O- and X-mode Radial Correlation Doppler Reflectometry in 2D Full Wave Simulations and Experiments

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Introduction

Plasma turbulence plays a key role in determining the transport properties of fusion plasmas, therefore a deep understanding of turbulence properties is required for performance predictions of fusion devices. Radial Correlation Doppler Reflectometry (RCDR) is a diagnostic used to study perpendicular wavenumber ($k_\perp$) resolved density turbulence. It uses two Doppler channels with a oblique probing angle θ at slightly different probing frequencies. The correlation of the signals of both channels allows to study the radial structure of the turbulence and gives an estimate of its radial correlation length L_r [1].

Recent results using simple models and synthetic turbulence [2] have shown that it can also be possible to extract the tilting and elongation of the turbulent structures. However, the wave-plasma interaction may induce a complex non-linear response [3, 4], which makes the interpretation of the experimental data and the evaluation of L_r, elongation and tilting difficult.

In this paper the role of the relevant parameters for the RCDR response (turbulence level, $k_\perp$ and probing frequency) is systematically studied by means of 2D Full Wave Simulations (2DFW) for both, Ordinary(O)- and Extraordinary(X)-mode propagation. Moreover experimental results from the ASDEX Upgrade tokamak are presented and compared with the simulated data.

2D Full Wave Simulations

The effects of the wave-plasma interaction produce a complex and in general non-linear response of RCDR. This has been numerically studied in [5] using 2D Full Wave simulations (2DFW) [6], which solve the Maxwell equations in the plasma containing all the relevant physical effects. Here we extend such numerical studies presented in [5] using the same code. We study a more realistic k-spectrum and perform a broad scan of the parameters involved.

The simulations are performed in slab geometry, where x and y correspond to the radial and poloidal coordinates, respectively. The background density profile is linear, $n_0(x) = n_c \cdot x/l$, with a cut-off at $l = 5$ cm from the plasma boundary and a cut-off density $n_c = 4.5 \cdot 10^{19}$ m^{-3}. Simulations are performed for O- and X-mode with probing frequencies of 60.2 GHz and 94.4 GHz, respectively. An uniform magnetic field of 2 T is applied in the z-direction.

An elongated and tilted 2D Gaussian k-spectrum is taken in order to produce elongated and tilted turbulent structures. The synthetic turbulence field $\delta n(x,y)$ is computed using fast Fourier transform after including a random complex phase. The selected correlation length of the turbulence is 1.4 cm in x-direction (L_r) and 0.5 cm in y-direction. The normalization of the turbulence field is chosen to set the required turbulence level given by rms $= \delta n_{\text{rms}}/n_c$

Results of the simulations

We study the turbulence level effect on the measured correlation length from the O-mode 2DFW data. It can be observed in Fig. 1a that the correlation as a function of the separation of the channels decays faster for a higher rms. Hence the *measured* L_r, defined as the distance at which the correlation decays to $1/e$, decreases with the turbulence level. The dependence of L_r with rms for a broad range is also shown in Fig. 1b.

For small rms an approximately constant L_r is observed, this corresponds to a linear regime, notice however that the L_r does not match the true value. For larger rms the L_r decreases rapidly underestimating strongly L_r, this shortening corresponds to the transition to a non-linear regime.

The probing angle θ hence the probed $k_\perp$ also have an effect on the measured L_r. In Fig. 2a the correlation decays faster for a larger θ, which corresponds to larger $k_\perp$. This effect induces a dependence of L_r with θ, which differs for linear and non-linear regimes, Fig. 2b.

