Development of a Real-Time Power/Polarization Monitor using FPGA for Electron Cyclotron Resonance Heating on LHD*)

Ryohei MAKINO[1)], Shin KUBO[1,2)], Kenya KOBAYAHI[1)], Sakuji KOBAYASHI[2)], Takashi SHIMOZUMA[2)], Yasuo YOSHIMURA[2)], Hiroe IGAMI[2)], Hiromi TAKAHASHI[2)], Shinya OGASAWARA[1)] and Takashi MUTOH[2)]

[1)]*Department of Energy Engineering and Science, Nagoya University, Nagoya 464-8603, Japan*
[2)]*National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan*

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For optimization of electron cyclotron resonance heating (ECRH), it is important to measure power and polarization states of injected millimeter-waves in real-time. Arbitrary polarization states of millimeter-waves are realized by two grating mirror polarizers set at miter-bends in the corrugated waveguide transmission system on the Large Helical Device (LHD). The polarization state of an injected millimeter-wave determines the mode excitation purity, and therefore the power absorption efficiency in plasmas. The real-time power/polarization monitor of the injected millimeter-wave is required for optimization and/or feedback control of ECRH. The real-time power/polarization monitor is under development to be installed on a miter-bend near the ECRH antenna on LHD. Amplitudes and phases of two orthogonal polarizations of injected millimeter-waves are measured to determine the power and polarization states of waves. In this paper, the design and performance test of the real-time power/polarization monitor are reported. Intensities and relative phase of two orthogonal polarizations are measured by a newly developed monitor with heterodyne interferometer and fast ADC (800 MHz) with FPGA. Hardware of the power/polarization monitor works as designed qualitatively.

Keywords: power/polarization monitor, millimeter-waves, electron cyclotron resonance heating, LHD, miter-bend, FPGA

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1. Introduction

Electron cyclotron resonance heating by using millimeter-waves is one of main heating methods used in the fusion devices. More than 20 MW at 170 GHz is required for ITER (international thermonuclear experimental reactor) ECRH and electron cyclotron current drive (ECCD) [1]. ECRH/ECCD by millimeter-waves is used for the control of plasma electron temperature/current profiles [2]. The polarization state of an injected millimeter-wave determines the mode excitation purity, and therefore it affects the power deposition and current drive in plasmas. The waves are coupled to extraordinary (X-mode) waves or ordinary (O-mode) waves at the boundary between plasmas and vacuum [3]. Arbitrary polarization states of millimeter-waves are realized by two grating ($\lambda/4$ and $\lambda/8$) mirror polarizers set at miter bends in the corrugated waveguide transmission system on LHD [4]. However, polarization monitors are not installed on LHD. Polarization states of injected millimeter-waves are calculated based on an ideal model of ECRH transmission line including polarizers. Millimeter-waves are transmitted into plasmas in LHD through waveguides over 100 m. Each transmission line has more than 10 miter-bends. The calculation of transmission of waves is complicated. The real-time power/polarization monitor of the injected power and polarization state is required for optimization and/or feedback control of ECRH.

Polarization monitors have been designed to measure the polarization state [4–6]. This paper described the new design and performance tests of the real-time power/polarization monitor to install on LHD.

2. Design of the Real-Time Power/Polarization Monitor System

The polarization states of an electric field of injected millimeter-waves can be described by the polarization angle α and the ellipticity β, as shown in Fig. 1. α is the angle between the major axis of the ellipse and a reference axis (X-axis). The reference axis here is defined to be perpendicular to the injection vector in the plane constructed by injection vector and toroidal direction. Optimum combination of α and β should be determined depending on the injection angle, magnetic shear and density profile. However, it is not possible that the monitor is installed on boundary between plasmas and vacuum practically. Therefore, the monitor is set on a miter-bend, which is a part of the transmission line of millimeter-waves and

author's e-mail: makino.ryohhei@ms.nifs.ac.jp

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bend millimeter-waves to 90 degrees, and a reference axis is taken in the direction perpendicular to the plate of a miter-bend. β is the arctangent angle of the ratio of the minor radius to major radius of the ellipse. The plus and minus of β indicate the direction of rotation, which is right or left hand rotation.

An electric field E of waves can be described by two orthogonal polarizations E_x, E_y.

$$E_x = E_{x0}\cos(\omega t), \quad (1)$$

$$E_y = E_{y0}\cos(\omega t + \varphi), \quad (2)$$

where E_{x0} and E_{y0} are amplitudes of two orthogonal polarizations and φ is a phase difference between E_x and E_y. The polarization angle α, the ellipticity β and the power P_{in} of injected millimeter-waves can be written as follows [7].

$$\alpha = \frac{\tan^{-1}\left[\tan\left(2\tan^{-1}\frac{E_{y0}}{E_{x0}}\right)\cos\varphi\right]}{2}, \quad (3)$$

$$\beta = \frac{\sin^{-1}\left[\sin\left(2\tan^{-1}\frac{E_{y0}}{E_{x0}}\right)\sin\varphi\right]}{2}, \quad (4)$$

$$P_{\mathrm{in}} = C(E_x^2 + E_y^2). \quad (5)$$

The power of waves in the transmission line is proportional to sum of square of the electric field of two orthogonal polarizations. Millimeter-waves power and polarization can be estimated from amplitudes and phases of two orthogonal polarizations as shown in Eqns. (3) – (5).

