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Development of a real-time power/polarization monitor for ECRH on LHD
LHDにおける電子サイクロトロン共鳴加熱のための
リアルタイム電力/偏波モニター装置の開発

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It is needed to measure power and polarization of millimeter waves for optimization of the electron cyclotron resonance heating (ECRH). The mode excitation ratio of millimeter waves in plasmas which is a key of determining the power deposition profile is controlled by the polarization states at the plasma injection point. The purpose of this study is a development of a real-time power/polarization monitor. In the past it has been demonstrated to work properly in principle but without calibration. In order to calibrate, it is installed in a miter bend of ECRH transmission lines of the large helical device (LHD) where a linear polarization with a known rotation angle is propagated. Consequently the calibration data which are necessary to deduce the polarization state in the corrugated waveguide are acquired.

1. Introduction

Millimeter waves of 77 and 154 GHz have been used for ECRH in LHD. O- and X- mode are excited in the plasma in the millimeter wave range. The power ratio of these modes is determined by the injection polarization states. It is important to excite as pure mode as possible at ECR layer to maximize the absorption power and define the power deposition profile. If millimeter waves are injected perpendicularly from the antenna to magnetic field lines in plasmas, the pure ordinary (O) / extraordinary (X) wave is excited by the linear polarization in parallel/perpendicular direction to the magnetic field line when the magnetic shear effect is negligible.

So far, the power of one fixed linear polarization component of millimeter waves propagated in ECRH transmission lines has been measured. However the polarization states can not be determined from this measurement. Injection polarization states have only relied on the calculation. Previous study of the power/polarization monitor with two arrays of coupling holes was tested in the miter bend[1]. This type of polarization monitor had been tested up to the power level of few hundreds of transmission power, had caused arcing problems in the recent high power of the order of 1MW transmission test. In order to solve this problem, a real-time power/polarization monitor with one array of coupling holes has been developed. In the past it has been demonstrated to work in principle but needs calibration to deduce the polarization states properly[2,3].

2. Design of a real-time power/polarization monitor system

Three parameters: millimeter wave power: P_{in}, polarization angle: α and ellipticity: β have to be derived from a measurement. These parameters are determined by measuring two electric field components perpendicular to the propagation direction. The amplitude E_{xo} , E_{yo} and the phase difference $\Delta\phi$ between them can be directly deduced from the measured quantities. P_{in}, α and β are expressed by those values as

$$P_{in} \propto {E_{x_0}}^2 + {E_{y_0}}^2 \tag{1}$$

$$\alpha = \frac{1}{2}\tan^{-1}(\tan(2\tan^{-1}\frac{E_{y_0}}{E_{x_0}})\cos\Delta\phi) \tag{2}$$

$$\beta = \frac{1}{2}\sin^{-1}(-\sin(2\tan^{-1}\frac{E_{y_0}}{E_{x_0}})\sin\Delta\phi) \tag{3}$$

Eqs. where two electric field components E_x and E_y can be expressed as

$$E_x = E_{x_0}\cos\omega t \quad and \quad E_y = E_{y_0}\cos(\omega t + \Delta\phi).$$

α and β on an elliptically polarized wave is shown in Fig.1. α is defined as angle which shows the inclination of polarization from reference direction. Ellipticity is defined by tan β and +/- sign indicates the counter/co-clockwise rotation as seen from wave propagation direction. Here β is defined in the range from -45° to 45°.