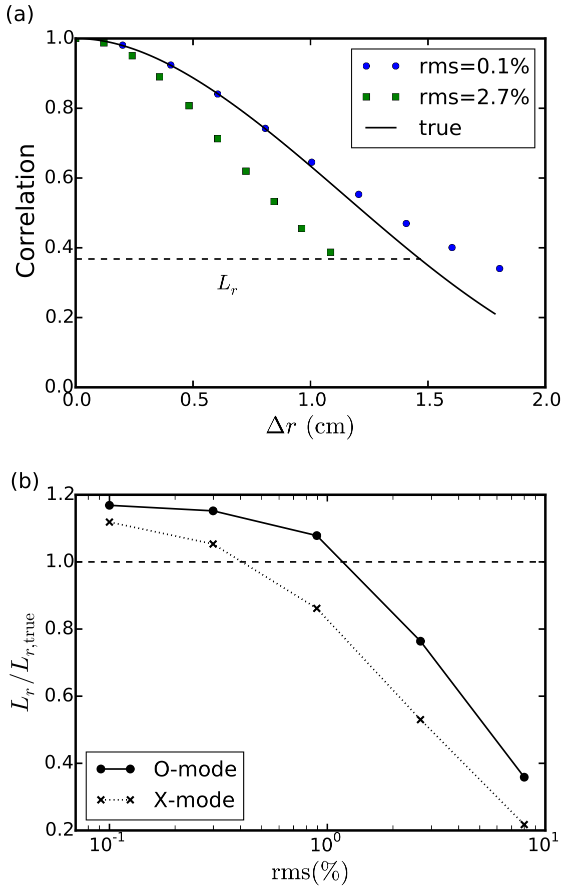

Figure 1: *Simulated (a) O-mode correlation for different rms values and (b) L_r as a function of rms for O- and X-mode. All cases for $\theta = 8.7°$.*

In the linear regime L_r is over(under)-estimated for small(large) θ. This is in disagreement with the matching of the true L_r at large θ predicted in [3]. The true value of L_r is matched only at some probing angle, however from such a scan it is possible estimate the true L_r [5]. On

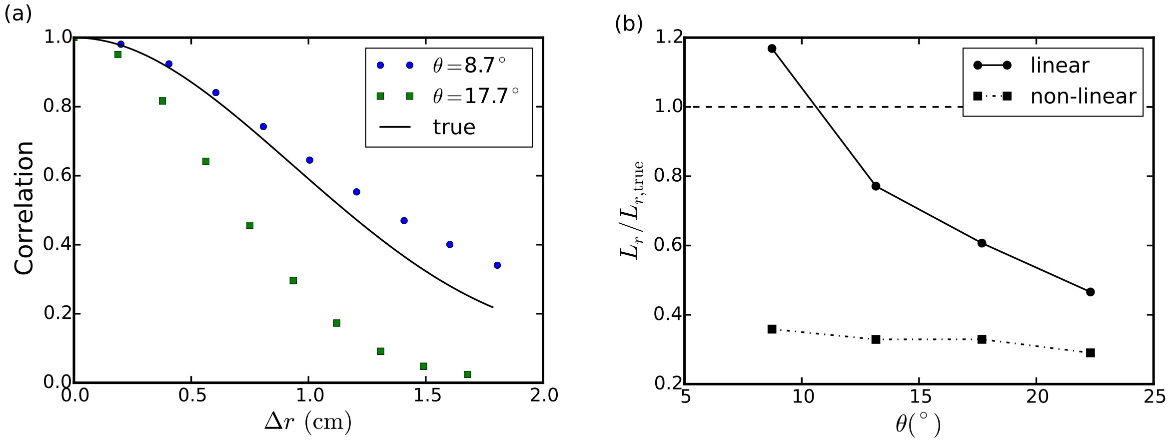

Figure 2: *Simulated (a) O-mode correlation for two θ values with rms=0.1%, and (b) L_r as a function of θ for linear (rms=0.1%) and non-linear (rms=8%) regimes.*

the other hand in the non-linear L_r is short and does not depend on the angle, this null or slight dependence can be taken as a signature of non-linearity.

Results of O- and X-mode are compared in order to study the role of the polarization and probing frequency (which in this case differs by $f_x \approx 1.5 f_O$) for the linearity of the response, however from Physical Optics modeling [7] the second effect is expected to be significantly more relevant. In Fig. 1b the dependence of L_r with the rms value is compared for O- and X-mode. It can be observed that the O-mode remains linear for a larger rms range while the X-mode runs faster into the non-linear regime [3]. From these result it can be concluded that the high probing frequencies are more likely to give a non-linear response, and therefore O-mode is better suited for RCDR measurements.

