From a reflectrometry code to a "standard" EC code to investigate the impact of the edge density fluctuations on the EC waves propagation

N. Bertelli, G. J. Kramer, and E. J. Valeo

Princeton Plasma Physics Laboratory, Princeton, NJ,USA

Introduction. Recent modelling and experimental studies [1, 2, 3, 4] have shown that the edge density fluctuations can affect the electron cyclotron (EC) wave propagation in a tokamak plasma. In particular, the presence of density fluctuations in the scrape-off layer (SOL) can modify the EC beam propagation causing a power deposition broadening at the EC resonance location. This aspect could play a major role in the efficiency of the EC waves in stabilizing/suppressing the neoclassical tearing modes (NTMs). Moreover, this effect can be even more significant in large machine, such as ITER, where the distance between the edge of the plasma and the EC resonance is larger than two meters. In this work, we show a new numerical tool originally developed for reflectometer simulations [5, 6] to address the points described above. This code was commonly used for reflectometer antenna-plasma coupling calculations that include density fluctuations [7]. The main capabilities of the codes are: (i) it solves the Maxwell equations in both 2D and 3D geometries; (ii) the numerical domain can be divided in three regions: a vacuum region, a paraxial region, and a full-wave region, each with the appropriate wave solving strategy for high computation efficiency; (iii) it incorporates an edge density fluctuation model. A brief description of the code will be presented in the next section. Moreover, a comparison between the paraxial and the full-wave solutions with and without edge density fluctuations is discussed. Finally, a 3D application of FWR3D is also shown.

FWR2D & FWR3D. FWR2D and FWR3D are two- and three-dimensional codes, respectively, developed specifically to simulate correlation reflectometry in large-scale fusion plasmas [5, 6]. In these codes the computational domain is divided into three regions: (i) a vacuum region, (ii) a paraxial region, and (iii) a full-wave region. This hybrid approach was implemented in order to be computational efficient and, at the same time, to be able to take into account the full physics near the reflection layer (with the full wave description) where the standard ray-tracing and paraxial approaches fail. The user can set an arbitrary computational domain size and an additional collisional damping on the bounday of the computational domain can be added to avoid possible wave reflection. An antenna is specified at a plane outside the plasma providing the wave field pattern. In the vacuum region the waves propagates from the antenna to the plasma edge by making use of the free-space Greens function to project the wave field between the antenna and plasma boundary. Between the edge plasma and the surface close to

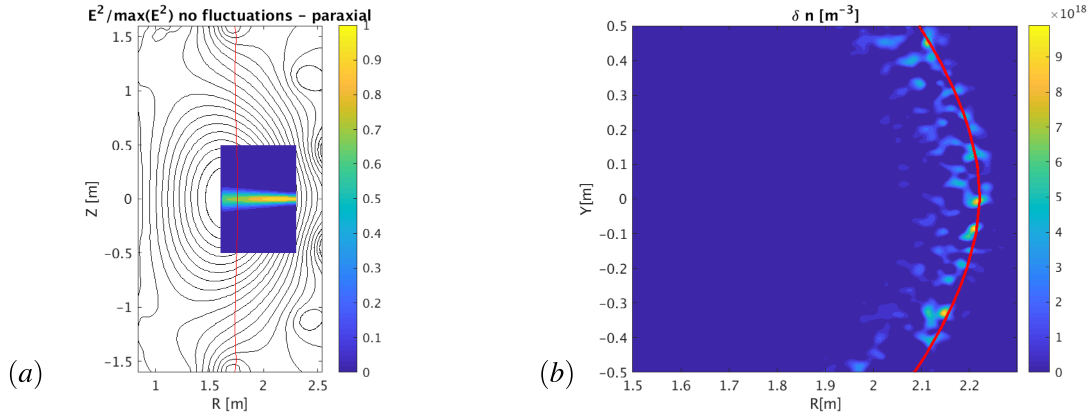

Figure 1: *(a) The EC divergent beam propagation with the magnetic flux surfaces for DIII-D-like plasma in black and the 2nd EC harmonic in red. (b) 2D density fluctuations used in the simulations where the red curve represents the last closed flux surface.*

the refection layer the paraxial technique to solve the wave equation [8, 5, 7] is used. At the boundary between the paraxial and the full wave region, the incoming paraxial solution is used to construct the source for the full wave solution. In the full wave region the code solves the wave equation (here in 2D) [5]

$$\left(\nabla^2 + k_0^2 \varepsilon(x,y)\right) E(x,y,t) + 2i\frac{\omega}{c^2}\frac{\partial E(x,y,t)}{\partial t} = 0 \quad (1)$$

until a steady state solution is reached. In equation 1, $E(x,y,t)$ represents the wave electric field as a function of space (x,y) and time t; $k_0 = 2\pi/\lambda_0$ where λ_0 is the vacuum wavelength. The dielectric tensor implemented in the code is the magnetized cold plasma X- or O-mode dielectric [9] including the electron thermal corrections [10, 11]. FWR2D has been generalized to 3D geometry with a code named FWR3D [6].

