Microwave Imaging Reflectometry in LHD

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Microwave Imaging Reflectometry (MIR) is under development for 2-D/3-D measurement of the electron density fluctuations in Large Helical Device (LHD). A rotatable ellipsoidal mirror has been installed inside the vacuum chamber of LHD in order to optimize the illumination beam angle vertically and horizontally. The illumination and reflected beam paths near the reflection surface are calculated by using the ray-tracing code. The illumination angles are optimized in the plasma experiment.

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1. Introduction

Microwave reflectometry is a radar technique for the measurement of the electron density profiles and its fluctuations by probing the density-dependent cutoff layer in the plasma [1]. A multi-channel reflectometry system equipped with the imaging optics has been developed for the microwave imaging reflectometry (MIR) [2–6]. The MIR has a potential to obtain the 2-D/3-D image of the turbulences and instabilities with good time and spatial resolutions. The MIR system is under development in the Large Helical Device (LHD), which is a superconducting heliotron-type fusion device [7]. This paper describes the recent development of MIR system in LHD. The system design will be presented in Section II, and the system performance is described in Section III, followed by the conclusion in Section IV.

2. System Design

Figure 1 shows a schematic view of the MIR system of LHD. Illumination sources with frequency of 69, 66 and 53 GHz are utilized to probe beams. The beam is launched from port 4-O to the plasma center in X-mode or O-mode. In the case of X-mode it is reflected at the right-hand cutoff layer in the peripheral plasma as shown in Fig. 1. In the case of O-mode it is reflected at the plasma cutoff layer

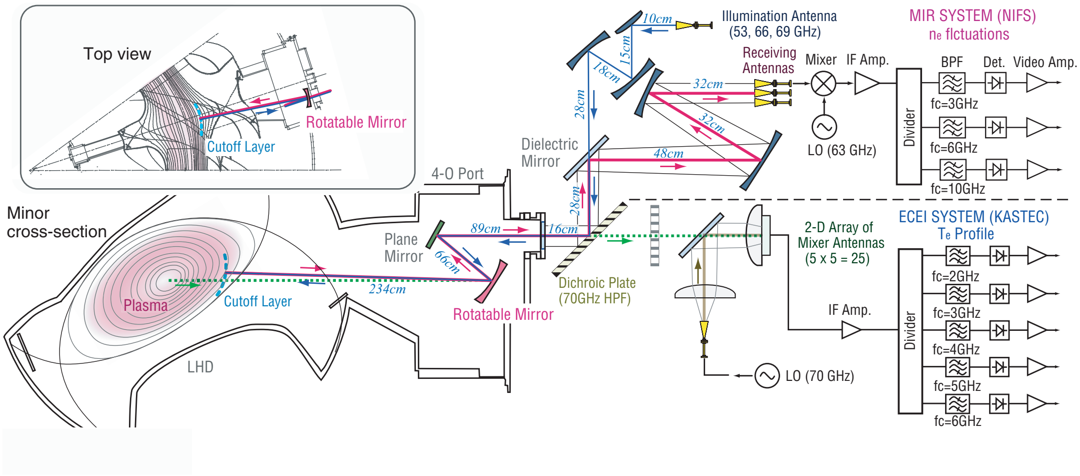

Fig. 1 Schematic of the microwave imaging system combined with MIR and ECEI in LHD.

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in plasma core. Since the cutoff layers of X-mode and is less bent and the wavelength of X-mode is shorter than O-mode, the X-mode illumination is better than O-mode. The reflected beam is focused by the imaging optical system, and it is detected by the heterodyne receivers.

The MIR system is combined with the Electron Cyclotron Emission Imaging (ECEI) [8, 9] system for the measurement of the electron temperature profile. The MIR/ECEI system share the same optical imaging system in vacuum, and their beam paths are separated by a 8 mm thick dichroic plate, which works as an optical high pass filter. The optical layout enables to measure the cross-correlation between the MIR and ECEI signals at the same measurement point.

