X-mode pulsed radar reflectometer for density fluctuation measurements on LHD

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A four channel pulsed radar reflectometer system has been installed on the Large Helical Device (LHD). The complicated magnetic structure in LHD causes mode conversion and/or polarization rotation of the microwaves. Pulsed radar reflectometry is a suitable reflectometric technique, because it measures the delay time of the reflected wave, not the phase, and *X*-mode and *O*-mode polarized waves can be distinguished. By using *X*-mode operation of the pulsed radar reflectometer so that each pulse width is about 2 ns, and the repetition rate is up to 200 kHz, the critical density where the microwave is reflected is about $1\times10^{16}\ \mathrm{m}^{-3}$. Also it is found that the static natural island affects the *X*-mode reflectometric measurements.
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I. INTRODUCTION

It is very important to know information of the density profile and fluctuation for magnetic-confined plasma experiments. In order to measure these plasma parameters with high temporal and spatial resolution, we applied a microwave reflectometer on the Large Helical Device (LHD) (the major radius is around 3.75 m, the averaged minor radius is 0.6 m, and the magnetic field strength on the plasma axis is up to 2.95 T).[1,2] The reflectometer is a compact system that needs only a small access to the device, and also has a higher resolution than conventional diagnostic methods. For these reasons, several types of reflectometers have been used in the world's fusion devices.[3–15] Since the LHD has a complex magnetic field configuration and also has a large magnetic shear, there were two theoretical predictions that mode conversion and/or polarization rotation would occur in the launched and reflected microwave.[16,17] To study the effect of the strong magnetic shear, the pulsed radar reflectometer is a suitable reflectometric technique. Because pulsed radar reflectometry measures the delay time of the reflected wave from the cutoff layer in the plasma, a distinction can be made between *X*-mode and *O*-mode polarized waves even if unexpected pulses are returned.

The density profile of the LHD plasma is almost flat or hollow. By using the *X*-mode right-hand cutoff in the plasma, the reflectometer signal is affected by not only the electron density but also by the magnetic field. We have the possibility of measuring both the density and the magnetic fluctuations in the core region.

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II. PULSED RADAR REFLECTOMETER SYSTEM

We have currently constructed a four channel pulsed radar reflectometer system. The schematic of the four channel pulsed radar reflectometer system is shown in Fig. 1. Four Gunn oscillators are used as a source. The frequencies of the oscillators are 33, 39, 60, and 65 GHz. The output power of each is about 100 mW. A *p*-*i*-*n* switch is used as a pulse modulator that uses the tuned signal of the generated impulse output. The series of microwave pulse passes through the oversized waveguide in order to avoid deformation. Separate transmitter and receiver horns are used in order to avoid the mixture of spurious reflecting components in the waveguides, vacuum window, etc. The antenna is a conical horn with a Teflon lens for focusing the microwave beam. It can be slid horizontally and rotated using remote control. The reflected waves from the corresponding critical cutoff layers in the plasma are picked up by the receiver horn and mixed with the local microwave, of which the frequencies of the local oscillators are 51 GHz for *R* band and 78 GHz for *V* band, in a mixer. The intermediate frequency signals are filtered by bandpass filters each with a bandwidth of ±1.0 GHz and then detected and converted from the envelope of the reflected wave to a pulse. Reference pulses for the time-of-flight (TOF) measurement are measured using *R*-band and *V*-band detectors, which are located before the antenna to avoid jitter from the pulse generator and the *p*-*i*-*n* switch. Each pulse width is around 2 ns and the repetition rate is 200 kHz in standard operation. The detected pulses are fed to the diagnostics room using electro-optical converters and optical cables. Then the TOF measurement is carried out. A constant fraction discriminator is used to obtain the start and the stop pulses for the time-to-amplitude converter, because the pulse

