Scattering of lower hybrid radio frequency waves by cylindrical turbulent structures in the plasma edge in tokamaks (*)

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Lower hybrid (LH) radio frequency (RF) waves are used in fusion tokamak devices to generate non-inductively toroidal currents. LH waves are effective in imparting toroidal momentum to electrons in the core of the confined plasma. Since the LH waves are generated by wave guide structures near the wall of a tokamak, the waves have to propagate through a turbulent plasma in the edge region before coupling to the core. It is especially important to quantify the effect of this plasma region on the propagation characteristics of the LH waves, since fusion reactors like ITER will have an extended edge region. Structures in the plasma edge like filaments and blobs which have highly varying density fluctuations compared to the background density, span radial spatial scales that are comparable to the LH wavelength. We study the scattering of the LH waves by the filamentary structures using Maxwell's equations, in which the plasma permittivity is given by the cold plasma dispersion tensor. The collisional absorption of LH waves in the edge region is included by a modification to the elements of the dispersion tensor. The filaments are assumed to be cylindrical with the axis predominantly aligned along the direction of the toroidal magnetic field. Our studies are both analytical and numerical [1,2] and show that these structures can lead to reflection, refraction, diffraction, and side-scattering of both an incident LH plane wave and a Gaussian beam. We will present a variety of different density variations and collisional absorption rates in plasmas with filamentary structures of varying sizes.

(a) Main assumptions and analytical theory

The axis of the cylindrical filament considered parallel to the externally imposed magnetic field. The cylinder is considered to have infinite length, with z being the axis of the cylinder and the direction of the magnetic field lines. The plasma is assumed to be homogeneous and cold (so that the thermal velocity of electrons and ions is considered zero). Incident plane waves (or Gaussian beams) which have their own orientation, are propagating in the ambient plasma region

(with different electron density from the filament plasma region), are hitting the cylindrical filament and are being scattered. Faraday-Ampere equation in the Fourier domain is used, with the electric field being analyzed in the cylindrical vector functions. Dispersion relation is calculated by using the permittivity tensor and then solved. Boundary conditions are also used and finally, for the normalized with respect to the incident fields, dimensionless, independent of z (denoted by a tilde) electric field and magnetic field respectively, in cylindrical coordinates one obtains:

$$\tilde{\mathbf{e}}(\rho,\varphi)_{(FI,SC)} = \sum_{M=O,X} \sum_{m=-\infty}^{m=\infty} i^m e^{im\varphi} \left[\mathcal{E}_{mr}^M(\rho)\hat{\mathbf{r}} + \mathcal{E}_{m\varphi}^M(\rho)\hat{\boldsymbol{\varphi}} + \mathcal{E}_{mz}^M(\rho)\hat{\mathbf{z}} \right]_{(FI,SC)} \quad (1)$$

$$\tilde{\mathbf{h}}(\rho,\varphi)_{(FI,SC)} = \frac{E_0}{H_0}\sqrt{\frac{\varepsilon_0}{\mu_0}} \sum_{M=O,X} \sum_{m=-\infty}^{m=\infty} i^m e^{im\varphi} \left[\mathcal{H}_{mr}^M(\rho)\hat{\mathbf{r}} + \mathcal{H}_{m\varphi}^M(\rho)\hat{\boldsymbol{\varphi}} + \mathcal{H}_{mz}^M(\rho)\hat{\mathbf{z}} \right]_{(FI,SC)} \quad (2)$$

(*SC*: scattered field, *FI*: field inside the filament) where $\mathcal{E}_{mr}^M(\rho)$, $\mathcal{E}_{m\varphi}^M(\rho)$, $\mathcal{E}_{mz}^M(\rho)$, $\mathcal{H}_{mr}^M(\rho)$, $\mathcal{H}_{m\varphi}^M(\rho)$ and $\mathcal{H}_{mz}^M(\rho)$ are functions only of ρ and can be calculated by an appropriate mathematical analysis. The expressions for the incident field are similar, but the first sum which is referring to the O-mode polarization and the X-mode polarization is missing (it has only the launched polarization, either O-mode or X-mode). As expected, since the cylinder blob has infinite length, the results for the electric field and magnetic field are z independent. It should be also noted that the parallel to the cylinder axis wave vector component stays the same for all regions. From equations (1) and (2) the calculated Poynting vector can be easily calculated. Moreover, the scattering effects are studied in the presence of absorption, too. The wave absorption is described by appending an imaginary part to the frequency and to the wave vector as well (*R:* real part, *I:* imaginary part):