The dichroic plate has a clear cut-off feature at 70 GHz, so that it can separate the operational frequency band for MIR (50-70 GHz) and for ECEI (70-140 GHz). The dichroic plate contains close-packed circular holes with 2.5 mm in diameter and separated by 2.8 mm (center-to-center). This configuration provides the cutoff frequency of 70 GHz. The large size of the dichroic plate (300 mm × 260 mm, with 45 degree incident angle) preserves the wave fronts of both illumination and reflected beams.

The illumination beams are generated by high-power IMPATT oscillators (Quinstar QIO-5327CZ, QIO-6627CZ and QIO-6927CZ with output power of 0.5 W). They are combined to one beam with two 3 dB directional couplers and it is launched from a scalar horn antenna. The polarization of the illumination beam can be changed by using twisted or straight fundamental waveguide behind the antenna. The launched beam is firstly diverged by a convex parabolic mirror (size of 110 mm × 80 mm, focal length of 102 mm) and it is reflected by a plane mirror (size of 190 mm × 120 mm). And it is focused by an ellipsoidal mirror (size of 290 mm × 216 mm, focal length of 310 mm). And then it passes though a beam splitter (acrylic plate with size of 260 mm × 200 mm) and it is reflected by the dichroic plate. The launched beam converges at the fused quartz window (the diameter of 192 mm) in order to enter the vacuum vessel. Finally the launched beam becomes parallel and illuminate the plasma by using the oval plane mirror (size of 300 mm × 257 mm) and the ellipsoidal mirror (size of 500 mm × 430 mm, focal length of 1064.7 mm), which are mounted in vacuum. All mirrors are made of aluminum alloy by using a numerically controlled milling machine with the cutting pitch of 0.2 mm, and the surface is polished by using a rotating sponge with compound “PiKAL”. The mirror finish is necessary to check the beam focusing and the stray light by using of a bright halogen lamp. Microwave absorber (over −24 dB attenuation at 60-70 GHz) is affixed inside of the optics box in order to delete the stray light. It is also attached at the edge of imaging mirrors in order to decrease diffraction at the edge of mirror. The imaging optics can de modified for a 2-D detector array with a transmitted LO beam in the air.

A mechanical shutter is installed on the vacuum side of the port window in order to prevent impurity coating on it during titanium deposition and discharge cleaning. In the previous setup, the port window without the shutter becomes dark and obscured for about a week of the plasma experiment. Transparency of the window is decreased by −8 dB at 50-60 GHz during the 9th campaign of LHD experiments. The shutter enhances the reflected power and it keeps still clear for two months from starting of the 10th campaign.

The LHD plasma has a twisted elliptical or triangular cross-section, so the elliptical cross-section is tilted downward near the equatorial plane at the port 4-O as shown in Fig. 1. Therefore, the optimum illumination angle is different between O-mode and X-mode. For example, as the density is higher, the right-hand cutoff layer is more tilted. And as the magnetic axis shifts to outboard, the illumination beam should be more tilted upward. The illumination angle should be adjusted according to the inclination of the reflection surface. The Illumination and reflection paths in X-mode are simulated by using a ray-tracing code [10] in the case of the high-density plasma. Figure 2(a) shows the

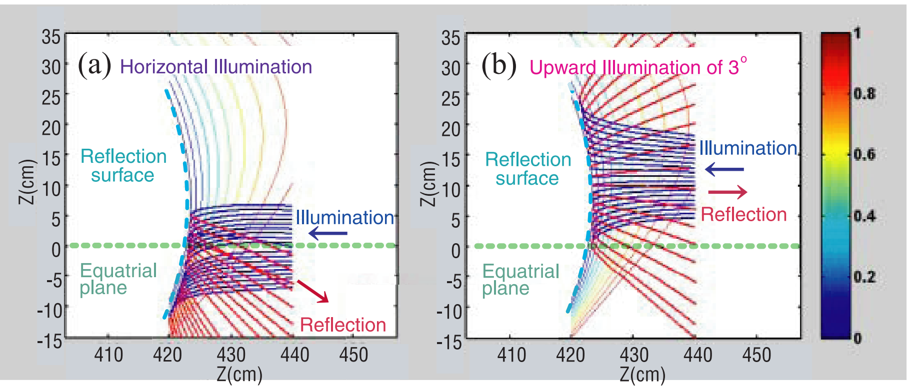

Fig. 2 Simulation result of the ray-tracing nearby the right-hand cutoff layer in the LHD plasma.