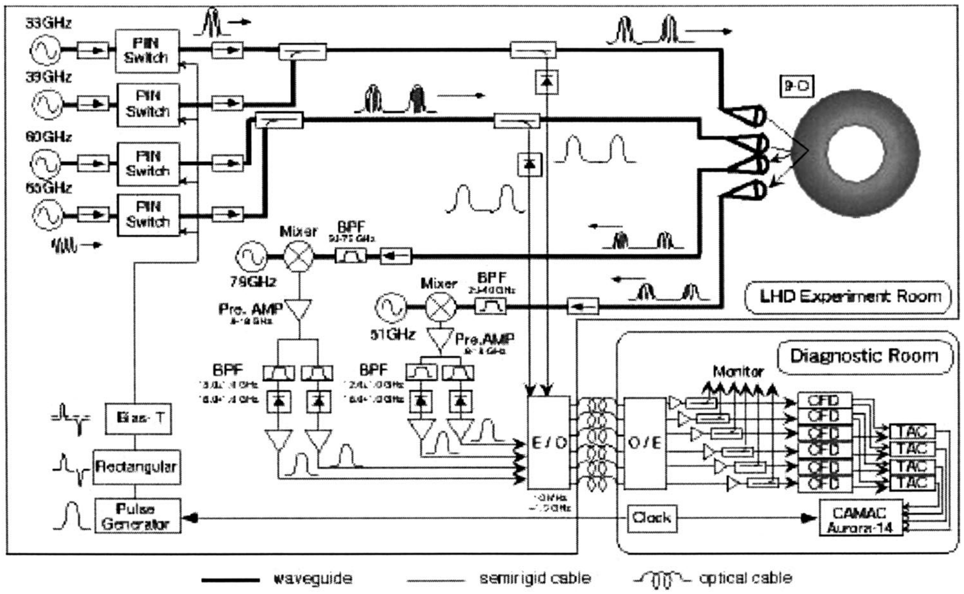

FIG. 1. Schematic of four channel pulsed radar reflectometer system.

amplitude is changed during the plasma discharge. The data are acquired by a CAMAC based analog-to-digital converter (Aurora 14 with 12 bits 1 Mword memory) and stored in a personal computer. Also, we constructed the real-time video acquisition system of the oscilloscope screen, where the reflected pulses are monitored directly, to get information on the change of both the pulse amplitude and the pulse shape.

III. EXPERIMENTAL RESULTS

Since LHD has a steady state magnetic field, it is a suitable experimental device to investigate the critical density inferred from the reflection from the *X*-mode right-hand cutoff. Two *X*-mode microwave pulses are launched to the LHD plasma under the conditions the magnetic field strength is 2.951 T and the magnetic axis position is 3.53 m. Figure 2(a) shows the time evolution of the averaged electron density measured by the millimeter wave interferometer[18] at the end of the plasma discharge. The delay times of both 60 and 65 GHz microwave pulses by TOF measurement are shown in Fig. 2(b). Here, the reflection from the inner wall of the vacuum vessel is used as the standard point where the delay time is zero, and the negative value of the delay time means that the cutoff layer moves to the edge. Also, Fig. 2(c) shows the time evolution of the pulse amplitude of 65 GHz microwave reflected from both the plasma and the inner wall, measured using the oscilloscope monitor output. It is found that the reflected signals from the plasma still appear under the condition that the averaged density is lower than $1 \times 10^{16}\ m^{-3}$. Therefore, by using *X*-mode polarized waves, a pulsed radar reflectometer can measure the density fluctuations and density profile even of a very low-density plasma.

Next we introduce the typical behavior of the *X*-mode pulsed radar reflectometer signal on LHD. Figures 3(c)–3(f) show the time evolution of the delay time for the condition that the magnetic field strength is 1.52 T and the magnetic axis position is 3.75 m. In the lower density case (32 876), the delay time of 33 GHz falls down to about minus 3 ns

