On the possibility to use a fast 2D interpretative model for analysis of fusion plasma turbulence from reflectometry data

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Introduction

Reflectometry is expected to be one of the main diagnostics for core turbulence measurement in ITER. In particular ultra-fast swept frequency reflectometry can provide valuable information about the level and radial k-spectrum of turbulence. But due to the complexity of wave propagation processes into turbulent plasmas, analysis of reflectometry data becomes tricky. For radial swept reflectometry data interpretation a close-loop algorithm with 1D full wave code can be used [1]. However it was shown that it is very important to take into account 2D effects [2]. Due to elongation of turbulence structures in the toroidal direction the third direction is thought to have little influence. In this paper we take a closer look to the interpretation of radial ultra-fast swept reflectometry data. To compute the transfer function (linking the reflectometer response to the turbulence properties) with full wave code, the phase fluctuation spectrum should be averaged over a set of different turbulence realizations [1]. Despite the constant progress of computer speed 2D full-wave computations are still very time-consuming and their routine use for reflectometry data interpretation remains limited. The validation of simplified 2D models, much faster than full-wave computations, is then a prime interest. In this paper we use reciprocity theorem [3] to compute the reflectometer phase variations induced by turbulence. This model is valid for low level of density perturbations, provided that the amplitude of phase fluctuations varies linearly with the turbulence level. This linear regime usually applies for turbulence levels of tokamak core plasmas. But in the plasma edge region one can have high density perturbation levels up to 25% of the cut-off density n_c. The influence of high amplitude density fluctuations in core reflectometry measurement is investigated in the next section.

Edge turbulent layer effects on phase perturbation of reflectometry signal

The crossing of high level of turbulence in the edge region results in probing wave front distortion and probing beam widening, which can be seen as the incoherent part of the probing

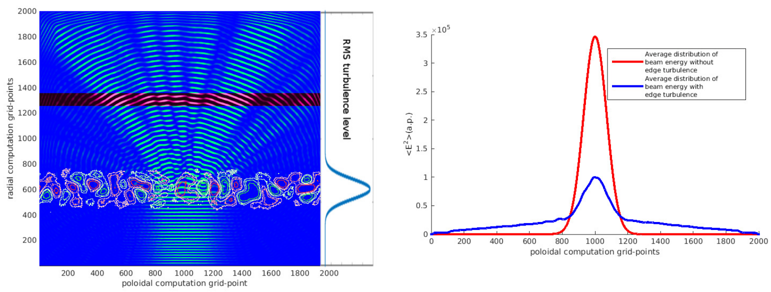

Figure 1: Left: Full-wave computation of the electric field amplitude after propagation through a turbulent layer (turbulence with rms amplitude of 10% of the cut-off density and with isotropic and flat spectrum for $0 < k < 0.5k_0$) where k_0 is the vacuum probing wave-number) Right: electric field power averaged over a set of turbulence realizations at one radial position after turbulent layer (red line on left figure). Red - without edge turbulence layer, Blue - with edge turbulence layer

beam. In the meantime another part of the beam propagates through the turbulence layer without changing its phase and its shape, the so-called coherent part of the beam. On Fig.1 one can see comparison of energy distribution of the beam propagating trough tokamak plasmas with and without turbulence layer in the plasma edge region. It is clearly seen that the beam energy distribution consists of two Gaussian components. This figure was obtained using average over a set of FDTD full-wave code [4] runs with different turbulence realizations. Theory, which explains these effects, can be found in the following papers[5][6]. It was shown that attenuation of the coherent part and widening of the not coherent part depends on the turbulence correlation length. After crossing the edge turbulence layer the coherent part of the probing beam amplitude can be expressed as $E = E_0 e^{-\alpha l}$ where l is the turbulence correlation length, E_0 is the coherent wave amplitude before propagation through the turbulent layer and E after. On the other hand the widening of the non-coherent part can be expressed as $\delta w^2 = \beta / l$ where δw^2 is the change of the beam size, α and β are coefficients depending on turbulence properties [5][6]. Therefore one can notice from these two expression that when the turbulence correlation length l increases the amplitude of coherent part E decreases while the widening of the non-coherent beam is less pronounced [5][6].

