Simulation Study of Ultrashort-Pulse Reflectometry by Signal Record Analysis

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Reflectometry is expected to be come one of the key diagnostic tools for measuring density profiles in large fusion devices. It provides good spatial and temporal resolutions, while requires only a single viewing chord and minimal vacuum access, in contrast to interferometry and Thomson scattering. We applied an ultrashort-pulse reflectometer (USPR) to Large Helical Device (LHD) at the National Institute for Fusion Science (NIFS), and a signal record analysis (SRA) method was used as a reconstruction method. Here, we report a simulation study of USPR conducted using a finite-difference time domain (FDTD) method to confirm the effectiveness of the SRA reconstruction method.

Keywords: ultrashort-pulse reflectometer, SRA method, FDTD

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Reflectometry is a radar technique that probes the density-dependent cutoff layer by measuring the phase or group delay between reflected a wave and a reference wave. This technique is expected to be come one of the key diagnostics used for measuring density profiles in large fusion devices, since it provides good spatial and temporal resolutions while requiring only a single viewing chord and minimal vacuum access, in contrast to interferometry and Thomson scattering. We applied an ultrashort-pulse reflectometer (USPR) to Large Helical Device (LHD) at the National Institute for Fusion Science (NIFS). In a USPR, an impulse with a pulse width less than 100 ps is used as a source [1–3]. Since the bandwidth of an impulse is proportional to the inverse of the pulse width, we can employ the frequency of micro- to millimeter-waves as a single source. Data handling becomes straight forward, since the measurement is performed in the time domain. The density profiles can be reconstructed by collecting time-of-flight (TOF) signals for each frequency component of an impulse reflected from the O-mode cutoff layer. However, a large number of detection channels are required for each frequency component to achieve a precise reconstruction of the profile. We proposed an efficient and precise solution to this problem using the signal record analysis (SRA) method [4]. In this study, we performed a simulation study of the USPR to investigate the suitability and efficiency of the SRA method.

The reflectometer signal can be expressed as

$$s(t) = \int |S| e^{i\omega t - i\psi(\omega)} d\omega. \tag{1}$$

This allows us to find the fitting functions ψ and S, which are related to the plasma parameters. The signals $s_w(t)$ and $s_p(t)$ are recorded for the waves reflected from a vacuum wall (without plasma) and from the plasma, respectively. These waveforms are then transformed into a phase spectrum as a function of incident frequency, which is given by $\psi_{w,p} = -\arg(S_{w,p})$. The phase difference $\psi_p - \psi_w$ is calculated after unwrapping ψ_p and ψ_w. The time delay at each frequency is then given by

$$\tau(f) = \frac{1}{2\pi}\frac{\delta\psi(f)}{\delta f}. \tag{2}$$

The plasma density profile is obtained as follows:

$$r_c(f_{pe}) = \frac{c}{\pi}\int_0^{f_{pe}} \frac{\tau(f)}{\sqrt{f_{pe}^2 - f^2}} df. \tag{3}$$

The frequency range of our system is 18-40 GHz, which allows us to obtain density profiles in the range $0.4\text{-}2.0 \times 10^{19}\ m^{-3}$. The SRA method is used to calculate the group delay and has the advantage that it does not require the filter bank used in a conventional method. In the course of the USPR experiment, a reconstruction error occurred due to the fact that we were unable to obtain data in the range 0-18 GHz. In order to ensure the validity of the SRA method for profile reconstruction and to investigate the cause of the errors, we performed a simulation study of the USPR.

The following two-dimensional simulation model was used. The basic equations to be solved are Maxwell's equations for the electromagnetic wave fields, E and B, and the

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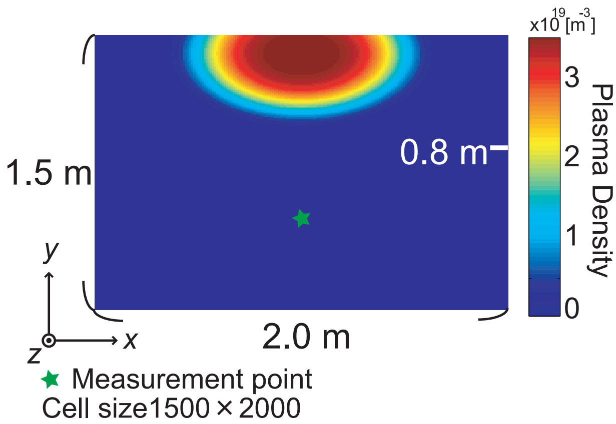

Fig. 1 Simulation model with plasma density. Contour plots of the plasma density profile for the simulation. The area is divided into 2000×1500 cells in x and y directions. The reflected wave is measured at the point marked by a star.

equation of motion for the induced current density J. The numerical scheme is based on the finite-difference time-domain (FDTD) scheme [5, 6]. This simulation method is a popular computational electrodynamics modeling technique. It is easy to understand and is straight forward to implement in a software. Since it is a time-domain method, the solutions can cover a wide frequency range for a single simulation run. The reflected wave can ideally be obtained from a FDTD simulation. Figure 1 shows the simulation model. The analytic expression in Ref. [7] is used to describe the external magnetic field B_0 for the LHD plasma, where the toroidal magnetic field is in the z-direction, and the poloidal magnetic field lies in the x-y plane. We assume a density profile from the experimental data. The wave is launched from the lower density region in the y-direction and the reflected wave is measured at 0.5 m from the edge, as shown in Fig. 1. To calibrate this position, a wave reflected from a metal plate located at a distance of 0.8 m from the edge is used in the simulation.