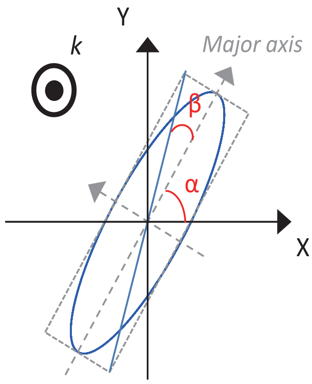

Fig. 1 Schematic of the definition of the polarization state, which is the polarization angle α and the ellipticity β.

LHD has three 1 - 1.5 MW 77 GHz gyrotrons, one 1 MW 154 GHz gyrotoron, one 0.45 MW 82.7 GHz gyrotron and two 0.2, 0.8 MW 84 GHz gyrotrons. The real-time power/polarization monitor is under development to be installed on a miter-bend, as shown in Fig. 2. The power/polarization is measured in real-time by the monitor composed of bi-linear polarization directional coupler and heterodyne detectors that enables to deduce the power and the phase difference of two orthogonal polarizations.

The bi-linear polarization directional coupler has several small holes at a miter-bend mirror to pick-up waves to the sub-waveguide with square cross section, as shown in Fig. 3. The electric field $E_{\mathrm{FW/BW}}$ of forward waves and backward waves, respectively, from holes in a sub-waveguide can be written as follows.

$$E_{\mathrm{FW/BW}} = \exp\left[\pm i k_z z\right] \times \sum_{d=1}^{N} A_d \exp\left[i\left(k_0\sin\theta \mp k_z\right) z_d\right]. \quad (6)$$

Here, k_z, k_0 are the wavenumber in the direction parallel to wave-guides in the sub-waveguide and the main-waveguide, respectively, A_d is amplitude of the electric field of waves, θ is incident angle, z_d is z position of hole d. The 77 GHz millimeter-waves are transmitted as HE_{11} mode in the main-waveguide. By similarity of HE_{11} mode and Gaussian beam, amplitudes of the electric field of waves A_d can be written as

$$A_d \propto \omega a_d^3 \exp\left[-k_z h\sqrt{\left(\frac{1.84}{k_z a_d}\right)^2 - 1}\right] \times \exp\left[-\frac{z_p}{W_b}\right], \quad (7)$$

where ω is the angular frequency, a_d is the diameter of holes, h is the depth of holes, z_p is the distance from the center of the miter-bend mirror to holes, W_b is the beam width of the Gaussian beam that is obtained from approximating HE_{11} mode [5]. Where $k_0\sin\theta = k_z$, the forward waves are summed up. On the other hand, the backward waves can be almost cancelled out and further minimized

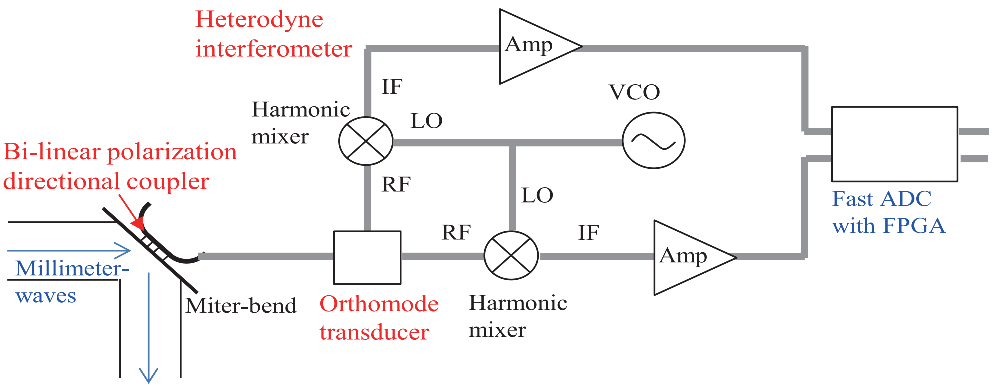

Fig. 2 Diagram of the real-time power/polarization monitor.

by optimization of interval of holes. A wave number k_z in a rectangular sub-waveguide can be described as

$$k_z = \frac{2\pi}{\lambda_0}\sqrt{1-\left(\frac{m\lambda_0}{2a}\right)^2-\left(\frac{n\lambda_0}{2b}\right)^2}, \quad (8)$$

where λ_0 is wavelengths in vacuum, a and b are lengths of rectangular, for TE_{mn} mode.

