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# Doppler reflectometry spectra simulations with velocity shear layer

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## Abstract

Doppler reflectometry is able to provide information on plasma poloidal rotation from the frequency shift of the backscattered spectrum at oblique plasma probing. It is usually assumed that the Doppler effect is due to the fluctuation rotation at cut-off vicinity. Full-wave modeling of the Doppler reflectometry signal is performed in a slab plasma geometry with a given shear velocity layer with inhomogeneous turbulence having realistic wavenumber spectrum and radial distribution. The first part of the presentation is devoted to the description of the code and to a short recall of the developed tools needed to simulate Doppler reflectometry. The advantages and limitations of the simulations will be also discussed.

## 1 Introduction

The reflectometry simulation code used in this work has been originally build for CWFMB broadband reflectometry for profile evaluation [1]. Here it will be used for Doppler simulations and we will discuss further on some modifications made to perform this task.

## 2 Characteristics of the code

Considering a cold plasma approximation on two dimensions ( $x$ - $y$  plane) without gradients in the perpendicular direction ( $\partial/\partial z = 0$ ) with the external magnetic field (plasma field  $\mathbf{B}_0$ ) taken along the  $z$ -direction, the current density flow  $\mathbf{J}$  is restricted to the same direction. The response of  $\mathbf{J}$  to the electric field  $\mathbf{E}$  accounts for plasma effects. Considering a transversal magnetic propagation (TM) ( $E_z, B_x, B_y$ ) and using a FDTD Yee scheme [2] we obtain for the O-mode, for the electric field  $\mu_0 \varepsilon_0 (\partial t E_z)_{i,j}^n = (\partial x B_y - \partial y B_x - \mu_0 J_z)_{i,j}^n$  and for the magnetic field  $(\partial t B_x)_{i,j+1/2}^{n+1/2} = -(\partial y E_z)_{i,j+1/2}^{n+1/2}$ ;  $(\partial t B_y)_{i+1/2,j}^{n+1/2} = (\partial x E_z)_{i+1/2,j}^{n+1/2}$ . The equation for the current density is  $(\partial t J_z)_{i,j}^{n+1/2} = e^2/m_e (n_e E_z)_{i,j}^{n+1/2}$ , where  $e$  is the electron charge,  $m_e$  the electron mass and  $n_e$  the electronic density.

## 3 Plasma model

Coupling between the electromagnetic wave and the plasma is taken into account by the current density,  $J_z$ , which depends on the plasma density  $n_e$ . The density  $n_e(\mathbf{r}, t)$  is in general a function of space and time since the code allows time evolution of the density profile due to modifications of the base plasma  $n_{e0}(\mathbf{r}, t)$  on time, coherent plasma modes  $\delta n_{eMOD}(\mathbf{r}, t)$  and turbulence  $\delta n_{eTRB}(\mathbf{r}, t)$ :  $n_e(\mathbf{r}, t) = n_{e0}(\mathbf{r}, t) + \delta n_{eMOD}(\mathbf{r}, t) + \delta n_{eTRB}(\mathbf{r}, t)$ . The plasma has a generic density profile across elliptical iso-density lines. Turbulence is modeled as a sum of modes with random phase according to the scheme proposed in [3]. The density perturbation at each point obeys to  $\delta n_{eTRB} = \sum_{i=i_m}^{i_M} \sum_{j=j_m}^{j_M} A(i, j) \cos [k_x(i)x + k_y(j)y + \varphi(i, j)]$ .

The amplitude  $A(i, j)$  is chosen in agreement with experimental data [4] and may be modified during the simulation to accommodate several plasma scenarios. Keeping the same amplitude spectrum and varying  $\delta n_{e_{TRB}}$  with time allows the setting of several turbulence *snapshots* with the same spectral conditions.

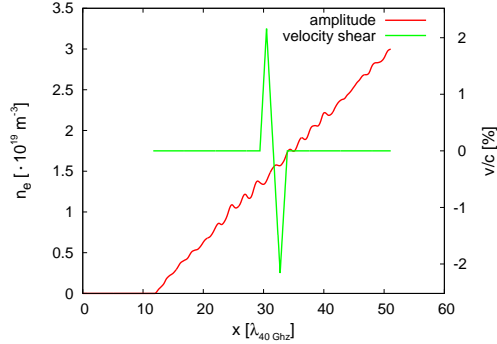


Figure 1: Radial cut of density profile with velocity shear profile superimposed.

The shear model is implemented imposing, on the original *static* matrix, a shear velocity profile (see Fig. 1). The columns of the original turbulence matrix on the shear region are shifted poloidally, each column sliding at a speed given by the velocity shear imposed. The process is illustrated in Fig. 2: The columns of the original turbulence matrix  $\delta n_{e_{TRB}}$  (top left), as the simulation runs its course, slide with a velocity given by the shear profile (Fig. 1). Its effect on the turbulence structure is shown on Fig. 2 (bottom left). This model for velocity shear implies a modification of the angular wavenumber spectrum ( $k$ -spectrum) on the shear layer (both poloidal and radially). On Fig. 2 the original spectrum (top right) and the spectrum at iteration  $50 \times 10^3$  are shown. The deformation on the shear zone reflects the elongation of the turbulent structures along the poloidal direction and the radial squeezing as the matrix columns are slid. This choice of model has been made to improve drastically the computation time.

