Reconstruction of Edge Density Profiles Using Ultrashort-Pulse Reflectometry in LHD

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An ultrashort-pulse reflectometer (USPR) has been applied to the measurement of the edge density profile of the Large Helical Device at the National Institute for Fusion Science. The reflectometer signal is recorded directly using a high-speed digitizing scope, and is analyzed by means of a signal record analysis method to reconstruct the density profiles. This method has the advantage of using raw signal records instead of poorly localized frequency modes. The density profiles in the edge region are successfully determined and compared with those obtained by an FIR laser interferometer.

Keywords: plasma diagnostics, reflectometry, microwave, plasma density, LHD

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Reflectometry is a promising method for measuring electron density profiles without perturbing plasma. The advantages of this method lie in its high spatial resolution, non-invasive nature, and minimal requirement for port access. Ultrashort-pulse reflectometry (USPR) uses an impulse generator producing pulses in the picosecond range as an incident wave. Since the Fourier frequency component is proportional to the inverse of the pulse width, frequencies up to the microwave to millimeter-wave range are expected from an ultrashort pulse. An incident wave of higher frequency is reflected from a higher density plasma layer. Thus, plasma density profiles can be reconstructed by collecting the time-of-flight (TOF) signal of each frequency component reflected from each cutoff layer [1–3].

We have applied two methods for reconstructing density profiles. One measures the TOF between incident and reflected waves as a function of frequency. The TOF measurement is performed using a constant fraction discriminator and a time-to-amplitude converter after the signal passes through a bank of band pass filters. The TOF for a wave with frequency ω from the plasma edge to the cutoff layer at x_c is given by

$$\tau(f) = \frac{2}{c}\int_0^{x_c} \frac{1}{\sqrt{1-\omega_{pe}^2/\omega^2}}\,dx, \tag{1}$$

where $\omega = 2\pi f$, c is the velocity of light, and ω_{pe} is the electron plasma frequency. In order to obtain the density profile, Eq. (1) can be Abel inverted to obtain the position of the cutoff layer,

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

The other method signal record analysis (SRA) is based on the analysis of a raw signal regardless of the time localization of the signal spectrum [4]. The signal written as

$$s(t) = \int |S|\, e^{i\omega t - i\psi(\omega)}\, d\omega \tag{3}$$

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 cases of pulses reflected from the port window and from the plasma, respectively, by a sampling scope. These waveforms are transformed into a phase spectrum as a function of incident frequency as $\psi_{w,p} = -\arg(S_{w,p})$. 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

$$\tau(f) = \frac{1}{2\pi}\frac{\delta\psi(f)}{\delta f}. \tag{4}$$

The density profile of the plasma can be obtained by using Eq. (2).

The schematics of the USPR system employed on the Large Helical Device (LHD) have been shown elsewhere [5]. An impulse generator (Picosecond Labs, model 4015C) is utilized as a source. The pulse width, height, and the impulse repetition rate are 22 ps, 3 V, and 1 MHz, respectively. The output of the impulse generator is fed to a 30 cm WRD-750 waveguide to obtain a chirped pulse with a frequency range of 7-20 GHz. The chirped pulse is

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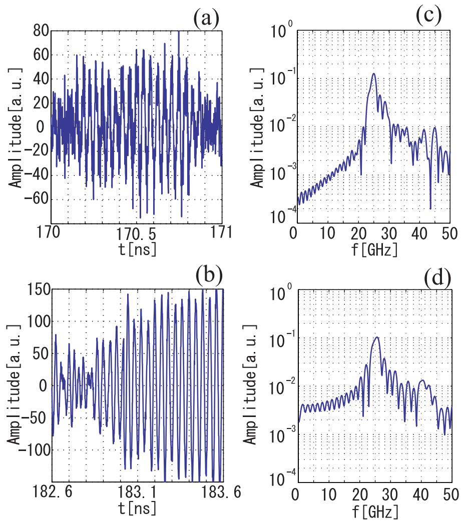

Fig. 1 Reflected waves from the wall (a) and from the plasma (b), and their spectra (c,d).