$$\omega = \omega_R + i\omega_I \quad (3)$$

$$k = k_R + ik_I \quad (4)$$

(b) Results for lower hybrid plane wave scattering by a cylindrical filament

By using the previous analysis in an appropriate code, we can get the following figures for plane lower hybrid wave scattering by a single cylindrical filament:
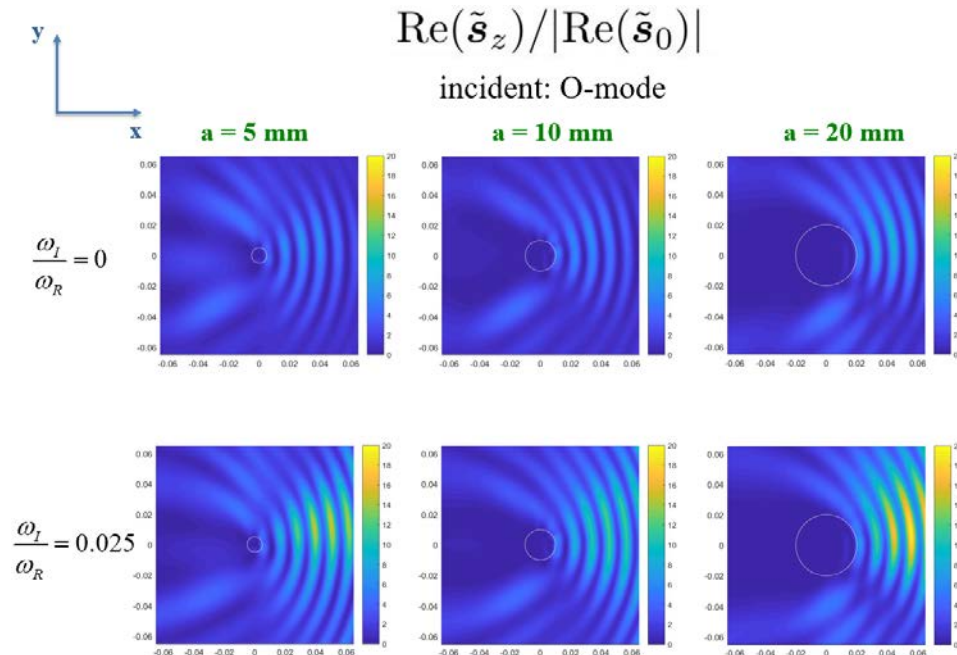
Figure 1: Poynting z component, $f = 4.5$ *GHz* (LH), polarization of incident wave: O-mode, ambient density 10^{19} m^{-3}, filament's density 1.8×10^{19} m^{-3}, $B = 4.5$ *T*, in the absence (above) and the presence (below) of absorption
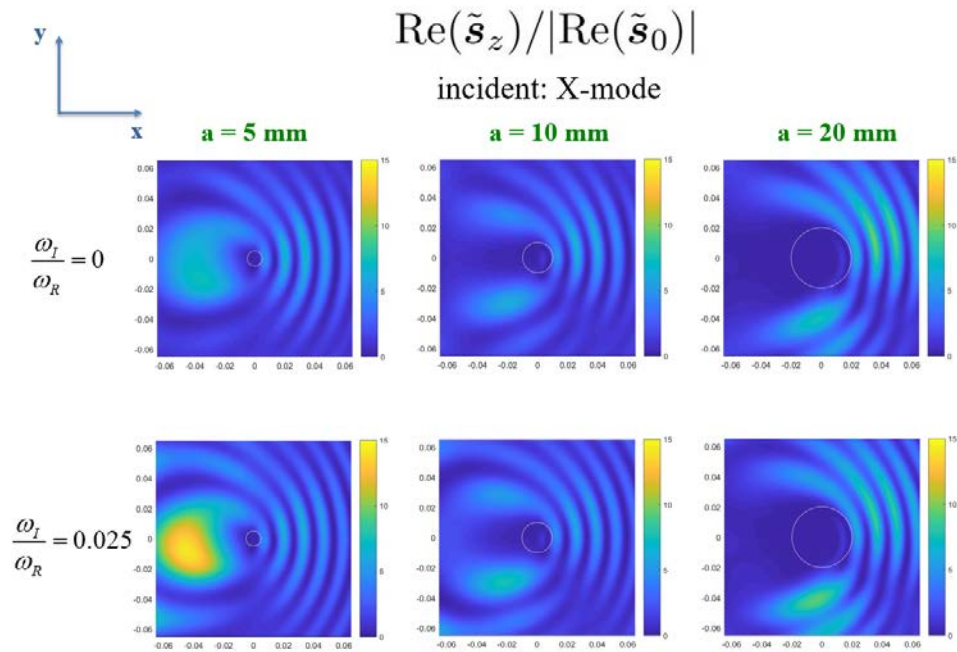

Figure 2: Poynting z component, $f = 4.5$ *GHz* (LH), polarization of incident wave: X-mode, ambient density 10^{19} m^{-3}, filament's density $1.8 \ 10^{19}$ m^{-3}, $B = 4.5$ *T*, in the absence (above) and the presence (below) of absorption