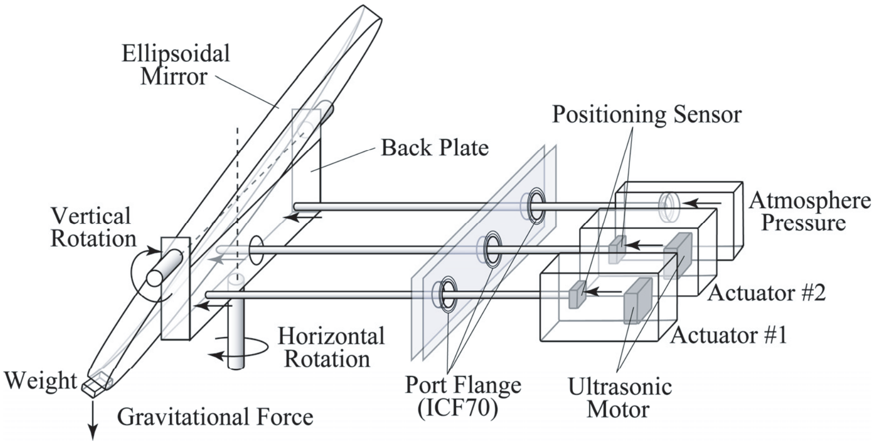

Fig. 3 Schematic of the rotatable ellipsoidal mirror with the three pushrods in vacuum.

simulation results in the previous setup. The horizontally illuminated beams are reflected downwards as shown in Fig. 2 (a). To obtain considerable reflected power, the ellipsoidal primary mirror should be tilted by 3 degrees upward as shown in Fig. 2 (b).

In the new setup, the angle of the ellipsoidal primary mirror can be adjusted by using remote-controlled actuators with ultrasonic motors (Shinsei USR60-S3N), which is driven by the piezoelectric ceramic elements. Since the ultrasonic motor is non-magnetic, it doesn't disturb the magnetic fields of plasma. Figure 3 shows the schematic of the rotating mechanism with three pushrods and one weight.

The ellipsoidal mirror is connected to a rectangular back plate with a horizontal rotation axis. The back plate is connected to the base plate with a vertical rotation axis. Both the horizontal axis and the vertical axis pass the center of the concave surface of the ellipsoidal mirror. The left hand side of the back plane is pushed by the rod of actuator #1. The right left hand side of the back plane is pushed by a free rod, which is connected an ICF70 flange. This flange is guided by two bars and is connected to the LHD vacuum vessel with a bellows. The free rod can move freely in one direction and the atmosphere pressure pushes the ellipsoidal mirror with the free rod. So the ellipsoidal mirror can be rotated around the vertical axis by controlling the actuator #1.

The lower part of the ellipsoidal mirror is pushed by a rod of actuator #2. A weight is attached at the bottom of the mirror. Since the gravitational force due to the weight pushes the mirror to the rod of actuator #2, the ellipsoidal mirror can be rotated round the horizontal axis by controlling the actuator #2. The slide bearings are coated with the titanium nitride so that the friction is fairly reduced in vacuum. Non-magnetic stainless-steel (SUS304) ball bearings are used as well. These mechanisms allow the smooth mirror rotation by one degree per second with the allowance of the mirror angle less than 0.1 degree.

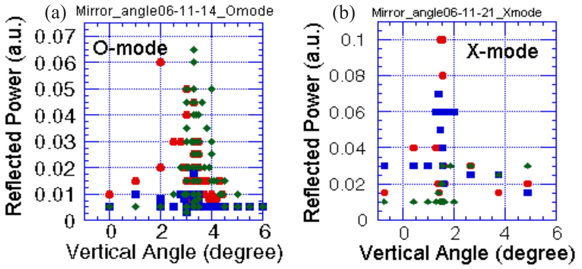

Fig. 4 Optimized illumination angle in the case of O-mode (a) and X-mode (b) measured in the plasma experiment.