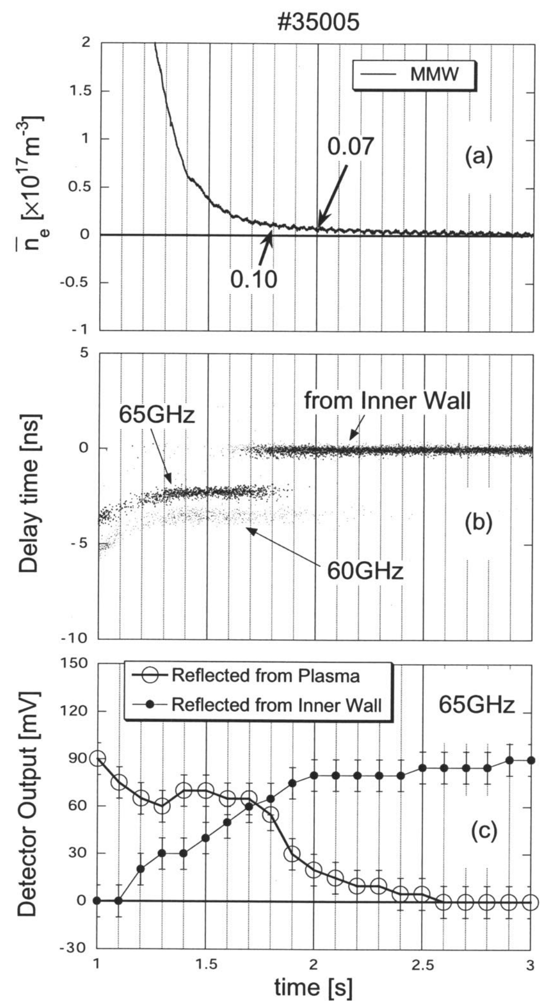

FIG. 2. (a) Time evolution of the averaged electron density measured by millimeter wave interferometer. (b) Time evolutions of the delay times of both 60 and 65 GHz microwave pulses in the end of the plasma discharge. Here, the reflection from the inner wall of the vacuum vessel is used as the standard point where the delay time is zero. Negative value means that the cutoff layer moves to the edge. (c) Time evolution of the pulse amplitude of reflected 65 GHz microwave from the plasma and the inner wall.

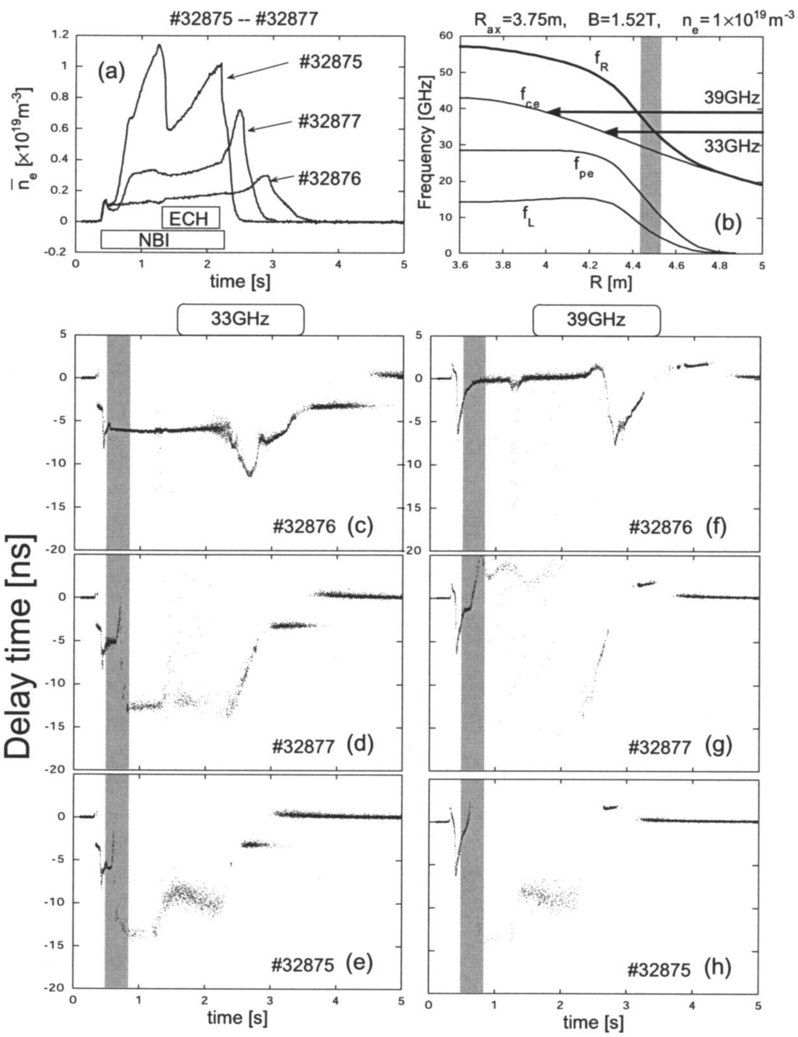

FIG. 3. (a) Time evolutions of the averaged electron densities measured by FIR interferometer in three plasma discharges of low (32 876), middle (32 877), and high (32 875) density. (b) Radial profiles of characteristic frequencies. Here the typical density profile is used. The location of the static natural island is estimated in the hatched region by the magnetic calculation. (c)–(h) Time evolutions of the delay times of both 33 GHz (c)–(e) and 39 GHz (f)–(h) microwave pulses.

