2D Full Wave Simulation on Electromagnetic Wave Propagation in Toroidal Plasma

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Global full-wave simulation on electromagnetic wave propagation in toroidal plasma with an external magnetic field imaging a tokamak configuration is performed in two dimensions. The temporal behavior of an electromagnetic wave launched into plasma from a wave-guiding region is obtained.

Keywords: electromagnetic wave, microwave, millimeter-wave, toroidal plasma, plasma diagnostics

Electromagnetic wave propagation in a plasma is one of the basic problems in plasma physics. The wave trajectory in the microwave and millimeter-wave regimes is very important from the viewpoint of electromagnetic wave-based plasma diagnostics such as interferometry, reflectometry, and ECE imaging in magnetic confinement devices[1, 2]. In addition, the present study is a response to the inadequacy of usual geometrical optics for the ray-tracing of an electromagnetic wave beam in the above-mentioned frequency ranges. Recently, striking differences between geometrical optics and wave optics based on Maxwell equations have been reported[3].

In this paper, we study the propagation of electromagnetic waves in the microwave and millimeter-wave regimes in toroidal plasma. Figure 1 shows the simulation box in which the white-colored region indicates the plasma and wave-guiding region to be computed, and the gray-colored region indicates a region unnecessary for the computation of the wave propagation. In order to separate these two regions, we introduce an artificial conductivity σ and the real part of dielectric constant ε_r normalized by ε_0 (i.e., $\varepsilon_r = \mathrm{Re}(\varepsilon)/\varepsilon_0$). The basic equations for simulations are

$$\frac{\partial}{\partial t}\mathbf{B} = -\nabla\times\mathbf{E} \qquad (1)$$

$$\frac{\partial}{\partial t}\mathbf{E} = \frac{c^2}{\varepsilon_r(\boldsymbol{r})}\nabla\times\boldsymbol{B} - \frac{1}{\varepsilon_0\varepsilon_r(\boldsymbol{r})}[\boldsymbol{J} + \sigma(\boldsymbol{r})\boldsymbol{E}] \qquad (2)$$

$$\frac{1}{\varepsilon_r}\frac{\partial}{\partial t}\boldsymbol{J} = \omega_{pe}^2[n(\boldsymbol{r})]\boldsymbol{E} - \frac{e}{\varepsilon_0 m_e}\boldsymbol{J}\times\boldsymbol{B}_0(\boldsymbol{r}) \qquad (3)$$

where $\mathbf{E}$ and $\mathbf{B}$ are electromagnetic wave fields, $\mathbf{J}$ the plasma current, c the speed of light, ω_{pe} the electron plasma frequency, and $\mathbf{B}_0$ an external magnetic field. The last term of the right-hand side of eq.(2) is an artificial one introduced to separate the above two regions already discussed. We here assume that $\sigma/\omega\varepsilon_0 = 0$, $\varepsilon_r = 1$ for plasma and the wave-guiding region (white-colored); otherwise (gray-colored) $\sigma/\omega\varepsilon_0 = 10$, $\varepsilon_r = 10$. In this case, the electromagnetic wave becomes strongly damped in the gray-colored region, and the interface

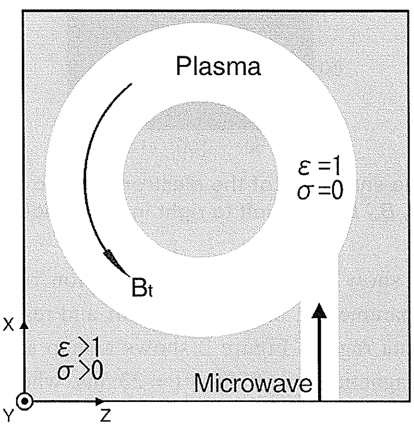

Fig. 1 Schematic of the present simulation model.