The bi-linear polarization directional coupler has been designed so as to satisfy $k_0 \sin\theta = k_z$ and the interval of holes is three-fourths of a wavelength in the sub-waveguide to minimize the interaction between scattered waves at holes. The directivity D is defined as Eq. (9) and can be deduced from Eqns. (6), (7).

$$D \equiv 10\log(E_{\mathrm{Fw}}^2/E_{\mathrm{Bw}}^2). \quad (9)$$

The parameters of the bi-linear polarization directional coupler are as follows: Both of lengths of rectangular of the sub-waveguide a and b is 2.755 mm. The interval of holes is 4.14 mm and the number of holes is 9. The diameters of holes are from 0.72 mm at the two ends to 0.80 mm

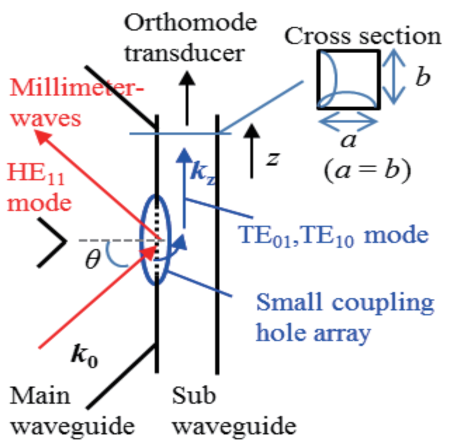

Fig. 3 Schematic of the bi-linear polarization directional coupler in the miter-bend.

at the center. The diameter of the main corrugated waveguide is 88.9 mm for 77 GHz millimeter-waves. The beam width of the Gaussian beam that is obtained from approximating HE_{11} mode is 28.8 mm in the main-waveguide. The directivity is 32 dB as designed. Sub-waveguide was designed quadrate to transmit only both of TE_{10} and TE_{01} mode, which are two orthogonal polarizations. This structure has an advantage that two orthogonal polarizations can be measured at the same position.

The coupled wave is separated into two orthogonal polarizations by an orthomode tranducer. The heterodyne interferometer is composed of harmonic mixers, tunable local oscillator which is voltage-controlled oscillator (VCO), and so on. The two orthogonal-polarized waves are down-converted by harmonic mixers with VCO. IF signals can be less than 400 MHz by calibration of VCO with harmonic mixers. The power and polarization states of millimeter-waves can be evaluated from phases and amplitudes of two orthogonal polarizations. The phases and amplitudes of two orthogonal polarizations are directly measured by FPGA (Field Programmable Gate Array) with fast ADC which has sampling rate of 800 MHz in real-time. By using fast ADC with FPGA, millimeter-waves and IF-components can be much reduced. It indicates that the reliability of the system increases, and allows to install the power/polarization monitor on LHD. Furthermore, flexible analysis in wide frequency range and therefore multi-channel application is also possible by using FPGA. The use of FPGA also enables a real-time feedback control of a millimeter-wave polarization in the future.

3. Performance Test of Hardware of the Monitor

Performance tests of the power/polarization monitor have been performed. The monitor was set on a miter-bend in a transmission line of 77 GHz ECRH as shown in Fig. 4.

First, Schottky diodes were directly set on the orthomode transducer of the monitor instead of the interferom-

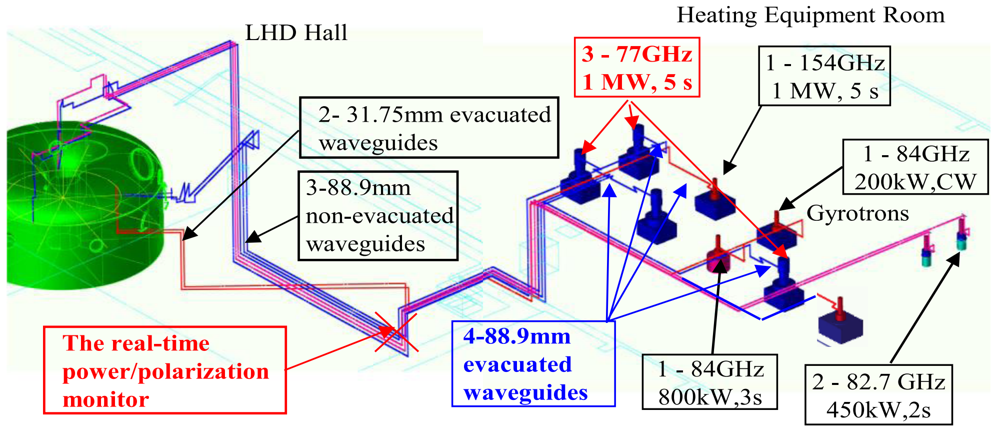

Fig. 4 ECRH systems on LHD. The corrugated waveguide for 77 GHz is evacuated and its diameter is 88.9 mm. The real-time power/polarization monitor set on a miter-bend in ECRH transmission line for hardware tests.