In FWR2D a time-dependent random density field is implemented in the code where each time slice represents a two-dimensional random density distribution drawn from a distribution with the following spectral properties [12]:

$$\frac{\langle \tilde{n}_1 \tilde{n}_2 \rangle}{n^2} = \left(\frac{\tilde{n}}{n}\right)^2 \exp\left[-\left(\frac{\Delta t}{\tau}\right)^2\right] \exp\left\{-\left[\frac{(\mathbf{x}+\mathbf{v}t)\cdot\Delta\mathbf{k}}{2}\right]^2\right\} \cos(\mathbf{x}\cdot\mathbf{k}) \quad (2)$$

where $\tilde{n}/n$ is the density fluctuation level, τ is the density de-correlation time, $\mathbf{v}$ is the poloidal velocity of the turbulence, $\mathbf{k}$ is the mean value of the fluctuation wave number, $\Delta\mathbf{k}$ represents its spread, and $x = (x_1 - x_2, y_1 - y_2)$, with $x_1 - x_2$ and $y_1 - y_2$ the radial and the poloidal displacement, respectively. In this paper we assume the following parameters for the edge density fluctuations with respect equation 2: $\Delta t = 0$ s, $\mathbf{v} = (0,0)$ m/s, $\mathbf{k} = (0,0)$ cm^{-1}, and $\Delta k = (1,1)$ cm^{-1}. For FWR3D, the random density distribution shown in equation 2 is generalized to include the third dimension.

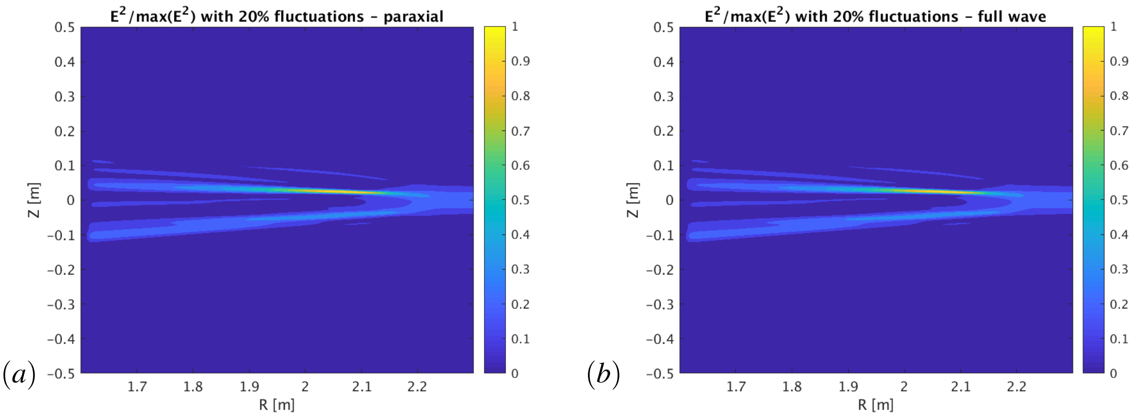

Figure 2: *2D EC beam propagation evaluated by the paraxial (figure (a)) and the full-wave (figure (b)) methods in the presence of the density fluctuations shown in figure 1(b) with* $\max(\delta n/n) = 20\%$.

DIII-D-like scenario considered. We consider a DIII-D-like plasma as shown in figure 1(a). The center magnetic field is $B = 2$ T. The central density is $n_e(0) = 5.0 \times 10^{19}$ m^{-3} and the edge density at $\rho_{pol} = 1$ is $n_e(1) = 2.0 \times 10^{19}$ m^{-3}. The density profile in the SOL is described by an exponential decay from the LCFS as a function of ρ_{pol} with an e-folding length of 0.03 m. In figure 1(a) the red line indicates the second EC resonance assuming a wave frequency $f = 110$ GHz. For this specific case the EC resonance is located at the low field side. In figure 1(a) we also show the EC beam propagation without any density fluctuations for a Gaussian beam with X-mode polarization and 5 cm beam width with focal length = 100 cm evaluated by FWR2D by using the paraxial method only. Figure 1(b) shows a single δn realization adopted in the simulations described below when density fluctuations are included.