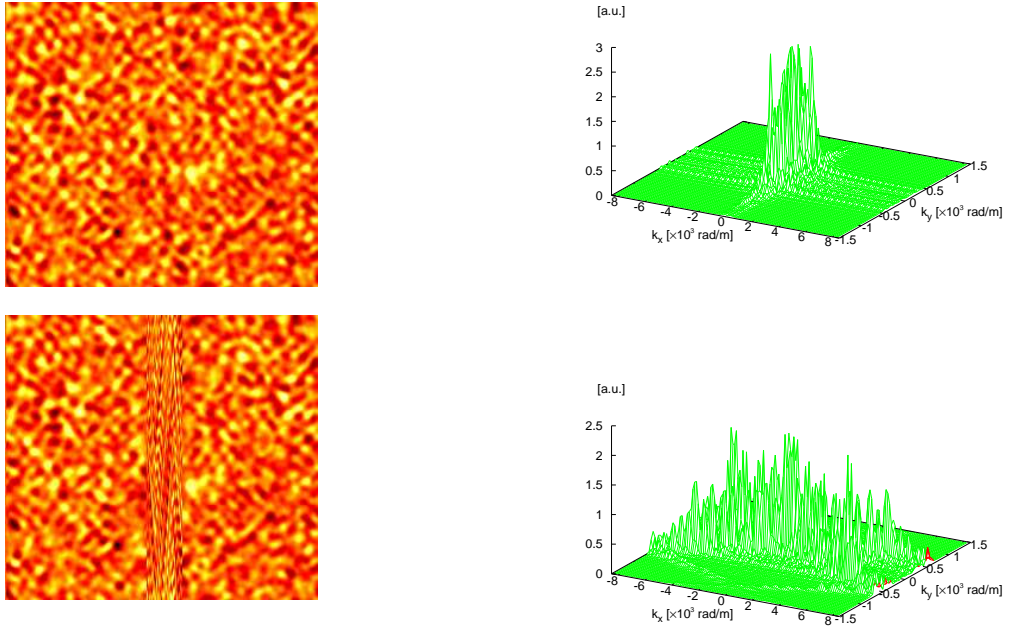


Figure 2: Original turbulence matrix  $\delta n_{e_{TRB}}$  (top left) and the amplitude  $k$ -spectrum (top right). Matrix of turbulence at iteration  $50 \times 10^3$  (bottom left) and the modified spectrum at the shear region (bottom right).

## 4 Classic reflectometry versus Doppler reflectometry setups

The code is usually run using a monostatic setup (one antenna used both for emission and reception). The emitting structure (antenna/waveguide) is obtained imposing the electric field on the structure to null,  $E_z = 0$ . The signal is excited in the waveguide as a TE<sub>10</sub> waveguide mode using a Unidirectional Transpar-

ent Source (UTS) [5] which allows unidirection injection of the probing wave (towards the plasma) while allowing the returned wave to be pick-up beyond the injection point separated from the source excitation. In Fig. 3, a monostatic setup for a 2D H-plane horn with a half power beam width of  $\approx 30^\circ$  appears on the left. The Doppler effects using this setup will be due to *lateral* probing of the plasma through the relatively large antenna radiation pattern. The response of the direct reflection of the plasma (density iso-surfaces at  $\pi/2$  with the axis of the antenna) is much strong than the Doppler effects.

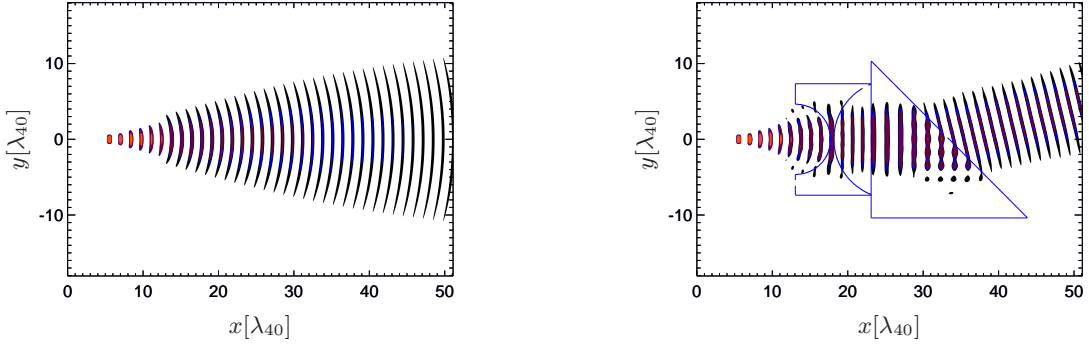


Figure 3: *Classic* reflectometry antenna setup (left) and Doppler setup with a converging lens and prism to launch beams with a high directivity (right).