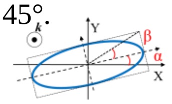

Fig.1. An elliptically polarized wave

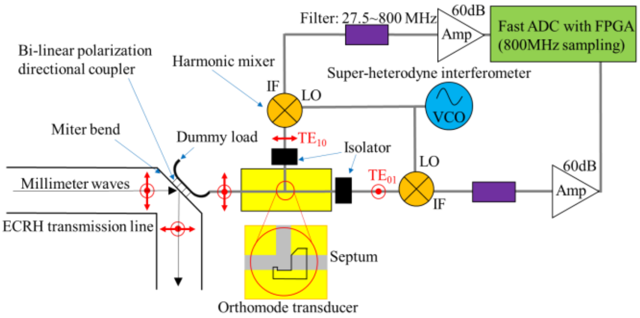

Fig.2. A real-time power/polarization monitor

Schematic of a real-time power/polarization monitor is shown in Fig.2. The millimeter wave power in ECRH transmission lines is coupled approximately -70dB to a sub-waveguide embedded in the miter bend mirror through one array of coupling holes. The coupled millimeter wave excites only fundamental mode of TE_{10} and TE_{01} which have orthogonal linear polarization each other in the sub-waveguide because the dimension of the square cross-section is chosen so that the other modes as to be cutoff. For the case of 77 GHz, the dimension of square-waveguide is determined to be 2.755×2.755 mm^2. Such exicted TE_{10} and TE_{01} modes are separated by an orthomode transducer (OMT) and detected by a super-heterodyne interferometer. The interferometer is composed of two channel analog digital converter (ADC) of 800 MHz sampling, and field programmable gate array (FPGA) is used to deduce both intensity and phase difference in real-time.

3. Calibration experiment

In order to calibrate, it is installed in a miter bend of ECRH transmission lines of the LHD where a linear polarization with a known rotation angle is propagated. Polarization angle is changed manually by rotating the miter bend around the waveguide axis. Experimentals has been carried out at frequency: 77 GHz, power: 500 kW and pulse time: 10 msec of the millimeter wave. The calibration equation is expressed as

$$\begin{pmatrix} V_{\mathrm{s}i} \\ V_{\mathrm{m}i} \end{pmatrix} = \begin{pmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{pmatrix} \begin{pmatrix} \sin\theta_i \\ \cos\theta_i \end{pmatrix} = \begin{pmatrix} C_{11}\sin\theta_i + C_{12}\cos\theta_i \\ C_{21}\sin\theta_i + C_{22}\cos\theta_i \end{pmatrix}, \quad (4)$$

$$\begin{pmatrix} P_{\mathrm{s}i} \\ P_{\mathrm{m}i} \end{pmatrix} = \begin{pmatrix} D_{11} + D_{12}\cos 2\theta_i + D_{13}\sin 2\theta_i \\ D_{21} + D_{22}\cos 2\theta_i + D_{23}\sin 2\theta_i \end{pmatrix} \quad (5)$$

Here, $P_{\mathrm{si}} = V_{\mathrm{si}}V^*_{\mathrm{si}}$ and $P_{\mathrm{mi}} = V_{\mathrm{mi}}V^*_{\mathrm{mi}}$ are measured intensity at port “s” and “m” corresponding to TE_{10} and TE_{01}. C_{11}, C_{12}, C_{21} and C_{22} are complex coupling coefficients of electric field Coefficients D_{11}, D_{12}, D_{13}, D_{21}, D_{22}, D_{23} are can be expressed by the combination of C_{ij} and C^*_{ij}. θ_i is the rotation angle of the monitor miter bend relative to TE_{10} electric field direction. Such simplified formulation is possible since each input electric filed depends as $\sin\theta_i$ and $\cos\theta_i$ In an ideal case where the cross-talk between TE_{10} and TE_{01} is negligible ($C_{12} = C_{21} = 0$), The relation is reduced to

$$\begin{pmatrix} P_{si} \\ P_{mi} \end{pmatrix} = \begin{pmatrix} C_{11}C^*_{11}\sin^2\theta_i \\ C_{22}C^*_{22}\cos^2\theta_i . \end{pmatrix} \quad (6)$$

These relations indicate that calibration is possible with the θ scanning experiment even with the finite cross-talks but is much simpler without them. In Fig. 3 are shown the data obtained from the calibration experiments. The calibration experiments executed so far are suffered from unknown large spurious signals and the reproducibility and reliability.

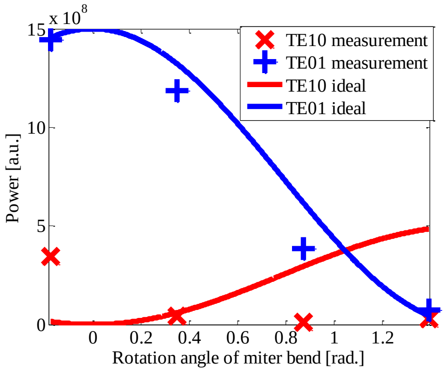

Fig.3. Measurement data

4. Summary

The calibration experiment of a newly developed polarization/power monitor are tried by rotating the transmitting linear polarization angle. The possibility and reliability of the method are shown, but complete calibration is left for the future work due to the poor quality of the data caused by a spurious noise. Finding the origin and suppression of the spurious noise is an urgent issue for the complete calibration of the system.

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