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 x 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 x 80 mm, focal length of 102 mm) and it is reflected by a plane mirror (size of 190 mm x 120 mm). And it is focused by an ellipsoidal mirror (size of 290 mm x 216 mm, focal length of 310 mm). And then it passes though a beam splitter (acrylic plate with size of 260 mm x 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 x 257 mm) and the ellipsoidal mirror (size of 500 mm x 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 be 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
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 through the center of the concave surface of the ellipsoidal mirror. The left hand side of the back plate is pushed by the rod of actuator #1. The right left hand side of the back plate 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.

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 centerpoint 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.

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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