Study of Elliptical Polarization Requirement of KSTAR 84 GHz ECH System*

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Abstract

Since the efficiency of the Electron Cyclotron (EC) wave heating and the wave-induced current drive depends on the mode of the wave propagating in the tokamak plasmas, the selective coupling of the wave to a particular plasma wave mode is required depending on the experimental objectives. The selective coupling into the plasma mode is determined by the incident wave polarization and its ellipticity at the plasma edge. The incident wave polarization and ellipticity are also control parameters to obtain the desired mode purity in the plasma center in the EC wave heating and the current drive experiments. For the KSTAR 84 GHz ECH system, two polarizer miter bends will be used to control the wave polarization and its ellipticity. Any wave polarization and its ellipticity can be produced by changing the mirror rotation angle of each polarizer miter bend. This paper shows the calculated ellipticity maps and the mode purity maps as a function of the mirror rotation angle. For the mode purity maps, the plasma density and the toroidal magnetic field in the plasma center are assumed to be 1 x 10^{20} m^{-3} and 3.5 Tesla, respectively.

1. Introduction

The KSTAR ECH system uses 84 GHz microwave that corresponds to the fundamental resonant toroidal magnetic field, B_T = 3.0 T. It is now under installation for Electron Cyclotron Heating (ECH) and Electron Cyclotron Current Drive (ECCD) for the KSTAR. This auxiliary plasma heating and current drive is necessary to control plasma current profile and to suppress the MHD instability mode of Neoclassical Tearing Mode (NTM).

The heating and the current drive efficiencies depend on the plasma mode [1]. So, the polarization study is also important to obtain the appropriate wave coupling to plasma. Considering the oblique injection from low field side, for instance, the wave polarization should be elliptical to excite the pure ordinary (O) or extraordinary (X) wave mode in plasma. This yields the efficient wave absorption in plasma. The KSTAR ECH system will use two polarizer miter bends fabricated by GA (General Atomics) company for the polarization control: a polarization rotator miter bend and a circular polarizer miter bend. This combination of two polarizer miter bends makes an elliptically polarized wave. Since all of these are evacuated oversized components due to the extremely high wave power, there is the chance that unwanted modes and polarization changes can be created in the transmission system. So, the polarization measurement should be performed after the installation of the transmission line.

In this paper, it is shown that an ellipticity map can be obtained by arbitrary mirror rotation angle of the polarization rotator and the circular polarizer miter bends. Also, the plasma mode purity map is investigated as a function of the mirror rotation angle of two polarizer miter bends for the KSTAR ECH system.

2. Calculation

2.1 KSTAR ECH transmission line system

The schematic drawing of 84 GHz KSTAR ECH transmission line system is shown in Fig. 1. The total length is about 25 m. The ECH system consists of a gyrotron, polarizer miter bends to control wave polarization, 31.75 mm ID corrugated waveguides with bends, and antennas.

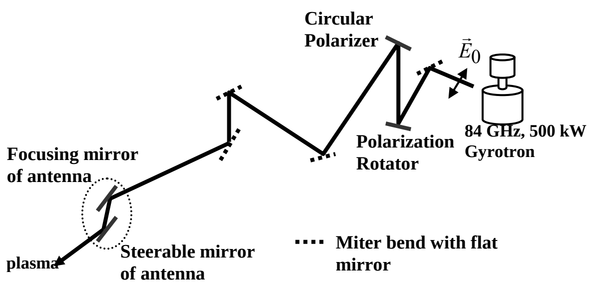

Fig.1. KSTAR ECH transmission line system.

The gyrotron system consists of an 84 GHz, 500 kW gyrotron, and the power supplies. The gyrotron is fabricated by CPI (Communications and Power Industries) and the acceptance test was done successfully at PAL (Pohang Accelerator Laboratory). The transmission line system is mainly composed of the evacuated 31.75 mm ID corrugated waveguides, a few miter bends, and a launcher that is composed of the fixed-focusing mirror and the movable steering mirror. This two-mirror launcher system can provide the local heating of the plasma. It is designed in collaboration

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with Princeton Plasma Physics Laboratory (PPPL), and it is now under fabrication at PPPL.

