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Reconstruction method of X-mode ultrashort-pulse reflectometry in LHD

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Abstract. Reflectometry is considered to be one of the key diagnostics to measure density profiles and density fluctuations of fusion oriented plasmas. When an electromagnetic wave is launched into a plasma, the wave is reflected at the corresponding cutoff layer of the ordinary (O) mode or the extraordinary (X) mode. Reflectometry measures the time of flight (TOF) or group delay of the reflected wave. We have applied ultrashort-pulse reflectometry (USPR) to Large Helical Device (LHD) at National Institute for Fusion Science (NIFS). The high spatial analysis method called signal record analysis (SRA) is utilized to reconstruct the density profiles from the TOF signal. Also, it is noted that the remote control system using super science information network (super-SINET) has been introduced to the present USPR system. This remote system is exclusive, and it seems to be quite effective for collaborating experiment of large devices such as ITER.

1. Introduction
Reflectometry is a radar technique utilized to measure plasma density profiles [1-7]. When the electromagnetic wave is launched into the plasma, the wave is reflected at the corresponding cut-off layer. The density profiles are obtained by calculating phase delay or group delay between reflected wave and reference wave, since the density at the cutoff layer is determined by the probing frequency. The advantages of the reflectometry lie in its high spatial resolution, non-invasive nature, and minimal requirement for port access. There are two modes for the waves propagating perpendicular to the magnetic field, that is, the ordinary (O) mode and the extraordinary (X) mode based on the dispersion relation for the electric field is parallel and
Figure 1. Overview of reflectometry system. Whole system can be controlled from the remote site using super-SINET.

The phase difference can be described as

$$\phi_p(f_n) = \frac{4\pi f_n}{c} \int_{r_0}^{r_c} \mu_{o,x}(r, f_n) dr - \frac{\pi}{2}. \quad (1)$$

Where $f_n$ is the frequency, $c$ is the velocity of light, $r_0$ is the edge of plasma, $r_c$ is the cutoff layer, and $\mu_{o,x}$ is the refractive index of each mode. The O-mode cut-off only depends on the local electron density. On the other hand, the X-mode cut-off depends on the local electron density and the magnetic field strength. For the O-mode propagation, this integral can be analytically solved for the density profile using the Abel inversion. For the X-mode propagation, however, no analytic solution exists and numerical methods have to be used. Though the reconstruction in the X-mode system is more complicated than the one in the O-mode system, the initial point of the density profile is expected to be obtained in the case of the X-mode system. This paper describes the present USPR system (Sec 2), the result of reconstructed density profile obtained by the O-mode system and application of the X-mode system (Sec. 3), and summary (Sec. 4).

2. USPR SYSTEM

Figure 1 shows the schematic of the USPR system applied to LHD at NIFS [8, 9]. The wide frequency band system is required to obtain wide density profile since an incident wave is reflected at the density layer corresponding to its cutoff frequency. Our reflectometry utilizes an ultrashort pulse as a source. Since the bandwidth of an impulse has an inverse relation to the pulse width, we can cover the frequency range of micro- to millimeter waves with a single source. The pulse width, height and the impulse repetition are 22 ps, 3 V and 1 MHz in the present system, respectively. The transmitter and receiver are identical conical horn antennas each having a collimating lens. The antenna gain is 30-34 dB in 18-40 GHz range. We can easily change the propagation from the O-mode to the X-mode by rotating the waveguides. The signal waveform is then digitized by a sampling scope with an equivalent sampling frequency of 250 GHz. We utilize the frequency range of 18-40 GHz in the present system The measurable plasma density is $0.4-2.0 \times 10^{19} \text{m}^{-3}$.

Remote control system using super-SINET [10] is introduced to the present USPR system. The general-purpose interface bus (GPIB) card is installed in each device. The whole operations
such as adjustment of supply voltage fed to the amplifiers and the doubler, the timing control of the impulse, and the data acquisition and monitoring can be performed from the remote site (Kyushu University). It seems to be quite effective for collaborating experiment of large plasma devices such as ITER.

The reflected wave is analyzed with a signal record analysis (SRA) method which is a software handling to calculate the phase difference of reflected waves with and without a plasma as a function of frequency [11]. The conventional system utilizes a filterbank to obtain the phase vs. frequency. Therefore, the measurable points are limited by the number of filters. On the other hand, continuous spectrums can be obtained with the SRA method since the reflected wave is directly recorded to the sampling scope. As a result of that, the reconstruction profiles are expected to have a good spatial resolution.

3. Experimental Result

In the present system, the reflected wave can be obtained in every 0.4 s. In the experiment, the reflected wave can be obtained especially in the case of high density and stable plasmas. This is because the cutoff layer works as a mirror wall in the edge region due to rapid change of density. Figure 2 shows an example of the experimental reconstruction profile for the O-mode system. The result was compared with the one obtained by the Thomson scattering method. It seems to be in good agreement between the profiles obtained by the USPR and the Thomson scattering.

In the X-mode propagation, the cutoff frequency changes by the local electron density and the magnetic field. The cutoff frequency is described as

\[ f_x = \pm \frac{f_{ce}}{2} + \frac{1}{2} \sqrt{f_{ce}^2 + 4f_{pe}^2}. \]  

where \( f_{pe} \) is plasma frequency and \( f_{ce} \) is cyclotron frequency. There are the two cutoff layers in the X-mode propagation. The higher frequency is called right hand cut off and the lower one is left hand cut off, respectively. Figure 3 shows the expected cutoff frequency of each position in which magnetic configuration is \( B_0 = -1.5 \text{ T} \). The solid line shows the right hand, the dashed line shows the left hand.
the conventional Abel inversion. The phase difference of the $n$th frequency is described as the equation (1). For the next frequency $f_{n+1}$, the measured phase can be represented as

$$\phi_p(f_{n+1}) = \frac{4\pi f_{n+1}}{c} \left( \int_{r_0}^{r_c(f_n)} \mu_x(r, f_{n+1}) dr + \frac{1}{2} \Delta r \mu_x(r_n, f_{n+1}) \right)$$  \hspace{1cm} (3)

where $\Delta r$ is the distance between the $n$th and the $(n+1)$th cutoff layer. All the other quantities, except $\Delta r$, are known because the profile for $f_n$ is known. Then $\Delta r$ is described as

$$\Delta r = \frac{2}{\mu_x(r_n, f_{n+1})} \left( \frac{c}{4\pi f_{n+1}} \phi_p(f_{n+1}) - \int_{r_0}^{r_c(f_n)} \mu_x(r, f_{n+1}) dr \right).$$  \hspace{1cm} (4)

The density profile can be extended in a step by step manner using the above algorithm. The behaviors of edge plasma and plasma position are important for stability control of magnetically confined plasmas. It is difficult for the other method such as FIR interferometer and Thomson scattering method to measure the density profile of the edge region. The USPR system seems to be useful for this purpose.

4. SUMMARY
In summary, an ultrashort-pulse reflectometry has been installed in LHD for measurement of density profiles in the edge region. Our reflectometer can be operated as the X-mode system as well as the O-mode system by rotating the waveguides. The whole system can be controlled from a remote site using Super-SINET. This remote system is effective for the collaboration experiments. The reflected waves from the O-mode or the X-mode system can be obtained especially in the case of high density and stable plasmas. The reconstructed density profiles obtained by the O-mode system are in good agreement with those obtained by the Thomson scattering system. In the X-mode system, the density profile of the edge plasma seems to be obtained by considering the present magnetic configuration by using the numerical method.

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