Impact of plasma edge and scrape-off layer turbulence levels on conventional O-mode reflectometry investigated with REFMUL and GEMR codes

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Introduction

The relative amplitude of electron density fluctuations $\delta n_e/n_e$, i.e. the plasma turbulence level, may determine both the analytical modelling possibilities and the measuring capabilities of reflectometry diagnostics. On one hand, high fluctuation levels may break down the Wentzel-Kramers-Brillouin (WKB) and Born approximations in modelling the scattering processes [1]. On the other hand, the experimental measuring capabilities, including of density fluctuations themselves, may become limited above a given turbulence level due to non-linearity and saturation of the reflectometry signals (e.g. see [2-3]). This is particularly relevant in the edge and scrape-off layer (SOL) plasma regions where density fluctuation amplitudes are usually high due to high turbulence levels ($\delta n_e/n_e$ > 10%) and/or the abundant presence of high density perturbations ($\delta n_e/n_e$ ~ 100%) known as blobs or filaments (e.g. see [4-5]). In this work, the impact of the turbulence level on conventional O-mode reflectometry is studied with a synthetic reflectometer, implemented on the well-established 2D full-wave code REFMUL [6], embedded on numerical plasma descriptions given by the 3D gyro-fluid code GEMR [7-8].

The REFMUL code

REFMUL is a full-wave code that solves the Maxwell equations in 2D for O-mode wave propagation. It employs the finite-difference time-domain (FDTD) technique using the Yee schema [9]. For O-mode, the cut-off condition $n_c = f_o^2(4\pi^2\varepsilon_o m_e/e^2)$, where f_o is the probing frequency, e the electron charge, m_e the mass of the electron and ε_o the permittivity of free space, sets the critical electron density n_c where reflection occurs in the plasma. In this work, the case of plasma probing at fixed frequency in conventional set-up (i.e. normal incidence) is treated, since such systems have been traditionally devoted to study density fluctuations. A monostatic design is employed together with a unidirectional transparent source, allowing separation of the emitted probing wave from any returning waves [6]. An H-plane horn antenna with half power beam diameter of ~ 6.5 cm at the plasma entry was chosen, with the on-axis line-of-sight at the low magnetic field side (LFS) mid-plane. An *I*/*Q* detection scheme, providing synthetic in-phase $I(t) = A(t)cos[\varphi(t)]$ and quadrature $Q(t) = A(t)sin[\varphi(t)]$ signals is included, similarly to what is typically measured in experiments. Details on how the *I*/*Q* signals can be combined to compute the returned amplitude $A(t)$ and phase $\varphi(t)$ reflectometry signals, in particular for the case where the background and turbulent terms of density fluctuations are probed independently as in the case of GEMR output data, will be published elsewhere [10].

The GEMR code

To obtain the characteristics of edge and SOL plasma turbulence, the evolution of density fluctuations and profile gradient was computed using a 3D electromagnetic gyrofluid model. This model solves the first six moments of the gyrokinetic equation in global geometry. The geometry is global in the sense that both poloidal and radial dependencies of geometrical quantities are kept, without using the flux tube approximation. GEMR simulations were carried out assuming a simplified magnetic equilibrium with circular plasma cross-section. The radial domain included both closed and open field line regions (edge and SOL regions, respectively) and local plasma parameters representative of a typical L-mode discharge at the ASDEX Upgrade (AUG) tokamak [11]. In particular, the major radius R = 1.65m, minor radius a = 0.5m, magnetic field B_t = 2.6T, ion and electron temperatures $T_i = T_e$ = 60eV, ion and electron densities $n_i = n_e = 1.2\times10^{19}\text{m}^{-3}$, temperature and density gradient scale lengths $L_T = L_n/2$ = 3.5 cm, nuclear mass of deuterium M_D = $3670m_e$, effective nuclear charge number Z_{eff} = 2, and safety factor q = 4.6. The evolution of electron density data, along the GEMR simulation, was recorded at several sequential time iterations. After post-processing the data, it was rendered on a poloidal plane thus taking into account the cross-section of the magnetic flux surfaces. Further details about the GEMR simulation run, the required steps for coupling of GEMR and REFMUL, and the first results obtained from using the two codes together will also be reported in [10].

An example of a GEMR density snapshot for AUG-like parameters is shown in Fig. 1. Also displayed in the figure is a zoom in a typical region of interest on the equatorial LFS used for REFMUL simulations. The region is chosen ensuring that it remains away from the boundaries where GEMR source and sinks act.

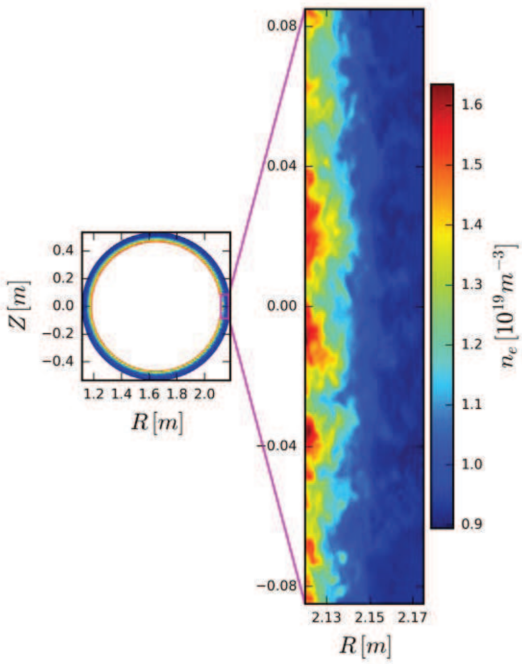

Fig. 1: GEMR electron density data on a poloidal plane cut, defined on a polar geometry, and zoom on region employed for REFMUL simulations.