2.2 polarization properties of polarizer miter bend

For the KSTAR ECH system, two polarizer miter bends will be used to control the wave polarization and its ellipticity. One is polarization rotator and another one is circular polarizer that has sinusoidal surface groove shape and installed in the miter bend. The combination of these two grooved surface mirrors can give an arbitrary polarization by means of the phase shift between field components of parallel and perpendicular to the grooves [3]. Because the phase shift is a function of the groove parameters (period, width, depth, and the mirror rotation angle) the grooves in the mirror of polarization rotator and circular polarizer have the same period but different depth [4-6].

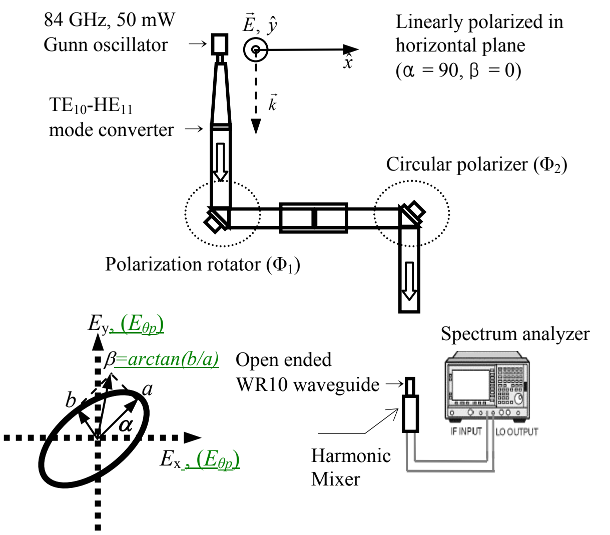

Fig. 2. Schematic of the low power test system composing of two polarizer miter bends and Gunn oscillator. The polarization angle and ellipticity of elliptical polarized wave are defined as α and *b*/*a*.

Figure 2 shows the low power measurement system. It is composed of the same transmission line components to be used for the KSTAR ECH system such as 31.75 mm ID corrugated waveguide, two polarizer miter bends. For a microwave source, 84 GHz, 50 mW CW Gunn oscillator is used. The output TE_{10} mode from Gunn oscillator is linearly polarized perpendicular to the plane of the miter bend (α = 90°). And it converted into the HE_{11} mode by a TE_{10}-HE_{11} mode converter. The radiated wave from the open-ended corrugated waveguide is picked up using WR10 rectangular open-ended waveguide followed by W-band harmonic mixer and the spectrum analyzer (Agilent E4407B). The polarization angle and ellipticity are easily measured by rotating the WR10 waveguide.

Measurement data and theoretical curves of the polarization rotation angle α and ellipticity b/a is shown in Fig. (3).

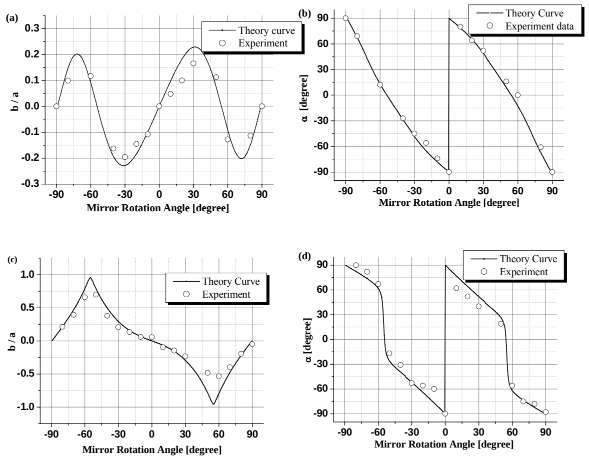

Fig. 3. Polarization rotation angle (=*α*) and ellipticity (=*b/a*) of reflected wave as functions of mirror rotation angle of polarizer miter bends. (a) & (b) for polarization rotator miter bend, and (c) & (d) for circular polarizer miter bend.

