§30. FDTD Simulation Study on Ultrashort-Pulse Reflectometry

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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 are important in order to obtain the better understanding of plasma confinement physics. We are developing a millimeter-wave diagnostic simulator to demonstrate computationally the usefulness of a new diagnostic method before actual experiments.

The basic equations for our 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]:

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

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

$$\frac{\partial}{\partial t}\boldsymbol{J} = \varepsilon_0\omega_{\mathrm{pe}}^2\boldsymbol{E} - \frac{e}{m_{\mathrm{e}}}\boldsymbol{J}\times\boldsymbol{B}_0\,, \tag{3}$$

where ω_{pe} is the electron plasma frequency, and $\boldsymbol{B}_0$ is the external magnetic field. We assumed that the induced current density $\boldsymbol{J}$ is approximated as $\boldsymbol{J} = -en_0\boldsymbol{v}_{\mathrm{e}}$, $\boldsymbol{v}_{\mathrm{e}}$ 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 $\boldsymbol{B}_0$. 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 eqs.(1)-(3) is based on the so-called FDTD method.

We here perform one-dimensional FDTD simulations on O-mode ultrashort-pulse reflectometry in a plasma with the modified electron mass, where a uniform magnetic field $\boldsymbol{B}_0 = B_0\mathbf{e}_z$, B_0 = 1T is assumed, and the density and electron temperature profiles are given by

$$n(x) = n_0\exp[-(\bar{x}/L_n)^2]\,,\quad \bar{x} = x - 1000\,, \tag{4}$$

$$T_{\mathrm{e}}(x) = T_{\mathrm{e}0}\exp[-(\bar{x}/L_T)^2]\,, \tag{5}$$

where $n_0 = 2\times10^{13}\mathrm{cm}^{-3}$ and L_n = 200mm, L_T = 300mm and $T_{\mathrm{e}0}$ = 20eV. We use a Gaussian O-mode pulse (E_z) with the pulse width 16.7ps (in FWHM). From the reflected wave signals, we obtain the time delay $\tau(\omega)$, and we can reconstruct the density profile $n(x)$ by using the Abel inversion equation for the cutoff position x_{r}:

$$x_{\mathrm{r}}(\omega_{\mathrm{pe}}) = \int_0^{\omega_{\mathrm{pe}}} \mathrm{d}\omega \frac{c\tau(\omega)}{\pi\sqrt{\omega_{\mathrm{pe}}^2 - \omega^2}}\,. \tag{6}$$

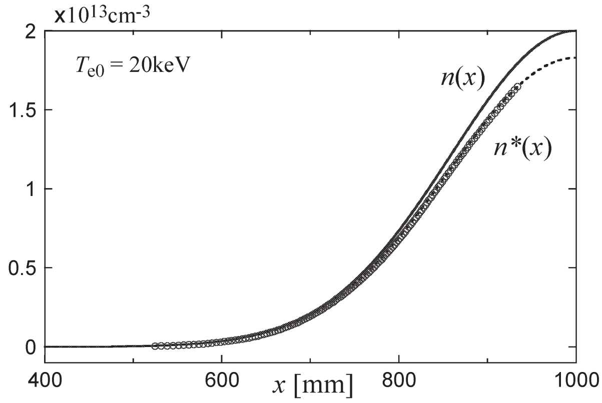

Fig.1 The reconstructed density profile(open circles) for $T_{\mathrm{e}0}$ = 20keV. The solid line shows the modeled profile $n(x)$ and the dashed line denotes $n^*(x)$ given by eq.(7).

Figure 1 shows the reconstructed density profile (open circles) for $T_{\mathrm{e}0}$=20keV. The solid line shows the modeled profile $n(x)$, and the dashed line expresses a fake density profile $n^*(x)$ with the cutoff shift due relativistic electron mass modification, which is given by

$$n^*(x) = \frac{n(x)}{\sqrt{1 + \dfrac{5T_e(x)}{m_{\mathrm{e}}c^2}}}\,. \tag{7}$$

In this case, we see that the relativistic shift in cutoff density is about 17mm at x ≈ 900mm for $T_{\mathrm{e}0}$ = 20keV, and the relativistic shift becomes larger for the higher electron temperature. We also note that this shift in cutoff density is more significant for X modes rather than O modes.

We finally discuss a possibility of electron temperature profile estimation from reflectometry. If the density profile $n(x)$ is known by means of the other measurements, measuring the fake density profile $n^*(x)$ from reflectometry, we could estimate the electron temperature profile $T_{\mathrm{e}}(x)$ as

$$T_e(x) = \frac{m_{\mathrm{e}}c^2}{5}\left[\left(\frac{n}{n^*}\right)^2 - 1\right]. \tag{8}$$

This reconstruction of electron temperature is not good for $T_{\mathrm{e}0}$=20keV. However, it could provide us a rough estimation of electron temperature in ITER-like plasmas.

References
1) H. Hojo et al., Rev. Sci. Instrum. **70**, (1999) 983.
2) H. Hojo et al., Rev. Sci. Instrum. **75**, (2004) 3813.