The effect of edge density large perturbations on swept reflectometry signal probing the plasma core region has not been clearly investigated. To study this we have carried out swept reflectometry modelling with the "FD3D" full-wave code [4] for O-mode wave. The turbulence is assumed to be isotropic, homogeneous, small level (0.5% of cut-off density) of density perturbations in the plasma core and high level with gaussian-amplitude envelop in the plasma edge region. In order to discriminate contribution from high level edge turbulence and from the core region we use only high k components for core turbulence and only small k components for edge turbulence. One can see results of these full-wave computations on Fig.2. For both edge and core turbulences here we use isotropic, flat spectrum. As a result we notice that the reflectometry response from high k-numbers (plasma core) becomes higher when the edge turbulence level increases. This could be explained by faster loss of received amplitude of the reflected wave E_{out} than received amplitude of scattered wave E_s, which tends to increase phase variations $\delta\phi = atan(E_s/E_{out})$ [7]. We can see that some effects start playing a role from very high values of turbulence amplitude. Triggering non-linear effect with high values of perturbation amplitude results from the fact that widening of the not coherent part leads to strong wave spreading near the cut-off layer. On the way back the probing beam crosses the edge turbulence layer once more and if the antenna position is far from the turbulence region, the not coherent beam becomes so wide that the antenna receives only very small part of it. As the not coherent beam widening increases with shorter correlation length of the turbulence, wider spectrum of turbulence does not change the phase spectrum up to higher values of perturbations amplitude and thickness of the turbulent layer (magenta curve in Fig.2). This means that in most of the cases edge turbulence does not break the linear approximation assumption when probing the plasma core region. In these cases we can use the analytical model [3] to determine the scattered field and the resulting phase variations. This result was found with relatively small thickness of turbulence layers (16 vacuum wavelengths). If the turbulence layer is thicker it decreases the limit of turbulence amplitude up to which the edge turbulence does not affect core measurements.

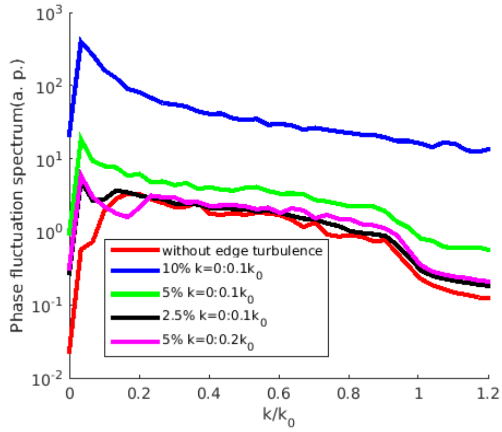

Figure 2: k-spectrum of phase variation from full-wave computations with the same core turbulence spectrum ($0.2k_0 < k < k_0$) and different edge turbulence spectra: red - without edge turbulence, blue - $rms(\delta n) = 10\%n_c$, $0 < k < 0.1k_0$, green - $rms(\delta n) = 5\%n_c$, $0 < k < 0.1k_0$, magenta - $rms(\delta n) = 5\%n_c$, $0 < k < 0.2k_0$, black - $rms(\delta n) = 2.5\%n_c$, $0 < k < 0.1k_0$

Validation of the method based on the reciprocity theorem with 1D and 2D X-mode full-wave computations in JET plasmas

We have compared the analytical model [3] with 1D and 2D full-wave computations. Turbulence is assumed with isotropic spectrum $S_k \propto k^{-\alpha(R)}$. Fig.3 shows that even for the big scale of JET tokamak, reciprocity theorem approach results is very close to 2D full wave modelling. But phase variation spectrum from 1D code has higher amplitude. It can be explained by the fact that 1D code does not take into account phase blurring due to turbulence poloidal spectrum.

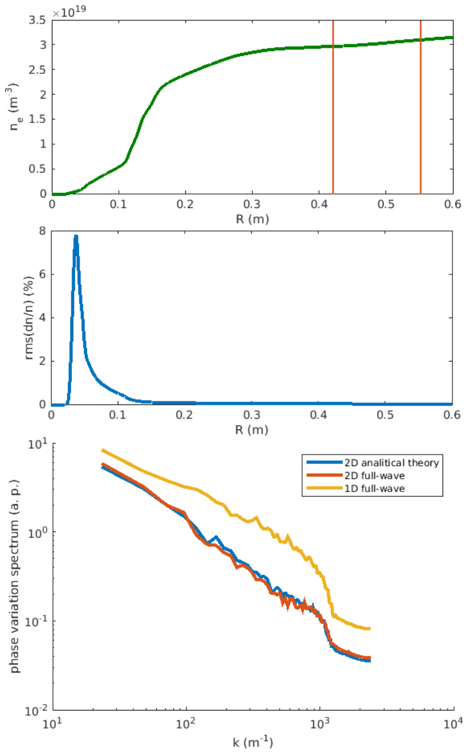

Figure 3: up: $n_e(R)$ and $\frac{rms(\delta n(R))}{n(R))}$ profiles with cut-off positions. down: $\delta\phi$ k-spectrums: blue - 2D analitical model, red - 2D full-wave code, yellow - 1D full-wave code

Conclusions

The change of phase variation spectrum due to high level edge turbulence was studied. It was shown that edge turbulence increases the sensitivity of phase variations to low level core turbulence. This effect becomes stronger with higher edge turbulence amplitude. Small correlation length of turbulence can reduce this effect. For most of typical plasma discharges edge turbulence is not believed to significantly affect the reflectometer measurement of small level core turbulence. Comparison of analytical model to 1D and 2D full-wave computations has shown that the reciprocity theorem is a good approximation for small levels of turbulence and can be used with close loop algorithm. 2D effects reduce phase variation amplitude and 1D full-wave computation is no longer valid in this case.

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