Experimental results are in good agreement with the plane wave theory [6]. In the case of the linear polarizer, an arbitrary polarization rotation angle α can be obtained as a function of mirror rotation angle Φ_1 [Fig. 3(b)]. And the polarization is purely linear only at Φ_1= 0°, ±56°, and ±90° [Fig. 3(a)].

2.3 mode coupling at the plasma edge

When the propagation direction is not perpendicular to the toroidal magnetic field in the plasma, the incident wave should have elliptical polarization to excite the pure O- or X-mode wave in plasma. Provided that there is no coupling between the X-mode and the O-mode in the plasma, the wave mode in the plasma would be determined by the specific coupling to O- or X-mode at the plasma edge. The ellipticity required for the pure O- or X- mode at the plasma edge is easily obtained by using cold plasma dispersion relation as follows [7].

$$\frac{E_{\phi p}}{E_{\theta p}} \equiv \begin{bmatrix} i\tan\beta_X \\ i\tan\beta_O \end{bmatrix} = \left[\frac{2i\tan\tau_p}{B_N\cos^2\tau_p \pm\sqrt{(B_N\cos^2\tau_p)^2+4\sin^2\tau_p}}\right]. \quad (1)$$

Where $B_N \equiv f_{ce}/f$ is the ratio of the electron cyclotron frequency to the incident wave frequency at the plasma edge where plasma density is zero. τ_p is the angle between the magnetic field direction $\hat{B}$ and $\hat{E}_{\phi p}$ as shown in Fig. 4. X-mode and O-mode correspond to plus sign and minus sign in front of square root, respectively in Eq. (1). Table 1 shows the τ_p and the ellipticities of pure X-mode and O-mode when the rf wave is injected from the low field side in KSTAR with a toroidal angle of 30° with respect to the radial direction of the tokamak center. In this case, the parallel component of refractive index to the magnetic axis ($n_{\|}$) is 0.5 by Snell's law. However, since the launcher of KSTAR ECH system is located below the medium plane of the KSTAR, the launcher will be tilted poloidally to launch the wave to an EC-resonant position in the medium plane. Therefore, τ_p of 28.9° is obtained from geometric calculation [8]. Since the toroidal magnetic field in the initial operation phase of the KSTAR will be 1.5 Tesla for high-beta experiment and the safety of superconducting toroidal coil, and it will be raised up to 3.5 Tesla in upgrade and advanced operation phases, Table 1 shows the required ellipticities for both toroidal magnetic fields.

B at plasma center [T]	B at plasma edge [T]	τ_p [deg]	b/a (X-mode)	b/a (O-mode)
1.5	1.17	28.9	0.84	-0.64
3.5	2.74	28.9	0.58	-0.45

Table 1. Required ellipticity parameters of pure O-/X-mode at the plasma edge for KSTAR ECH system.

The calculation coordinate is shown in Fig. 4. τ_p and θ are used to denote the angle between $\hat{B}$ and $\hat{E}_{\theta p}$, $\hat{B}$ and $\hat{k}_p$, respectively.

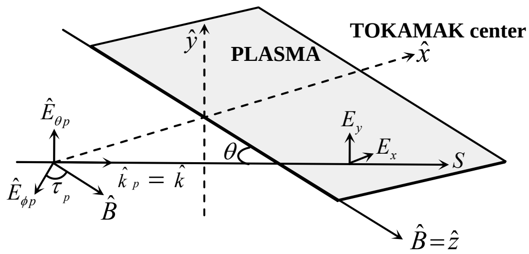

Fig. 4. The illustration of the calculation coordinates.

