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Full wave analysis of EC wave mode conversion in tokamak plasmas
トカマクプラズマにおける電子サイクロトロン波モード変換の波動光学的解析

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The mode conversion of electron cyclotron waves in a high density plasma is studied with full wave codes. First the linear mode conversion from O-mode to X-mode near the upper hybrid resonance layer is described by two-dimension full wave code TASK/WF2D with a collisional cold plasma model. Second the mode conversion to the electron Bernstein wave is described by one-dimensional full wave code TASK/W1 with an integral operator form of kinetic dielectric tensor.

1. Introduction

For heating and current drive in high-density core of toroidal plasmas, 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 and 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 absorption profile and optimizing the wave launching conditions. In the present analysis, two schemes of the full wave analysis in which the boundary value problem of Maxwell's equation is solved are presented. First one is the two-dimension full wave analysis using TASK/WF2D with a collisional cold plasma model and the linear mode conversion from O-mode to X-mode near the upper hybrid resonance layer is studied. Second one is the one-dimensional full wave analysis using TASK/W1 with integral operator form of kinetic dielectric tensor and the linear mode conversion to the electron Bernstein wave is demonstrated.

2. 2D analysis of O-X mode conversion

In order to describe the wave propagation in a high density plasma of a spherical tokamak, two-dimensional full wave analysis on a poloidal cross section was carried out by TASK/WF2D. In the full wave analysis, the wave electric field $\tilde{\boldsymbol{E}}(\boldsymbol{r},t) = \boldsymbol{E}(\boldsymbol{r})\,\mathrm{e}^{-\mathrm{i}\,\omega t}$ is calculated for the wave angular frequency ω. The wave amplitude $\boldsymbol{E}(\boldsymbol{r})$ satisfies Maxwell's equation

$$\nabla\times\nabla\times\boldsymbol{E} - \frac{\omega^2}{c^2}\overleftrightarrow{\epsilon}\cdot\boldsymbol{E} = \mathrm{i}\,\omega\mu_0\boldsymbol{j}_{\mathrm{ext}}$$

with the dielectric tensor $\overleftrightarrow{\epsilon}(\boldsymbol{r},\omega)$ for collisional cold plasma model. The waves are excited by a loop antenna or a wave guide, and plasma and wave parameters are given in TAB. I.

TAB. I : parameters for 2D analysis

major radius	$R_0 = 0.22\,\mathrm{m}$
minor radius	$a = 0.16\,\mathrm{m}$
central magnetic field	$B_0 = 0.08\,\mathrm{m}$
wave frequency	$f = 5\,\mathrm{GHz}$
toroidal mode number	$n_\phi = 8$
collision frequency	$\nu/\omega = 0.001$

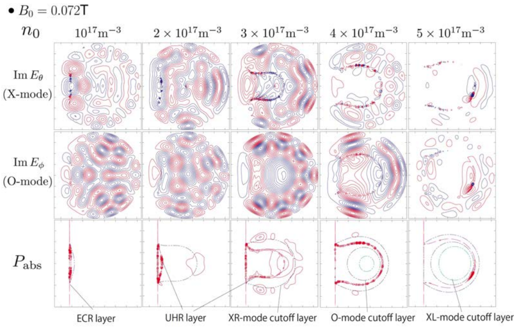

FIG. 1 Two-dimensional full wave O-X-B analyses with TASK/WF2D using collisional cold plasma model

FIG. 1 shows the contours of wave electric filed and absorbed power density for various plasma density. In this case, the wave is excited by a toroidal antenna current and the toroidal component of wave electric field corresponds to O-mode, while the poloidal components X-mode. In the case of the lowest electron density, the wave is absorbed near the electron cyclotron resonance (ECR) layer on the high field side. With the increase of electron density, the upper hybrid resonance (UHR) layer separates from ECR and so does the absorption layer. The XR mode cutoff layer exists on the low filed side of UHR, but the propagation of O-mode is not affected. With the further increase of density, the short-wavelength X-mode excited near UHR becomes appreciable and the absorption becomes dominant. Then the O-mode and XL mode cutoff appear in the central region, and the O-mode cannot penetrate there. Further increase of density reduces the mode-conversion efficiency owing to the steeper density gradient.