Two types of waves are used as incident waves. One is an ultrashort-pulse whose frequency range is 0-50 GHz. Another is an experimentally generated chirped pulse whose frequency range is 18-40 GHz, as shown in Fig. 2. Figure 3 shows an example of the simulation results obtained using the ultrashort-pulse with a frequency range of 0-50 GHz. The open circles denote a given radial plasma density profile. The solid line is the reconstructed profile obtained by the SRA method. A good agreement is obtained between the two profiles.

Figure 4 shows the simulation results obtained using the chirped pulse. In this case, we have to assume density profiles in the range 0-18 GHz. A given plasma density is indicated as the open circles. The dashed line is obtained similar to the previous one, i.e., by assuming a plasma edge as an initial point and assuming a value of τ. When the calculation was performed for the τ range corresponding to 0-18 GHz, we considered that the τ at 0 GHz is 0 s, and approximated the remaining τ values linearly in the range 0-18 GHz. The error stems from the integration of τ in Eq. (3). On the other hand, the solid line is obtained by assuming the cutoff density corresponding to 18 GHz as an initial point. Note that the reconstructed density profile agrees well with the given one. The problem is that we have to assume the position of the cutoff layer at 18 GHz in the experiment, although this position can be obtained from the simulation. In a practical sense, the determination of the initial position is easier than assuming the value of τ. It is desirable to expand the low frequency limit in order to decrease the errors that stem from assuming the position of the cutoff layer. The calculation error in the high frequency region is larger than the one in the low frequency region. This is because the reflectometer signal in the high frequency region is weak. To improve the accuracy, it is necessary to increase the signal strength in the high frequency region.

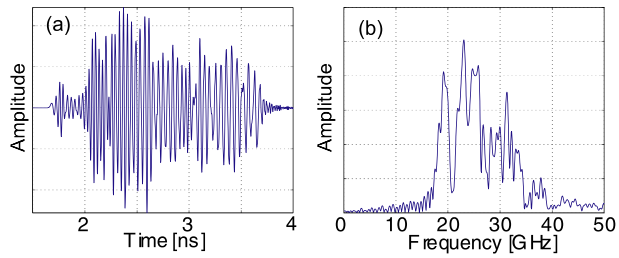

Fig. 2 Experimentally obtained incident wave. (a) Time dependence (b) Frequency spectrum.

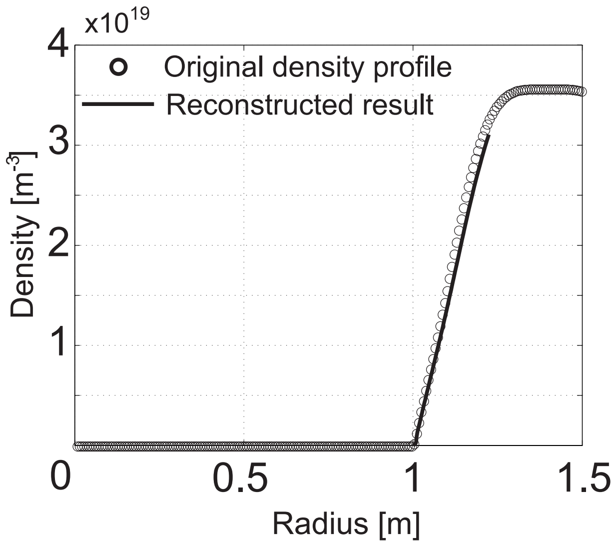

Fig. 3 Reconstructed result obtained using the SRA method with simulated data in the case of an ultrashort-pulse. This is then compared with the original density profile.

In summary, we performed a numerical study of USPR using a FDTD method to confirm the validity of the

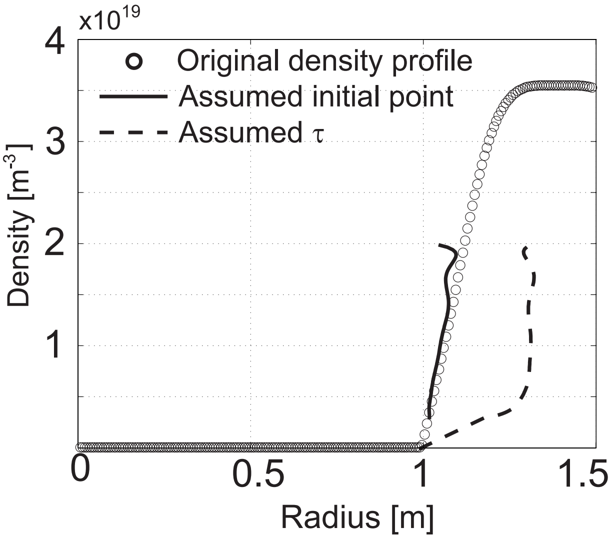

Fig. 4 Reconstructed result obtained by the SRA method with simulated data in the case of an experimental chirp pulse. This is then compared with the original density profile.

SRA method. We found that the density profiles can be suitably reconstructed using the SRA method. Although the density profile corresponding to the range 0-18 GHz, where we could not obtain the experimental data, has to be assumed, our results indicate that a careful determination of the initial position leads to a better profile than the one obtained by assuming τ. It is desirable to expand the low frequency limit in order to reduce the assumed range. The error in the high frequency region was due to the weak reflectometer signal at that range, and greater signal strength must be achieved to overcome this limitation.

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