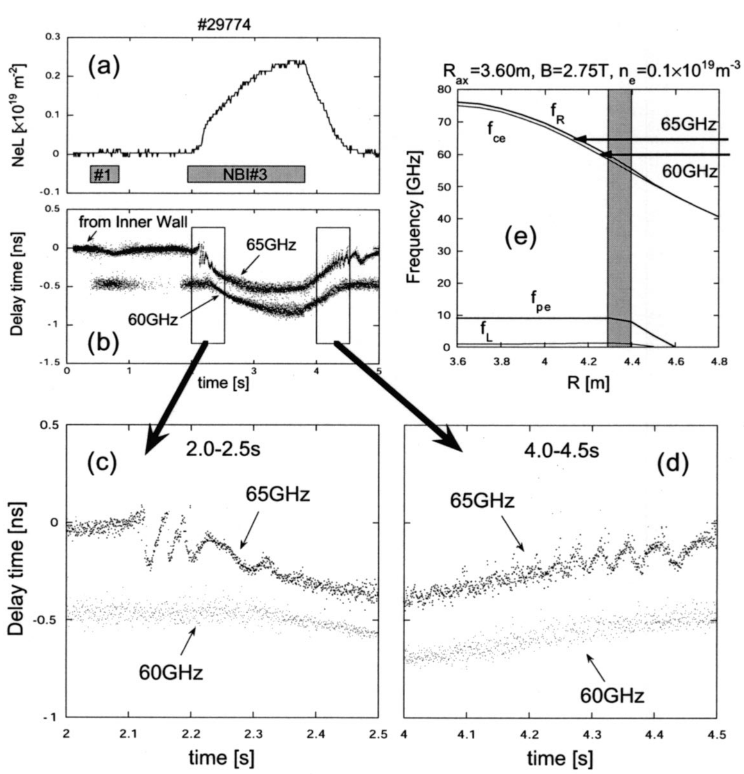

FIG. 4. (a) Time evolution of the line integrated electron density. (b)–(d) Time evolutions of the delay times of both 60 and 65 GHz microwave pulses. (e) Radial profiles of characteristic frequencies. The estimated static natural island is located in the hatched region.

when the plasma initiates and then it moves 3–4 ns closer to the edge as the plasma grows. However, in a dense plasma case (32 877 and 32 875), the delay time moves to the positive direction in the hatched temporal region and then the delay time jumps down to the negative direction. Especially, the 39 GHz signal keeps a large positive value during $t = 0.7–2.0$ s in the middle density case (32 877). The cause of this behavior may be the static natural island in the edge region. LHD has an $m/n = 1/1$ static natural island in the edge region shown in the hatched area in Fig. 3(b). When the density increases and the plasma expands to the edge, the cutoff layer moves to near this island area. If the density profile is hollow in this area, the radial gradient of the right-hand cutoff frequency profile near the cutoff layer becomes gentle and the group velocity of the microwaves becomes slow. Just after the density increases, furthermore, the cutoff layer moves outside the island region and the delay time jumps down to the negative direction. Unfortunately, now we have no definite information on the density profile in this area because our far-infrared interferometer system[19] does not have enough spatial resolution. In order to understand these phenomena caused by the island, we have been constructing higher resolution diagnostics of the density profile measurement such as a CO_2 laser imaging interferometer[20] and the Thomson scattering system.[21]

The reflectometer has good spatial resolution and can measure the local density fluctuation. Figures 4(b)–4(d) show the time evolutions of the delay time of both 60 and 65 GHz microwave pulses for the condition that the magnetic field strength is 2.75 T and the magnetic axis position is 3.6 m. The distance between corresponding cutoff layers of both frequencies is about 10 cm during $t = 2.0–2.5$ s and $t = 4.0–4.5$ s. Only for the 65 GHz signal does a density oscillation with a frequency of 30–50 Hz appear. This oscillation is located in the core region and the location seems to be almost steady.

IV. SUMMARY AND FUTURE WORKS

For density fluctuation measurement, the *X*-mode four channel pulsed radar reflectometer system has been applied on the LHD. It can be used to investigate the critical density where the microwave reflected is above about $1 \times 10^{16}\ \mathrm{m}^{-3}$. Also it is found that the delay time of the reflected wave is affected by the static natural island. However, more detailed measurements are necessary with simultaneous measurements using new diagnostic systems. The localized density fluctuation is found by the high spatial resolution of the reflectometer. More multichannel systems will be installed to measure more detailed structure of the fluctuation and also the density profile in the future.

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