We have applied an ultrashort-pulse reflectometer (USRM) to large helical device (LHD) plasmas for density profile measurement. This system can be controlled and monitored from remote site (Kyushu University) by using ultra wideband science information network (super-SINET) that ideal bandwidth reaches up to 1 Gbps. As a result of the measurement, we have confirmed reflection wave from the plasma, and succeeded to reconstruct density profiles corresponding to two plasma operation condition by means of SRA method. Applicability of microwave imaging reflectometry (MIR) for the case of mirror device was numerically studied. The questions concerning radial localization of measurements, optimal position of optical system and imaging properties of MIR system were considered. The high curvature of the plasma cutoff layer and a relatively small distance from the plasma to the port are known to improve the performance of a conventional reflectometer. Nevertheless in the case of density fluctuations with wide wavenumber spectrum and large amplitude, the imaging reflectometry shows better results than the conventional one.

I-1. INTRODUCTION OF USRM MEASUREMENT

Ultrashort pulse reflectometer (USRM) systems for density profile measurement are applicable in wide electron density range such as from inductively coupled plasma (ICP) to fusion experimental plasma. Since the propagation duration of probing beam inside plasma is less than a few nano seconds, the signal obtained by the USRM system is hardly influenced by density fluctuations. Since a sampling scope is utilized for a detection system in the present experiment, which takes about 10 ms to acquire a set of waveform, plasma density must be fixed during the measurement. However, utilizing the sampling scope will provide us cost effective solution to reconstruct precise density profile by means of signal record analysis method (SRA). Furthermore, the injection of an impulse enable us to measure a density profile over a wide spatial region since it contains broad-band frequency range inside an impulse. We report here the USPR system, application of the system to the large helical device (LHD), and remote operation system utilizing super-SINET.

I-2. USRM SYSTEM AND REMOTE OPERATION SYSTEM ON LHD

Figure 1 shows the USPR system on LHD. An impulse generator (Picosecond Labs Model 4015C) is utilized as a source, which transmits Gaussian impulses. The pulse width, height, and repetition rate of the impulse are 22 ps, 3 V, and 1 MHz, respectively. The pulse is fed to 30 cm section of a waveguide and chirped inside the waveguide. Bandwidth of the chirped pulse ranges from 7 GHz up to 20 GHz. The chirped pulse is then fed to an active doubler after passing through a 15 m low-loss coaxial cable. The active doubler doubles the frequency component
of the chirped pulse. The frequency range is between 26 GHz to 40 GHz. Then the chirped pulse is fed to a power amplifier with a gain of 30 dB and 1dB compression point of 17 dBm, and then transmitted to a plasma in the ordinary (O) mode by a conical horn antenna located at bottom port of section 3-O. The reflected wave from the plasma is received by another conical horn located at the same port. The signal is amplified by a low-noise amplifier, and further amplified by another low-noise amplifier after passing through a 15 m low-loss coaxial cable. The signal is then digitized by a sampling scope with equivalent sampling frequency of 250 GHz. In this measurement condition, it takes about 10 ms to acquire an array of 1024 data points with 2 times average. The impulse generator is controlled by a timing system. The timing system consists of an arbitrary function generator and a pulse-forming generator. The arbitrary function generator receives a master pulse, whose time is synchronized with plasma sequence, and transmits rectangular waves during the plasma operation. The frequency and duty cycle of the rectangular wave are 1 MHz and 50%, respectively. This rectangular wave is fed to a pulse-forming generator as a trigger. The pulse-forming generator transmits rectangular pulse with a moderately short pulse width less than 10 ns and rapid rise and fall time less than 100 ps at each trigger time. This rectangular pulse is fed to the impulse generator and the sampling scope as a trigger. In order to avoid affection of magnetic materials to helical magnetic field, most instruments of the USRM system are kept 10 m away from vacuum vessel of LHD. The directly recorded signal is analyzed and reconstructed by means of SRA method.

Remote control system using super science information network (super-SINET) has been introduced to the USRM system since 2003 as shown in Fig. 2. This network is promoted by National Institute for Informatics (NII). Bandwidth of the main backbone and branch line is 10 Gbps and 1 Gbps, respectively. The control client can operate the control server by using this network. The general purpose interface bus (GPIB) card is installed in the control server. The remote console, which has graphical user interface (GUI) as shown in Fig. 3, is prepared to control the instruments of USRM via GPIB. The operations such as adjustment of supply voltage fed to amplifiers and the doubler, timing control of the impulse, data acquisition and monitoring, adjustment of transmitter and receiver angle can be performed from the remote site (Kyushu University).
Figure 2 Remote control system by super-SINET  Figure 3 GUI control application