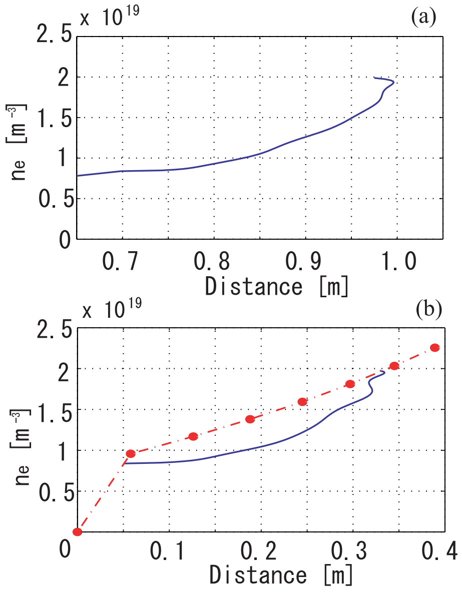

Fig. 2 Reconstructed density profiles. (a) The position of the separatrix is chosen as an initial value. (b) The profile is compared with that obtained by an FIR laser interferometer (dotted line in red). The difference between the horizontal axes shown in Fig. 2 (a) and Fig. 2 (b) is about 0.6 m.

fed to an active doubler after passing through a 15 m low-loss coaxial cable in order to double the frequency range to 26-40 GHz, and is then amplified by a power amplifier (30 dB gain and 1 dB compression point of 17 dBm). The transmitter and receiver are identical conical horn antennas each with a collimating lens. The antenna gain is 30-34 dB in the range of 26-40 GHz. The reflected wave is amplified by low noise amplifiers (50 dB total gain) to compensate for the transmission loss of the coaxial cable. The signal is then digitized by a sampling scope with an equivalent sampling frequency of 250 GHz. A filter bank and a time-of-flight analyzer are not needed for the profile reconstruction process.

Figure 1 shows the reflected signals and their frequency spectra from the wall and from the plasma. We utilized the waves reflected from the wall since the reflection from the window is difficult to detect in the present experiment due to the use of a bistatic antenna system. It is necessary to take the derivative of the phase difference for calculating of the TOF. We utilize an eleven degree polynomial approximation. Figure 2 (a) shows plasma density profiles obtained using the SRA method. We assumed here that the initial position where the electron density equals zero corresponds to the position of the separatrix. We assumed τ in the range of 0-26 GHz with a straight line when we integrated τ to calculate the distance. A multi-channel far-infrared (FIR) laser interferometer is installed in the LHD for measurement of density profiles. Therefore, we utilized the data of the FIR laser interferometer at a density of $0.8 \times 10^{19}\,\mathrm{m}^{-3}$ as an initial value, because the measurable density is limited to $(0.8\text{-}2.0) \times 10^{19}\,\mathrm{m}^{-3}$ in the present USPR due to the frequency range of 26-40 GHz. Figure 2 (b) shows a comparison of the density profiles obtained by the USPR and those obtained by the FIR laser interferometer. Dotted line and the solid line shows the profile obtained by the FIR laser interferometer and the SRA method, respectively. In the edge plasma region, the FIR laser interferometer can measure only a few chords. The USPR system seems to be useful for this purpose. The difference between the horizontal axes shown in Fig. 2 (a) and Fig. 2 (b) is about 0.6 m. The difference is due to the assumed τ. To further explore the potential of this system, measurements should be performed in the low frequency regime, and in future study we plan to expand the frequency range to 18-40 GHz. The range which we must assume decreases by half, since the measurable density becomes $(0.4\text{-}2.0) \times 10^{19}\,\mathrm{m}^{-3}$.

In summary, an ultrashort-pulse reflectometer has been applied to the LHD for measuring the plasmas' edge region. The reflected waves are directly recorded by a high-speed digitizing scope, and analyzed by signal record analysis for density reconstruction. The density profiles in the edge region are successfully determined during the shot and compared with those obtained by an FIR laser interferometer.

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