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(c) Results for lower hybrid Gaussian beam scattering by a cylindrical filament

A Gaussian beam can be approximated by a number of plane wave modes with parallel to the cylinder axis wave vector components around a central plane wave mode. In Figure 3, three cases of Gaussian beams appear, each one approximated by seven plane waves:
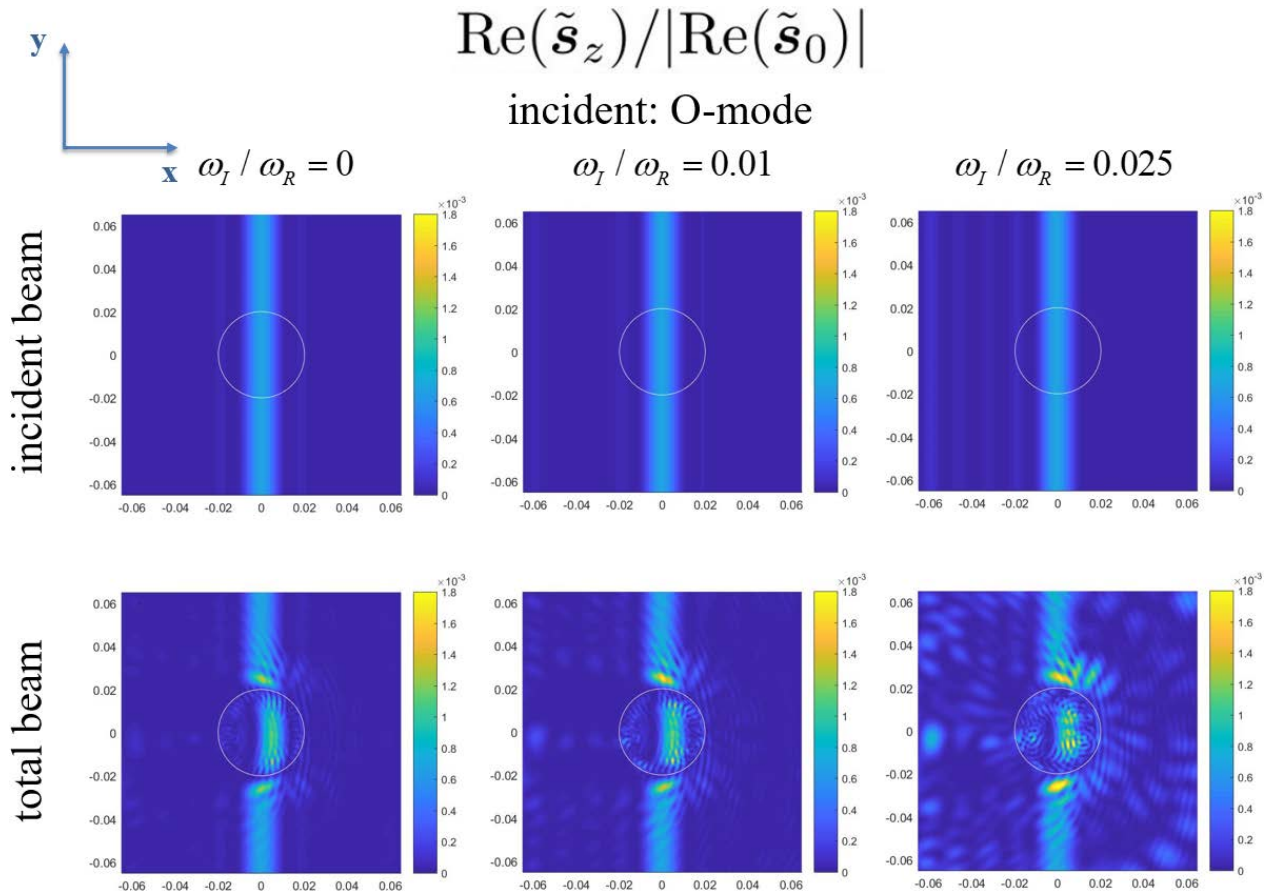

Figure 3: Poynting z component, $f = 4.5$ *GHz* (LH), polarization of incident wave: O-mode, ambient density 10^{19} m^{-3}, filament's density 1.8 10^{19} m^{-3}, a = 20 *mm*, B = 4.5 *T*, incident beam (above) and total beam (below)

References

[1] S. I. Valvis and others "Scattering of radio frequency waves by cylindrical filaments with general orientation relative to the magnetic field", Journal of Plasma Physics vol. 84, 745840604 (2018)

[2] Z. C. Ioannidis, A. K. Ram, K. Hizanidis, and I. G. Tigelis, "Computational studies on scattering of radio frequency waves by density filaments in fusion plasmas", Physics of Plasmas 24, 102115 (2017)

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