I-3. RESULTS OF THE MEASUREMENT

Figure 4 shows operational sequence of heating systems (a), time evolution of stored energy of the plasma (b), and electron density by FIR(c). The plasma is generated from 0.5 second, and density reaches $1.5 \times 10^{19} \text{ m}^{-3}$ at 2.0 second, which corresponds to the cutoff frequency of 35 GHz. Figure 5 shows an output signal observed by the sampling scope. Each figure corresponds to measurement time denoted in Fig. 4(b,c) as four gray lines and t1-t3 from top figure to bottom one. In the Fig. 5(a), we can confirm the reflected wave from the diagonal vacuum vessel from 186 ns to 187 ns when the plasma does not exist (t1). Figure 5(b,c) are the signals when the plasma exists. Two types of trace, which color is gray and black, indicate the raw observed signals and bandpass-filtered signals by 2nd order digital Butterworth filter, respectively. Frequency range of the bandpass filter is between 26 and 40 GHz, which corresponds to bandwidth of incident frequency. Noise level observed in Fig. 5(b,c) increases obviously compared to Fig. 5(a). This noise is considered to be detected due to interference of other microwave diagnostic systems and electron cyclotron emission. By using the bandpass filter, we successfully confirm reflection from the plasma as shown in Fig. 5(c). We can attribute the signal received around 178 ns to reflection from the plasma since the detection time is 10 ns former than that from the vacuum wall. However, we can not observe any obvious reflection in this temporal range as shown in Fig. 5(b), even though the value of the plasma density at t2 and t3 are almost same. As we describe above, it takes 10 ms to acquire a trace of data by using the sampling scope. From this reason, the cutoff layer should freeze during 10 ms in order to measure the reflected wave keeping its phase information. Plasma density at t2 changes rapidly during the measurement as shown in Fig. 4(c). We can not observe the obvious reflected waves since the cutoff layer moves back and forth at t2. While, we can observe them at t3 since the cutoff layer seems to freeze during the measurement as shown in Fig. 4(c). Fig. 6 shows preliminary results of density reconstruction by means of SRA method in the case of two plasma operations. It is confirmed that density profile is expanding to outside in high density operation regime compared to low one. We are scheduled to take more data to investigate reliability of our system in the next experimental cycle.
II-1. INTRODUCTION OF NUMERICAL STUDY OF MICROWAVE IMAGING REFLECTOMETER

The microwaves reflected from cutoff layer inside the plasma bear information about plasma parameters. Microwave reflectometry utilizes the reflected signal for plasma density profile and fluctuations measurements. In spite of long term usage and popularity of the method, extracting information from reflectometer signal is a challenge up to nowadays, since scattering by random fluctuations leads to complicated interference pattern far from a cutoff. As a possible solution, an imaging concept was suggested in order to project the signal near the cutoff to the receiving plane outside the plasma, and the feasibility of the method was proven for a wide range of density fluctuation parameters. An experimental and theoretical study was recently presented by Munsat et al.
where the authors performed laboratory characterization of an imaging reflectometer system by using a metal reflector with sinusoidal corrugations. The reflector was used as an approximation to the reflection by a plasma cut-off layer with turbulent fluctuations. The authors found that for the long wavelength, small amplitude corrugations both the conventional (without optics) and MIR systems accurately measure the target surface shape. For the shorter wavelength and/or higher amplitude, the conventional system was able to accurately reproduce the surface shape close to the target only. In contrast to conventional reflectometry, the imaging configuration was able to measure the shape of corrugations even far from the surface. All the parameters related to plasma and the machine geometry were selected in the original papers such as to correspond to tokamaks. We perform a numerical study of the MIR system in order to assess the feasibility of the method and to estimate possible obstacles and complications arising when microwave imaging reflectometry is applied to a smaller scale low density fusion device, such as the GAMMA 10 tandem mirror device.

II-2. NUMERICAL MODEL

The model employed in this study takes into account a free-space propagation of the launched microwaves, a phase front correction by the optical system, and a reflection from the plasma (Fig. 7). It comprises analytical and numerical (FDTD) solutions of 2D Maxwell's equations in vacuum and the equation for the induced current density $j$

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

$$\frac{\partial E}{\partial t} = c^2 \nabla \times B - \frac{1}{\epsilon_0} j,$$

$$\frac{\partial j}{\partial t} = \epsilon_0 \mu_0 E - \omega_{ce} j \times b_0,$$

where $B$, $E$ are the signal magnetic and electric fields respectively, $c$ is the speed of light in vacuum, $\epsilon_0$ is the permittivity of vacuum, $\omega_{pe}$, $\omega_{ce}$ are the electron plasma frequency and cyclotron frequency, and $b_0$ is a unit vector in the direction of the external magnetic field. Plasma parameters are included in the current density equation (3).

Plasma profile is assumed in an exponential form:

$$n(r) = n_o \exp(-r^2/\Delta^2)$$

with $n_o=2 \times 10^{12}$ cm$^{-3}$ and $\Delta = 10$ cm.