To adopt the code to an angular plasma probing several possibilities could be envisaged: (i) Antenna forming an angle with the plasma other than  $\pi/2$ ; (ii) Plasma forming an angle with an *horizontal* antenna; (iii) Use of an optical system. The antenna with an angle would be quite simple to implement but we would lose the UTS as it is implemented (the waveguide aligned with the grid points) or would require a much more complex reformulation of the UTS implementation to adapt it. The plasma forming an angle with the antenna would maintain the use of the UTS but calculations performed on the plasma matrix would become very time consuming since the plasma iso-density lines would not be aligned with the columns (poloidal direction) and lines (radial direction) of the matrix. The use of an optical system, as shown on Fig. 3 (right), to probe the plasma appears as the solution more fast to implement. It is also extremely easy to implement on the code requiring almost no modifications since we opt for a *plasma optical system*. The same code subroutine used to perform calculations on the *true plasma* region is used to calculate propagation on the lens region. It is only a matter of including the plasma optics on the same matrix were the plasma is defined. Furthermore, the code stability continues to hold. The first two solutions would present an additional problem: due to the fact that the antenna radiation pattern is somewhat large (to obtain a narrow diagram on 2D is a quite daunting task [6]) the plasma will be simultaneously probed with different angles and consequently the antenna will be integrating the response of a continuum of plasma angular wavenumbers. The use of a lens allows the emission of a non-diverging beam with a planar wavefront which will respond to a single wavenumber according to the injection angle chosen by the prism. The same impulsive response (IR) technique used to implement the UTS [5] is used to eliminate the spurious reflection from the lens and prism. The beam used has a width of  $14.7 \lambda_{40 \text{ GHz}}$  and the optics have a plasma frequency of  $f_{pe} = 20 \text{ GHz}$ .

## 5 Results

The procedure used to process the results was to collect the backscattered signal on the waveguide (separated from the probing wave due to UTS) and performing an FFT. Eight runs with different instances of the *start* matrix are made and an average of all FFTs is performed to obtain the *final* FFT result. Simulations were made for different fixed frequencies, 34, 35, 36 and 40 GHz, probing the regions where the shear is maximum, where it passes through null, the maximum counter-shear and finally a region beyond the shear region. The 8-runs averaged FFT for this different frequencies are shown on Fig. 4 for probing angles

of  $7^\circ$  and  $15^\circ$ . The poloidal velocity used with  $15^\circ$  ( $v_{pol}/c = 0.054$ ) was 1.5 times higher than the one used with  $7^\circ$  ( $v_{pol}/c = 0.036$ ), which accounts for the difference on the magnitude of the Doppler shifts appearing on Fig. 4. These are *code velocities* which would correspond to *real velocities* of  $21.6 \text{ Km} \cdot \text{s}^{-1}$  and  $32 \text{ Km} \cdot \text{s}^{-1}$ . With this rescaling of velocities the Doppler shifts would be reduced from the GHz (*code*) to around 2 MHz (*real*).

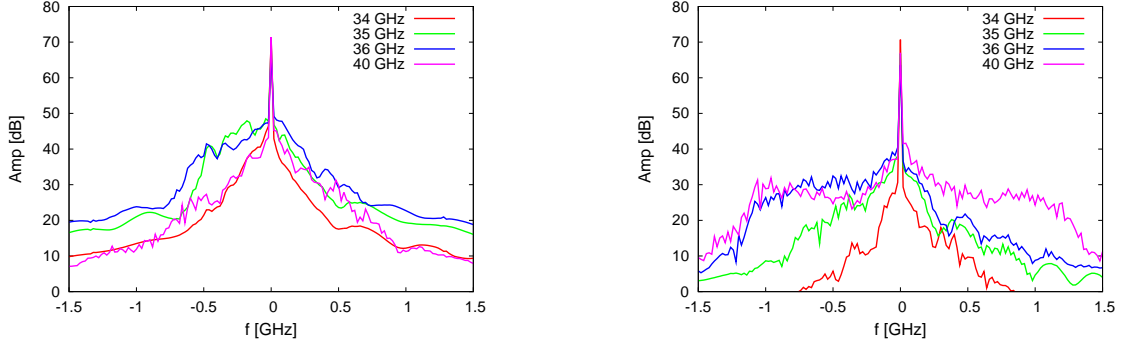


Figure 4: Averaged spectra of returned signals probed at  $7^\circ$  (left) and  $15^\circ$  (right).

## 6 Discussion

The code and its *Doppler adaptations* have proved adequate to study the effects of Doppler in general and the problem of a shear layer in particular. The use of the *plasma optics* together with the UTS and the IR correction technique can be a useful tools to obtain a probing beam to perform Doppler studies and it was also used in a study of nonlinear effects in Doppler reflectometry to compare the results of analytical theory and simulation [7]. The shear model used is a good starting point for reflectometry simulations on this subject where very few studies exist but clearly needs improvements in particular on the spectral modifications induced. This should be the subject of further modeling. The spectral analysis techniques can also be the object of further refinement.

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