Full wave analysis of EC wave mode conversion in tokamak plasmas

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For heating and current drive in high-density core plasmas of tokamaks, electromagnetic waves with electron cyclotron (EC) range of frequencies have been extensively studied theoretically and experimentally. The propagation and absorption of EC waves are usually analyzed by the ray tracing method based on geometrical optics for waves with short wave length. In a plasma with high density or low magnetic field, however, the presence of cutoff layer may prevent the waves from penetrating into the central part from the low field side. In this case, the full wave analysis of EC waves is required for evaluating the penetration and absorption and optimizing the wave launching conditions. In this paper, two schemes of the full wave analysis in which the boundary value problem of Maxwell's equation is solved are presented.

The first one is a two-dimensional analysis near the cutoff-resonance layer with the collisional cold plasma model using the TASK/WF2D code. The reflection, transmission, and absorption of an EC wave beam is calculated, and compared with the results of a combination of the ray tracing method and the one-dimensional estimate of absorption and transmission.

The second one is a one-dimensional kinetic analysis of the X-O-B mode conversion using the TASK/W1D code. The kinetic effects of plasma response is represented by an integral form of the dielectric tensor in Maxwell's equation:

$$\nabla \times \nabla \times \vec{E}(\vec{r}) + \frac{\omega^2}{c^2} \int \overleftrightarrow{\varepsilon}(\vec{r},\vec{r}') \cdot \vec{E}(\vec{r}')\mathrm{d}\vec{r} = \mu_0 \vec{j}_{ext}(\vec{r})$$

The wave-particle interaction and the finite gyro radius effects are expressed in separate integral form. In the present analysis only the finite gyroradius effects are taken into account, and the integral form is derived by integrating along particle orbits and introducing variable transformation from velocities to spatial coordinates. The kernel function depends on the particle position x, the location x' of wave electric field $\vec{E}(x')$, and the static magnetic field and the particle density and temperature at the gyro center position x_0. The kernel functions are essentially the inverse Fourier transform of the modified Bessel functions as pointed out by Sauter **??**.

The one-dimensional tokamak full wave code TASK/W1 was extended to use the finite element method and implement the integral form of the dielectric tensor. Some calculation results are show in Figure 1. We considered a small-size spherical tokamak: major radius $R_0 = 0.22\,\mathrm{m}$, minor radius $a = 0.15\,\mathrm{m}$, central magnetic field $B_0 = 0.08\,\mathrm{m}$, toroidal mode number $n_\phi = 24$. The central electron density is $3\times10^{17}\,\mathrm{m}^{-3}$, and the central electron temperature is (a) 2 keV and (b) 5 keV. The x-coordinates corresponds to the major radius direction, y the poloidal direction and z the toroidal direction. The wave electric field E_z represents the O-mode component excited by oscillating toroidal current on the antenna at $r = 0.17\,\mathrm{m}$. The E_y component represents the X-mode mode converted at the cutoff layer from the O-mode. A part of the X-mode is mode converted to the electron Bernstein mode at the mode-conversion layer (MCL) located on the high field side of the upper hybrid resonance (UHR) layer. The short-wave-length electron Bernstein wave propagates towards the high field side, and absorbed near the electron cyclotron resonance (ECR) layer. The separation between MCL and UHR and the absorption near ECR increases for higher electron temperature.

References

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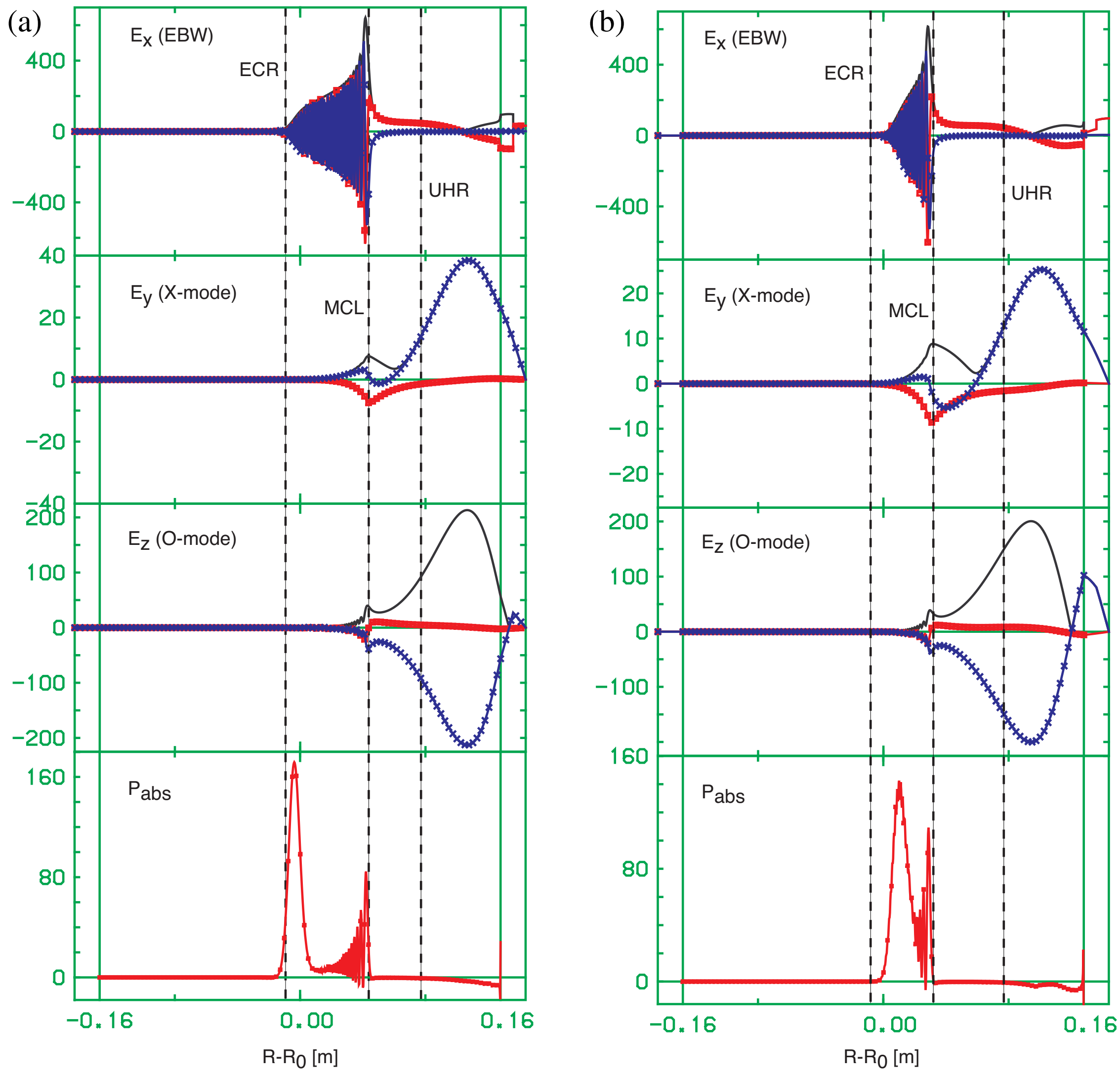

Figure 1: *Spatial profile of wave electric field and absorbed power density: (a)* $T_e(0) = 2\,keV$ *and (b)* $T_e(0) = 5\,keV$