3. System Performance

The mirror angle is optimized in the plasma experiment in LHD. The time-averaged amplitude of fluctuations in the MIR signal is measured by scanning of the vertical mirror angle as shown in Fig. 4. The optimum illumination angle is about 3 degree upward in O-mode, as shown in Fig. 4 (a) and that it is about 1.5 degree upward in X-mode, as shown in Fig. 4 (b). Since the profile is very narrow with half width of about 1 degree, the optimization of the illumination angles is very necessary to detect the reflected beam power from the twisted reflection surface.

The wave number vector of the electron density fluctuation is measured with three receiving antennas, which correspond to three reflection points. The first one is centrally positioned at the intersection of the optical axis with the reflection surface. The second one is separated from it by about 14 cm parallel to the field line. And the third one is separated from the center point by about 11 cm perpendicular to the field line. The two cutoff surfaces of 66 and 69 GHz are separated about 4 cm in typical in the radial direction.

The reflected power is measured by multi-channel heterodyne receiver (Figure 1). The received signal is down converted by the wide band balanced mixer (Millitech

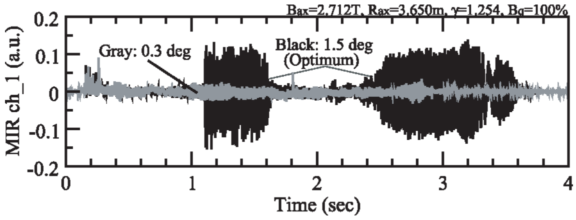

Fig. 5 MIR signals before and after the optimization of the mirror angle.

MXP-15-RSXSL) to the intermediate frequency (IF) of 3, 6 and 10 GHz with the local oscillator signal of 63 GHz. The resultant signal splits into 3 ways by the power divider and they are amplified by 23 dB. They are band pass filtered with a center frequency of 3, 6, 10 GHz and a −3 dB bandwidth of 300 MHz, and then they are detected by Schottky-barrier diodes (Herotek DHM185AA). The post-detector signal has a large DC offset. The initial DC offset level is sampled at the start of the plasma discharge, and is digitally stored. By using a differential amplifier, the initial DC offset which is the DA output of the stored one is subtracted from the post-detector signal. After the offset cancellation, the signal is amplified with the variable gain up to 40 dB in order to match the signal level to the input range of the PXI digitizer (National Instruments PXI-6133). It has a resolution of 14 bits maximum time resolution is 3 M-samples/sec, real-time recording. Since the time resolution is usually set to 1 M-samples/sec. The total time resolution of the MIR system is about 2.4 μsec. It is restricted by the upper cutoff frequency of the differential amplifier in the DC offset canceller.

The beams focusing on and near the reflection surface are measured by using a metal rod and a vector-network -analyzer (ANRITSU 37397C). The rod is scanned along the toroidal direction or the radial direction around the reflection center. The wave reflected on the narrow region (with width of a few millimeters) of the rod surface reaches to the receiving antenna. This profile is almost identical in the frequency range between 45-60 GHz. The beam waist is about 3.3 cm and the focal depth is about 1 m near the reflection surface.

Typical MIR signals before and after the optimization is shown in Fig. 5. By optimizing the beam direction, the MIR signal becomes high enough to measure the density fluctuation.

4. Conclusion

In conclusion, we have found that the optimization of the direction of microwave beam is a key of the microwave imaging reflectometry, which is expected to be a powerful tool to study the turbulence in plasmas. So far, we have very small signals. The illumination and reflected beam paths near the reflection surface are calculated with the ray tracing code. We have developed a mirror rotation mechanism using three rods and two actuators driven by ultrasonic motors. The mirror angle is changed shot by shot. The experimentally obtained optimum illumination angle in LHD is 3 degree upward in the case of O-mode and 1.5 degree upward in the case of X-mode. These angles are similar to the simulation. By optimizing the beam direction, the MIR signal becomes high enough to measure the density fluctuation.

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