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between the two regions plays the role of a wall boundary creating wave reflections. The details regarding this numerical scheme will be reported elsewhere. If we assume a density profile $n(\boldsymbol{r})$ and the external magnetic field $B_0(\boldsymbol{r})$ in the above equations, we can perform a simulation run for wave propagation under the initial condition for an incident electromagnetic wave. In the present simulation, we assume a tokamak-like magnetic field profile for B_0 given by

$$B_x = B_0 \frac{R}{r} \frac{z - z_0}{r} \tag{4}$$

$$B_z = -B_0 \frac{R}{r} \frac{x - x_0}{r} \tag{5}$$

$$B_y = B_{y0} \sqrt{2e} \frac{r - R}{d} \exp[-(\frac{r - R}{d})^2] \tag{6}$$

where $r^2 = (x - x_0)^2 + (z - z_0)^2$, R is the major radius, and B_0 is the value at $r = R$. The toroidal field is then given by $B_t = (B_x^2 + B_y^2)^{1/2} \approx 1/r$, and B_y corresponds to the poloidal field. We also assume a Gaussian density profile for $n(\mathbf{r})$ given by

$$n = n_0 \exp[-(\frac{r - R}{a})^2] \tag{7}$$

The number of grids in a simulation box is 3,000 × 3,000. In the simulation, the time step Δt is $0.1\omega_0^{-1}$, and the mesh size is $\Delta x = \Delta z = 0.1c/\omega_0$, where ω_0 is a reference frequency. The electron plasma, electron cyclotron, and incident wave frequencies are also normalized by ω_0, and the plasma and other simulation parameters can then be scaled by ω_0. The following parameters are used: R = 107 cm, a = 18 cm, B_{y0}/B_0 = 0.1, d = 24 cm, B_0 = 0.43 T, and $n_0 = 0.6 \times 10^{12}$ cm^{-3}. The incident wave is expressed as $E_z(z,t) = \exp[-(z - z_1)^2/L^2]\sin(\omega t)$ on the lower boundary in x, where ω = 8 GHz, z_1 = 107 cm, and L = 7.2 cm when we set (x_0, z_0) = (0, 0).

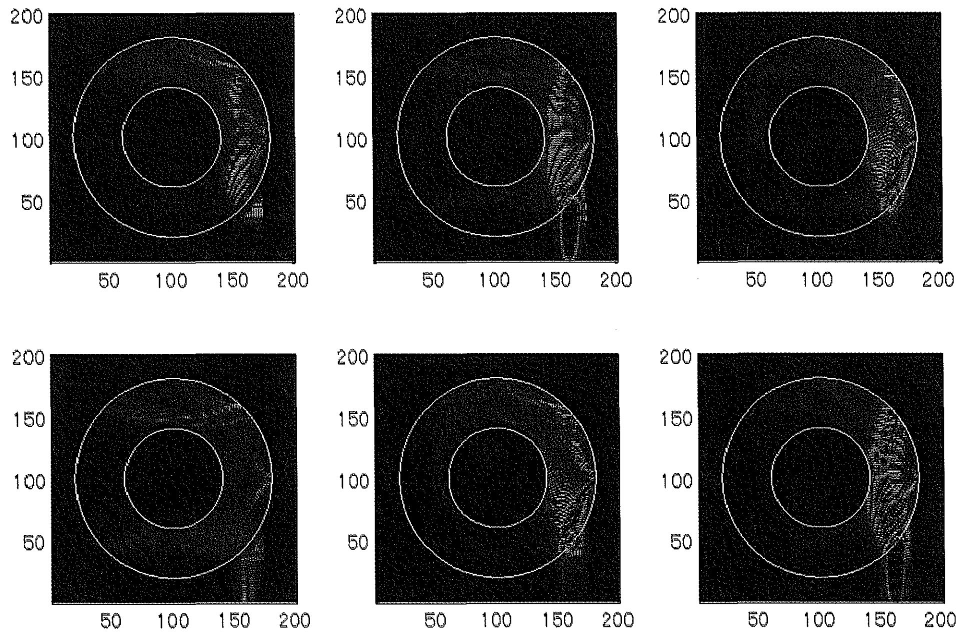

Fig. 2 The snap shot of the electromagnetic wave field at t = 23.5 ns, E_x, E_y, E_z (from left to right in upper side) and B_x, B_y, B_z (from left to right in lower side).

We show the result of a simulation run. In the present parameters, there is no cutoff and resonance in the plasma region. Figure 2 shows a snap shot of the electromagnetic wave field at t = 23.5ns, where E_x, E_y, E_z (from left to right in upper side) and B_x, B_y, B_z (from left to right in lower side) are shown in the absolute values. We see that a part of the electromagnetic wave propagates in the toroidal direction while repeating the reflection with the wall, which is shown by two solid circles.

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