Experimental measurements

Correlation measurements in the ASDEX Upgrade tokamak were performed. The chosen scenario was upper single null L-mode discharges with a mean density of $5 \cdot 10^{19}$ m^{-3}. The O(X)-mode reflectometers operate in the V(W)-band using frequencies in the range 50-75 GHz (75-105 GHz).

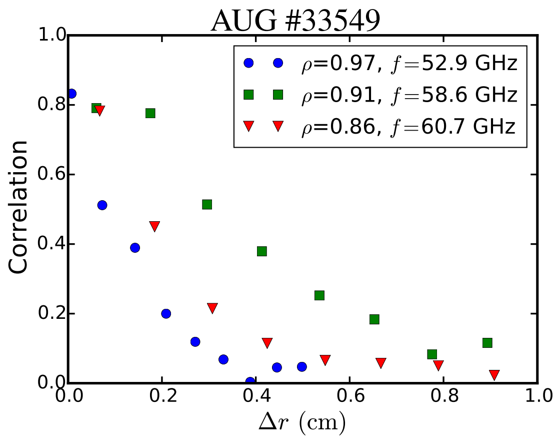

Figure 3: *Experimental O-mode correlation at different radial positions.*

The correlation measurements for O-mode are shown in Fig. 3, where three different radial positions for the same angle of incidence ($k_\perp \approx 6$ cm^{-1}) are compared, the heterodyne signal was used for the calculation. A faster drop of the correlation in the edge $\rho = 0.97$ compared with an intermediate position $\rho = 0.91$ can be observed, this can be understood as the transition from non-linear to linear due to the fast decrease of the turbulence level with decreasing ρ at the edge. For a more internal position $\rho = 0.86$ there is also a fast decay of the correlation, this might be explained either by a non-linear response due to the higher frequency required or by a real shortening of L_r in such an inner position.

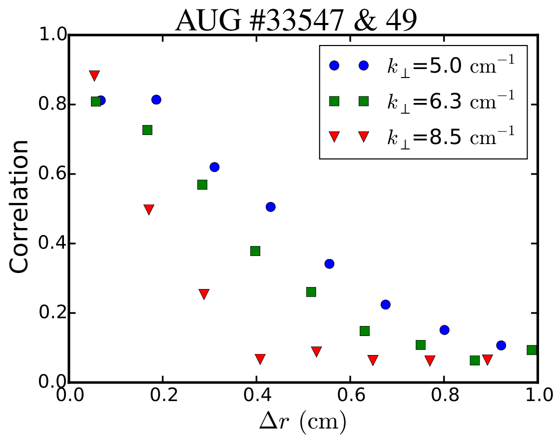

Figure 4: *Experimental O-mode correlation for different* $k_\perp$ *at* $\rho = 0.91$.

The correlation at $\rho = 0.91$ is compared for different $k_\perp$ in Fig. 4. A decrease of L_r with $k_\perp$ can be observed. This in agreement with the linearity at this radial position.

Notice that the O-mode correlation does not seem to converge to 1 for zero radial separation, even though both channels had the same electronics (emission and detection). For X-mode this problem is worse since both channels have different electronics, it reduces the level of correlation considerably obtaining maximum 0.4 correlation. Despite of the correlation reduction, X-mode results show similar trends as the O-mode. Further data analysis is required.

Conclusions

A systematic study of RCDR using 2D Full Wave simulations is presented, the role of the turbulence level (rms), probing angle and frequency is analyzed. It is found that the probing frequency has a major impact on the linearity of the diagnostics response, such that it is more convenient to use lower frequencies and therefore O-mode. A better understanding of $L_r(\theta)$ in the linear regime is required.

Correlation measurements for O-mode in the ASDEX Upgrade tokamak are presented and analyzed. The most useful correlation measurements are obtained at $\rho = 0.91$, edge and inner measurements seem to be non-linear. Further analysis of experimental data is undergoing.

References

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