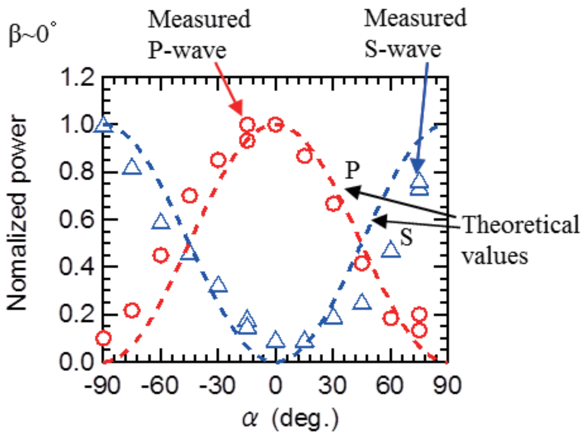

Fig. 5 The polarization angle dependence of normalized power of P-wave and S-wave separated by the orthomode transducer where the polarization ellipticity $\beta \sim 0°$. The circle and triangle show the measured values for S-wave and P-wave, respectively. Red and blue lines show theoretical values for P-wave and S-wave, respectively.

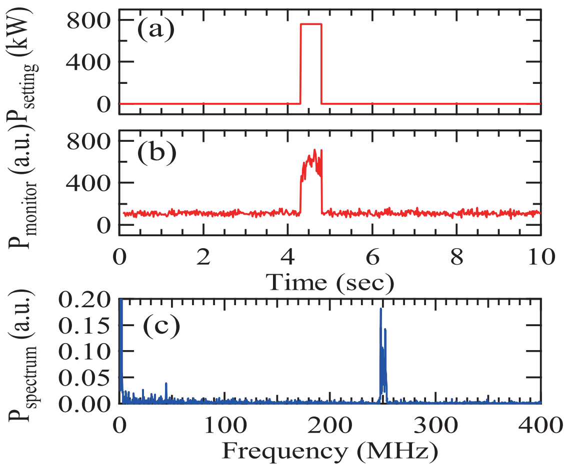

Fig. 6 (a) The temporal evolution of the power of millimeter-waves as setting of a gyrotron. (b) The temporal evolution of the power measured by the real-time power/polarization monitor. (c) Frequency response to millimeter-waves measured by the monitor.

eters to check the performance of the bi-polarization directional coupler and the orthomode transducer. 500 kW 77 GHz millimeter-waves were injected to the ECRH transmission line. Grating polarizers were rotated to change polarization states of the millimeter-waves. The polarization angle α was swept from −90 degrees to +90 degrees where the polarization ellipticity β was fixed at 0 degree, which is linear polarization. The power of two waves through orthomode transducer was measured by the Schottky diodes. Figure 5 shows polarization dependences of the powers of waves. The circle and triangle marks showed the normalized power of each wave. The power is normalized by the maximum power when the polarization angle α was swept. The lines showed theoretical values of the normalized power of two orthogonal polarizations. They are approximately consistent. Two orthogonal polarizations were separated qualitatively.

Next, a performance test of the real-time power/polarization monitor is performed with fast ADC with FPGA, as shown in Fig. 2. 759 kW 77 GHz ECRH was injected. The polarization ellipticity β was fixed at 45°. Figure 6 (a), (b) shows the temporal evolution of ideal and measured ECRH injected power, respectively. Figure 6 (c) shows a frequency response to the electric field of millimeter-waves deduced by taking FFT to the temporal evolution of voltage measured by the monitor. IF signals, which have 250 MHz, were detected by ADC with FPGA.

These two experiments indicate that millimeter-waves in the ECRH transmission line were successfully monitored independently in two orthogonal polarizations and these were measured by interferometer with fast ADC with FPGA. Hardware of the power/polarization monitor works as designed qualitatively. The calibration of signal amplitudes and the reference axis for calculation of the polarization angle α is needed to get the information of the polarization states.

4. Summary

Real-time power/polarization monitors are under development to be installed on miter-bends, which are part of ECRH transmission lines on LHD. The monitors are composed of bi-linear polarization directional coupler and heterodyne interferometer. To determine the polarization states of injected millimeter-waves, amplitudes and phases of two orthogonal polarizations should be measured. Two orthogonal polarizations were successfully measured separately. IF signals of the heterodyne interferometer, which have specific frequency (less than 400 MHz), were detected by fast ADC with FPGA. It is demonstrated that the hardware of the power/polarization monitor works as designed qualitatively.

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