Kinetic full-wave analysis of cyclotron waves in tokamak plasmas with the integral-operator approach

Atsushi Fukuyama

Professor Emeritus, Kyoto University, Kyoto, Japan

Full-wave analysis including kinetic effects of plasmas has been extensively employed in describing wave heating and current drive in tokamak plasmas. Most of previous kinetic analyses of wave propagation and absorption in an inhomogeneous plasma are based on the wave number. The dielectric tensor in a hot plasma has been usually expressed as a function of wave number. In the full-wave numerical analysis using the finite element method (FEM) or the finite difference method (FDM), however, the wave number is not available a priori. In order to describe the kinetic response of plasma without wave number, it seems most appropriate to use the dielectric tensor in the form of integral operator which is derived by integrating along an unperturbed particle orbit. Maxwell's equation with the integral form of dielectric tensor

$$\nabla \times \nabla \times E(r) - \frac{\omega^2}{c^2} \int \mathrm{d}r' \overleftrightarrow{\varepsilon}(r, r') \cdot E(r') = \mathrm{i}\,\omega \mu_0 j_{\mathrm{ext}}$$

can be numerically solved as a boundary-value problem by FEM. Numerical analysis with FEM may have higher performance with parallel processing owing to sparse coefficient matrix. Though the integration is localized in an element in usual FEM for differential equations, coupling between different elements occurs in FEM for integro-differential equations. In a magnetized plasma, the guiding center motion along an inhomogeneous magnetic field and the cyclotron motion perpendicular to the magnetic field can be separately taken into account in deriving the dielectric tensor as an integral operator. 1D full-wave analysis using the integral form of dielectric tensor was applied to ion cyclotron (IC) heating in the presence of energetic ions and the O-X-B mode conversion of electron cyclotron (EC) waves. In this presentation, 2D full-wave analysis with the integral form of dielectric tensor is provided. The first application is the analysis of 2D mode structure of the O-X-B mode conversion on the horizontal plane of tokamak. The tunneling of the wave over the evanescent layer between O-mode and X-mode cutoffs is described without any assumptions on the magnitude of inhomogeneity. The second application is the analysis of 2D mode structure on the poloidal plane of tokamak. The inhomogeneity of the magnetic field along the field line is taken into account, and the magnetic mirror motion of charge particles is taken into account. Examples of the O-X-B mode conversion of EC waves, and the mode conversion of IC waves to the ion Bernstein wave and the electrostatic IC waves will be demonstrated.