Paraxial vs. full-wave solutions. A comparison between paraxial and full-wave solutions is shown in figure 2 in the presence of the density fluctuations. The maximum value of the edge density fluctuations is here $\tilde{n}/n = 20\%$. Figures 2(a) and 2(b) show $E^2/\max(E^2)$ obtained by the paraxial and the full-wave methods, respectively. One can see an excellent agreement between the two methods even in the presence of the edge density fluctuations. Moreover, one can clearly see that the the edge density fluctuations can affect significantly the EC beam propagation (by using a single $\tilde{n}/n$ realization).

Extension to the 3D geometry with the FWR3D code. A 3D version (FWR3D) of the well established 2D hybrid simulation code, FWR2D, was developed [6]. Figure 3 show a focusing EC beam in 3D geometry using the same parameters employed in the previous section without (figure (a)) and with (figure (b)) edge density fluctuations. A comparison between the 2D and 3D soultions obtained by FWR2D and FWR3D, respectively, shows a very similar results (not presented here) Figure 3(b) shows that the initial EC Gaussian beam is split into two sub-beams

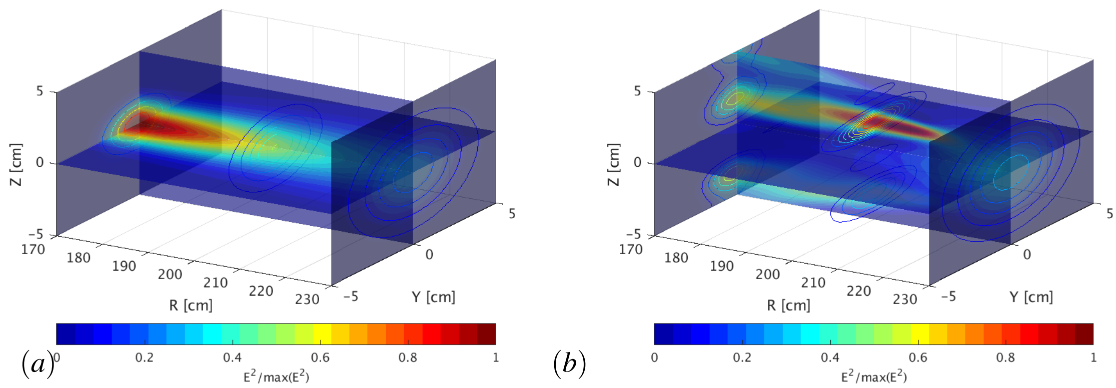

Figure 3: *3D EC beam propagation evaluated by the FWR3D with the paraxial approximation without (figure (a)) and with (figure (b)) edge density fluctuations. Same beam parameter used in the 2D calculation.*

due to the edge fluctuations ($\max(\delta n/n) = 20\%$) and this splitting occurs vertically along the z-axis. A tilt would have been occurred if the density fluctuations were taken to be along the equilibrium magnetic field line and not purely in the toroidal direction [7].

Conclusions. We have showed a new numerical tool together with its capabilities to study the impact of the edge density fluctuations to the EC wave propagation. Such effect has been shown to be important from both previous modeling and observations. This code has been originally developed for reflectometry studies. It incorporates an edge density fluctuation model and it solves the Maxwell equations in 2D and 3D. In this paper we have used a DIII-D-like plasma scenarios using an EC beam. We found an excellent agreement between the paraxial and the full wave methods with and without the presence of the edge density fluctuations. Finally, the 3D capability of FWR3D has been shown. In general, our work agrees with previous works showing that indeed the edge fluctuations can affect the EC beam propagation and this can have a consequence mainly for the NTM suppression.

Acknowledgment. Work supported by US DOE Contract DE-AC02-09CH11466.

References

[1] A. Snicker *et al.*, Nucl. Fusion **58**, 016002 (2018)
[2] A. Snicker *et al.*, Plasma Phys. Control. Fusion **60**, 014020 (2018)
[3] A Köhn *et al.*, Plasma Phys. Control. Fusion **60**, 075006 (2018)
[4] O. Chellaï *et al.*, Phys. Rev. Letters **120**, 105001 (2018)
[5] E. J. Valeo *et al.*, Plasma Phys. Control. Fusion **44**, L1 (2002)
[6] E. J. Valeo *et al.*, AIP Conf. Proc. **1187**, 649 (2009)
[7] G. J. Kramer *et al.*, Nucl. Fusion **58**, 126014 (2018)
[8] A. I. Smirnov and E. Y. Petrov. 26th EPS Conf. on Plasma Phys. and Control. Fus., **23J**, 1797, 1999
[9] T. H. Stix. Waves in Plasmas. American Institute of Physics, NY, 1992
[10] E. Mazzucato, Phys. Fluids B, **4**, 3460, 1992
[11] H. Bindslev, Plasma Phys. Control. Fusion, **35**, 1093, 1993
[12] G J Kramer, R Nazikian, and E J Valeo. Plasma Phys. Control. Fusion, **46**, 695, 2004