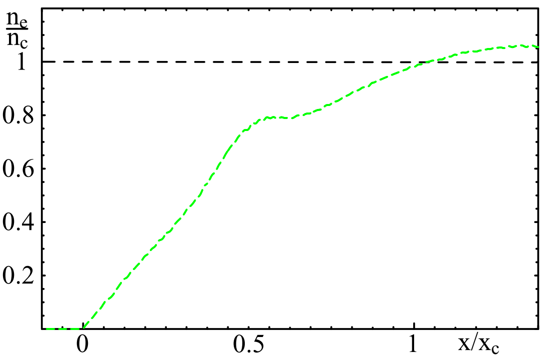

Figure 5a: Parabolic density profile with a MHD-like perturbation and extensive density fluctuations with an amplitude of 1 %

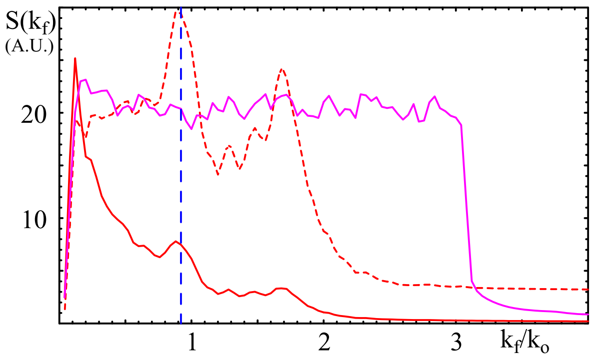

Figure 5b: Reconstructed density fluctuation spectrum (red dashed) from phase fluctuation spectrum (red) induced by the input spectrum (magenta).

If one assumes the same relative k_f-spectrum over all the plasma, it is then possible, from the analysis of the phase fluctuation spectrum, to determine the radial evolution of the amplitude of the density fluctuations: since a given position corresponds to each k_f, the range of the removed wavenumbers determine where the density fluctuation amplitude has disappeared. There are however several problems which need to be carefully analysed. For instance, the phase fluctuation response is very sensitive to the local density gradient length as shown on the figures 5. In this case the average density gradient (parabolic profile) is perturbed by a large amplitude MHD perturbation (figure 5a). The “turbulent” spectrum is superimposed on it. On figure 5b, the average parabolic profile has been taken into account to extract the k_f-spectrum. The large discrepancy between the reconstructed spectrum and the input spectrum result from the large density gradient zone due to the MHD perturbation. The vertical dashed line indicates the Bragg resonant wavenumber for this zone.

Application to Tore Supra experimental data

Our method used to obtain the k_f-spectrum of the density fluctuations has been applied to the phase data (30 ramps with 1000 points/ramp) given by the Tore Supra (TS) swept heterodyne reflectometer [4]. The preliminary results exhibit a maximum in the k_f-spectrum around 3-4 cm^{-1} in the case of ohmic discharges and the existence of the Bragg detection limit has been shown on figure 6. This information extracted from the standard TS reflectometer data permits to estimate the best operation conditions for fluctuation measurements: number of ramps ~100, number of points per ramp ~ 4000 and frequency range has to be wide enough to see small wavenumbers.

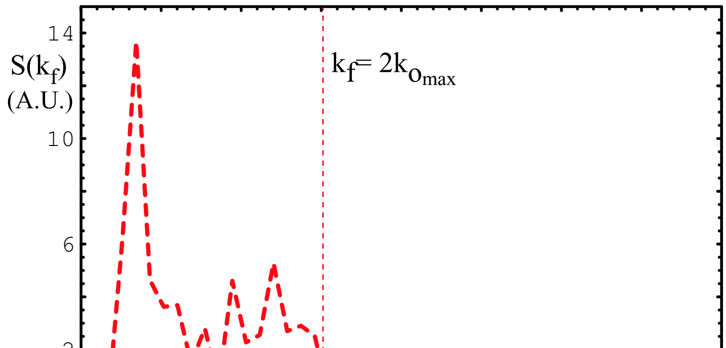

Figure 6: Reconstructed k_f-spectrum from Tore Supra reflectometer phase measurement with the O-mode reflectometer in ohmic discharge.

References

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