§4. Developments of Millimeter-Wave Diagnostic Simulator

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Millimeter-wave diagnostics such as reflectometry are receiving growing attention in magnetic confinement fusion research. The detailed measurements on density profile and its fluctuations might be required in order to obtain the better understanding of plasma confinement physics. Recently, the new methods of microwave reflectometry such as ultrashort-pulse reflectometry and imaging reflectometry have been developed. We here think that it is very important to demonstrate computationally the usefulness of the new diagnostic methods before the experiments. Therefore, we state that the development of millimeter-wave diagnostic simulator is also of importance.

The basic equations for the millimeter-wave diagnostic simulator are the Maxwell equation for the electromagnetic wave fields, $\boldsymbol{E}$ and $\boldsymbol{B}$, and the equation of motion for the induced current density $\boldsymbol{J}$ as follows[1,2]:

$$\frac{\partial}{\partial t}\boldsymbol{B} = -\nabla\times\boldsymbol{E}, \quad (1)$$

$$\frac{\partial}{\partial t}\boldsymbol{E} = c^2\nabla\times\boldsymbol{B} - \frac{1}{\varepsilon_0}\boldsymbol{J}, \quad (2)$$

$$\frac{\partial}{\partial t}\boldsymbol{J} = \varepsilon_0\omega_{pe}^2\boldsymbol{E} - \frac{e}{m_e}\boldsymbol{J}\times\boldsymbol{B}_0, \quad (3)$$

where ω_{pe} ($= (e^2n/m_e\varepsilon_0)^{1/2}$) the electron plasma frequency, and $\boldsymbol{B}_0$ is the external magnetic field. In the derivation of eq.(3), we assumed that the induced current density $\boldsymbol{J}$ is approximated as $\boldsymbol{J} = -en_0\boldsymbol{v}_e$, $\boldsymbol{v}_e$ being the electron flow velocity, as we consider electromagnetic waves in GHz range. The above coupled equations can describe both of the ordinary (O) and extraordinary (X) modes for the perpendicular propagation to an external magnetic field $\boldsymbol{B}_0$. When $\boldsymbol{B}_0 = B_0\mathbf{e}_z$, the wave component E_z denotes the O mode with the dispersion relation:

$$\omega^2 = \omega_{pe}^2 + c^2k^2, \quad (4)$$

on the other hand, E_x and E_y correspond to the X mode with the dispersion relation:

$$\left(\frac{kc}{\omega}\right)^2 = 1 - \frac{\omega_{pe}^2}{\omega^2}\frac{\omega^2-\omega_{pe}^2}{\omega^2-\omega_{pe}^2-\omega_{ce}^2}, \quad (5)$$

where ω_{ce} is the electron cyclotron frequency. The cross polarization scattering between the O and X modes is generated from the $\boldsymbol{J}\times\boldsymbol{B}_0$ term in eq.(3). The numerical scheme for solving eqs.(1)-(3) is based on the FDTD method.

Hereafter, we discuss the relativistic effects of wave propagation in plasma. The most important effect is the change of cutoff layer due to the relativistic electron mass modification[3]. The electron mass m_e is modified to $m_e(1+5/\mu)^{1/2}$, where $\mu = m_ec^2/T_e$, T_e being the electron temperature. In this case, the change of the cutoff density is given as follows:

$$\frac{\Delta n}{n_c} = \frac{n_{c,rel}-n_c}{n_c} = \begin{cases} \sqrt{1+5/\mu}-1, & \text{(O-mode cutoff)} \\ \dfrac{\sqrt{1+5/\mu}-1}{1-\omega_{ce}/\omega}. & \text{(upper X-mode cutoff)} \end{cases}$$

The shift of the cutoff density due to relativistic effects is more significant for X modes. Figures 1 and 2 show the result of 2-d simulation on X-mode beam propagation. Theoretical cutoff positions are $x_c = 98.2$ for $T_e = 0.1$keV and $x_c = 112.5$ for $T_e = 20$keV, and we see that the numerical result coincides with the theoretical estimation.

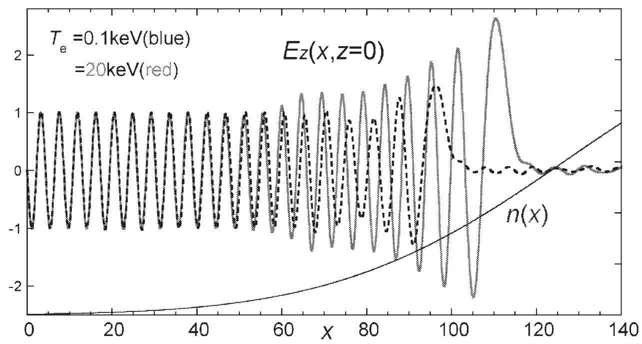

Fig.1. Snapshots of $E_z(x, z, t)$ with $T_e = 20$keV (solid line) and 0.1keV (dashed line) at the beam center $z = 0$.

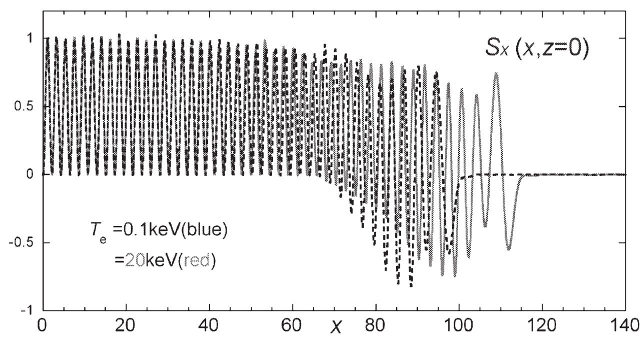

Fig.2. Snapshots of $S_x(x, z, t)$ with $T_e = 20$keV (solid line) and 0.1keV (dashed line) at the beam center $z = 0$.

References

1) H. Hojo et al., Rev. Sci. Instrum. **70**, (1999) 983.
2) H. Hojo et al., Rev. Sci. Instrum. **75**, (2004) 3813.
3) E. Mazzucato, Phys. Fluids B **4**, (1992) 3460.