3. 1D analysis of O-X-B mode conversion

In order to describe the electron Bernstein wave (EBW), we have to include the finite gyro radius effects in the dielectric tensor. Conventional kinetic analyses usually employ the Fourier transform by introducing the wave number. The fast Fourier transform (FFT) scheme is not efficient, however, for large-scale-computation, since the localized properties of wave-particle interactions are not taken into account. We have introduced the dielectric tensor of an integral operator form derived by integrating along particle orbits and introducing variable transformation from velocity variables to spatial variables. In the 1D kinetic full wave code TASK/W1, Maxwell's equation

$$\nabla\times\nabla\times\boldsymbol{E}(\boldsymbol{r},\omega)-\frac{\omega^2}{c^2}\int_V \mathrm{d}\boldsymbol{r}'\,\overleftrightarrow{\epsilon}(\boldsymbol{r},\boldsymbol{r}';\omega)\cdot\boldsymbol{E}(\boldsymbol{r}',\omega) = \mathrm{i}\,\omega\mu_0\boldsymbol{J}_{\mathrm{ext}}(\boldsymbol{r},\omega)$$

is solved by the finite element method (FEM). We applied this scheme to the O-X-B mode conversion in a tokamak configuration. Plasma and wave parameters are given in TAB. II.

TAB. II : parameters for kinetic 1D analysis

major radius	$R_0 = 0.22\,\mathrm{m}$
minor radius	$a = 0.15\,\mathrm{m}$
central magnetic field	$B_0 = 0.08\,\mathrm{m}$
wave frequency	$f = 2.45\,\mathrm{GHz}$
toroidal mode number	$n_\phi = 24$
central electron density	$3\times10^{17}\,\mathrm{m}^{-3}$

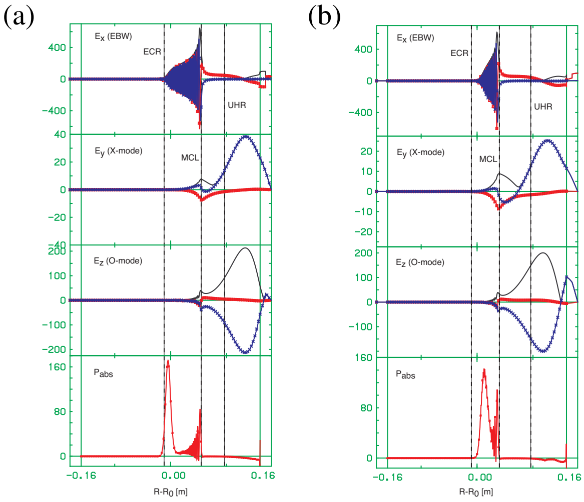

FIG. 2 One-dimensional full wave O-X-B analyses with TASK/W1 using the integral form of kinetic dielectric tensor for (a) $T_\mathrm{e}(0) = 2\,\mathrm{keV}$ and (b) $T_\mathrm{e}(0) = 5\,\mathrm{keV}$

FIG. 2 shows the wave structure and power deposition profile for low-field-side excitation. The toroidal wave electric field component (O-mode) is excited by a toroidal antenna current. The O-mode is reflected at the O-mode cutoff and a part of the energy is converted to the poloidal component (X-mode). Some of the the X-mode tunnels the evanescent layer of the X-mode, between the mode-conversion (MC) layer and XR-mode cutoff, while the rest of the X-mode is mode-converted to the short-wave-length EBW (electrostatic radial component). EBW is reflected back to the high-density region at MC layer, and finally absorbed at the Doppler-broadened electron cyclotron resonance. With the increase of the electron temperature, MC layer shifts away from UHR layer and so do absorption layer from ECR layer.

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