External magnetic $B_0=0.45$T is directed normally to the simulation plane. For the modelled parameters the cutoff layer is located at 10.3cm. The random fluctuations $\delta n/n$ were generated as a sum of $N$ modes with random amplitudes $\delta n_{oi}$ and uniformly distributed phases $\phi_{oi}$, similar to reference 10:

$$\frac{\delta n}{n} = \frac{2\gamma}{\sqrt{N\sigma}} \sum_{i=1}^N \delta n_{oi} \cos(k r (r \theta - \nu_o t) + \phi_{oi}) \times \cos(k r + \phi_{oi}).$$

Here $\gamma$ is a root-mean-square (RMS) amplitude of random fluctuations, $\sigma$ is a standard deviation of $\delta n_{oi}$, $r_o$ is a radius of normal incidence cutoff layer, $\nu_o = 6$km/s is a rotation speed. The amplitude $\delta n_{oi}$ has a Gaussian shape.
\[
\delta n_{ij} \propto \exp\left(-\frac{(k_{ij} - k_{i0})^2}{\Delta k^2} - \frac{(k_{rj} - k_{r0})^2}{\Delta k_r^2}\right)
\]

With \( k_{i0}, k_{r0} \) and \( \Delta k_{i0} \), and \( (k_{i}, k_{r} \text{ and } \Delta k_{r}) \) being the poloidal (radial) wavenumbers, the shift of a wavenumber spectrum and spectral width respectively.

The imaging optics considered in this paper consists of a confocal two-lenses optical system. The two identical lenses with correction of spherical abberation have zero widths and focus distances \( f_1 = f_2 = 70 \text{cm} \). Such a system transmits an image of the source with an enlargement factor equal to unity \(^1\). In order to check the imaging properties of the different size optics, a Gaussian signal with sinusoidal phase was generated and numerically projected through the optics in vacuum. The system with lenses of 100cm size reproduced the shape of amplitude and phase perfectly (Fig.8), while small size optics distorted the signal. Reflections from wall of the chamber and from the port window are not taken into account.

**II-3. RESULTS OF THE SIMULATION**

As it was shown in Fig.8, the simulated large lenses optical system can project microwave signal without distortions within a region of \(-6 \text{cm} < z < 6 \text{cm}\). The optical system thus restores a spacial distribution of density fluctuations as shown in Fig. 9(a). In order to check the imaging property of the simulated system in more details we put a single density disturbance of the amplitude 1% near the cutoff, shifted optics from cutoff by 3cm and recorded the z-profile of received signal. The reflectometer signal phase fluctuations profile transmitted by optics of 50cm size are found unable to reproduce the shape of density fluctuations at all (Fig. 9(b)). Large lenses system revealed a better performance and projected the image of density fluctuations within the area of \(3 \text{cm} < z < 3 \text{cm}\) without strong distortion. It can be explained by the high curvature of reflecting cutoff layer, which leads to a spread of the reflected signal over a wide angle. Small size optics miss huge part of scattered waves and thus appear to be unable to build an image. Even 100cm size optics is able to restore density fluctuations profile in the narrow region only. The rotation of the plasma in a mirror device can be utilized to create a time image of the fluctuations in the cutoff point illuminated by the microwave beam. The time dependent phase fluctuations of the imaging reflectometer replicate the shape of density fluctuations at the cutoff as it is shown in Fig.10(a). In order to compare the time imaging properties of a conventional and MIR systems, a scattering from density

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*Figure 7 Distribution of incident and reflected fields in the analytical and FDTD regions. The cutoff layer is shown with a solid line in the FDTD region.*
Figure 8 (a) Amplitude and (b) phase of the signal projected by the two-lenses confocal system. Optical system with large lenses transmits signal better than that with small lenses.

Figure 9 (a) Principle of space imaging, (b),(c) Figure 10 (a) Principle of time imaging, (b) Cross-correlation coefficient between the fluctuations of the received signal phase and the shape of density fluctuations as a function of fluctuation amplitude.

Figure 10 (b) Cross-correlation coefficient between the fluctuations of the received signal phase and the shape of density fluctuations as a function of fluctuation amplitude.

fluctuations with a wide wavenumber spectrum was simulated. Antenna of conventional reflectometer was located at x=60cm, which was close to the port window. As an estimation of imaging properties we used cross correlation coefficient between the fluctuations of the received signal phase and the shape of density fluctuations (Fig. 10(b)). At small fluctuation levels all the system show relatively high cross-correlation coefficient, but in the case of large fluctuations it was only the imaging system with large aperture optics which could reproduce properly the fluctuation shape.
III. SUMMARY
In summary, USRM diagnostics with remote operation system has been applied to LHD plasmas in order to measure density profiles. As a result of the measurement, we have successfully confirmed the reflections from the cutoff layer when the plasma is sustained in steady state. And we have succeeded to reconstruct the density profiles by means of SRA method. We also confirmed followings in the MIR simulation study. For the geometry of GAMMA 10 tandem mirror device the conventional reflectometer shows high performance even without any optics as far as fluctuation spectrum measurements are concerned. Possible reasons for that are the high curvature of the cutoff layer\(^{12,13}\), relatively low working frequency and the small distance from the cutoff to the receiving antenna. On the other hand a high cutoff curvature is an obstacle to the application of MIR system to the mirror device due to the spread of the reflected microwaves over a wide angle. As a result, only a large aperture optics is able to image the density fluctuation with a reasonable accuracy. For the case of tokamak devices the size of the required imaging optics can be reduces due to smaller plasma curvature in a reflecting layer and higher working frequencies.

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