Turbulence level scan

In this work, for the purpose of scanning a comprehensive range, of several orders, of plasma turbulence levels, the turbulent components of the GEMR density data, taken directly from the GEMR output, are scaled prior to being used in REFMUL. Note that the original GEMR data considered here displayed only a very narrow range of turbulence levels (~ 3-6%) across the region of interest. Simply, a scaling factor is applied in order to increase or decrease the fluctuation level. This may not guarantee a fully realistic description of turbulence along the conditions that set different turbulence levels in a tokamak, for instance w.r.t spatial correlation lengths. However, to characterize the reflectometer response it is useful to study the impact of $\delta n_e/n_e$ variations without further effects. Equivalently, the same background density (profiles) is taken as it was obtained from the self-consistent evolution of GEMR, for all turbulence levels. Only one probing frequency f_o = 30 GHz was selected. The density gradient length at the corresponding cut-off location was L_n = 10 cm. The root mean square of the density fluctuations at the cut-off position (i.e. turbulence level at the cut-off $\delta n_e/n_c$) was thus varied covering the range ~ 0.07-70% on a set of different REFMUL simulation runs. The phase fluctuations measured by the synthetic reflectometer across the entire turbulence level scan are displayed in Fig. 2. A linear relation between reflectometry phase fluctuations and the amplitude of small density perturbations is expected in simplified 1D theory, where Bragg backscattering (BBS) is accounted as the main scattering mechanism [12-13].

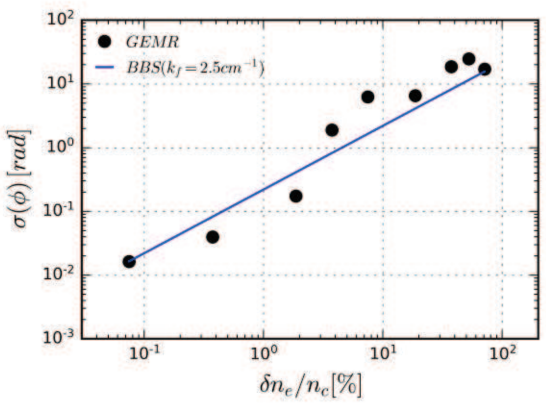

Fig. 2: Standard deviation of simulated reflectometry phase φ(t) at the corresponding turbulence levels at the cut-off location $\delta n_e/n_c$. Also shown (solid line) is the theoretical estimate of 1D Bragg backscattering contributions.

The relation $\delta\varphi = k_o (\pi L_n/k_f)^{1/2}\delta n_e/n_c$, where k_o is the probing wavenumber and k_f is a given wavenumber component of the density fluctuation spectrum, was given in [13]. This theoretical estimate is also shown in Fig. 2, computed with an effective turbulence wavenumber k_f = 2.5cm^{-1} estimated from the inverse radial correlation length $1/l_c$, where l_c was computed at the cut-off location directly from the GEMR data [10]. In previous studies, with different plasma models, an excellent agreement between the simulated data and expected linear response was observed only for low turbulence levels (up to $\delta n_e/n_c$ ~ 2-4%) followed by a transition to a non-linear regime and eventual saturation (e.g. [14-15]). In Fig. 2, the simulated data oscillates around the theoretical estimate, without departing considerably from the linear trend predicted by the 1D BBS theory. It appears that a better agreement is found across the whole turbulence range, at the cost of lower accuracy in the low turbulence levels. However, several GEMR runs would be required to assess the error associated with the simulated data.

The standard deviation of the amplitude fluctuations from the corresponding reflectometry signals are shown in Fig. 3.

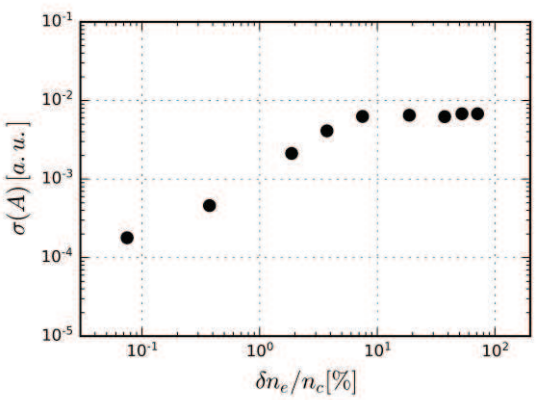

Fig. 3: Standard deviation of simulated reflectometry amplitude A(t) at the corresponding turbulence levels at the cut-off location $\delta n_e/n_c$.

The fluctuations in amplitude scale linearly with the amplitude of the density perturbations up to $\delta n_e/n_c$ ~ 10% and then saturate.

The possibility of inferring the turbulence level from either phase fluctuations or amplitude fluctuations appears to be improved in the case of GEMR simulations. If GEMR is more realistic than other models, experimental measurements might also be able to use the amplitude data or remain closer to linear phase regimes at higher $\delta n_e/n_e$ values than previously expected.

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