2.4 mode purity at the plasma center

In previous section, the specific coupling to O- or X-mode is considered only at the plasma edge. However, the wave polarization changes with plasma density and the toroidal magnetic field as it propagates into the plasma, hence the ellipticities different from those given in Table 1 are needed for the specific coupling to O- or X-mode at the EC-resonant position. For this, the ellipticity map of launched wave from the KSTAR ECH launcher is needed for the specific mode purity. The ellipticity map is obtained by the simple algebra of transformation matrix of the polarization of the propagating wave through ECH transmission line. The matrix calculation is done using IDL (Interactive Data Language) program [9]. Figure 5 shows the ellipticity map as a function of mirror rotation angle of two polarizer miter bends in the KSTAR ECH system. Ellipticity of b/a = 1, 0, -1 are shown in Fig. 5. b/a = 1, 0, -1, represent right-handed circular polarization,

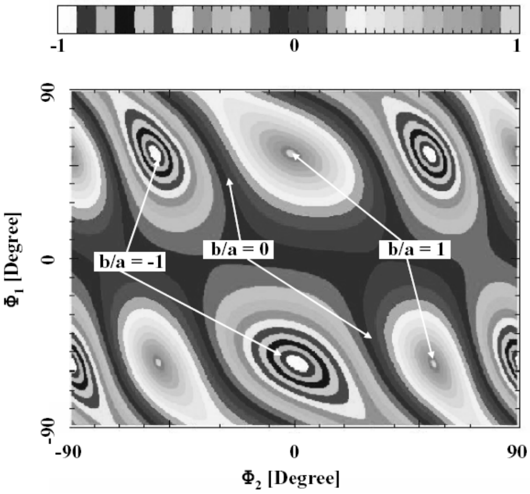

Fig. 5. The ellipticity map. Φ_1 indicate the mirror rotation angles of the polarization rotator and Φ_2 indicate the mirror rotation angles of the circular polarizer miter bend.

linearly polarization, and left-handed circular polarization, respectively. And also, it shows that any elliptical polarization can be obtained using two polarizer miter bends.

The wave polarization change in the plasma is obtained from the cold plasma dispersion relation [10].

$$\frac{E_y}{iE_z} = \frac{D(P - n^2 \sin^2\theta)}{n^2\cos\theta\sin\theta(S - n^2)}, \tag{2.1}$$

$$\frac{E_x}{E_z} = \frac{(P - n^2\sin^2\theta)}{-n^2\cos\theta\sin\theta}, \tag{2.2}$$

where n is the refractive index of plasma, written as

$$n^2 = \frac{(S^2 - D^2)\sin^2\theta + PS(1+\cos^2\theta)}{2(S\sin^2\theta + P\cos^2\theta)} \pm \frac{\sqrt{(S^2 - D^2 - PS)^2\sin^4\theta + 4P^2D^2\cos^2\theta}}{2(S\sin^2\theta + P\cos^2\theta)}. \tag{3}$$

Where + and - sign indicate the X- and O-mode, respectively, and P, S and D are defined as

$$S \equiv 1 - \frac{\omega_{pe}^2}{\omega^2}\left(\frac{\omega^2}{\omega^2 - \omega_{ce}^2}\right),$$
$$P \equiv 1 - \frac{\omega_{pe}^2}{\omega^2}, \tag{4}$$
$$D \equiv \frac{\omega_{pe}^2}{\omega^2}\left(\frac{\omega\omega_{ce}}{\omega^2 - \omega_{ce}^2}\right),$$

where, ω_{ce}, ω_{pe}, ω are an electron cyclotron frequency, a plasma frequency, and an incident wave frequency, respectively. The excited O- or X-mode purity of the wave inside plasma can be obtained from Poynting flux of the wave [11].

$$S_O = (\frac{E_{xO}^2 + E_{yO}^2}{E_{zO}^2} + 1) n_O E_{zO}^2, \quad (5.1)$$

$$S_X = (\frac{E_{xX}^2 + E_{yX}^2}{E_{zX}^2} + 1) n_X E_{zX}^2, \quad (5.2)$$

$$E_{zO} = \frac{E_{\theta p}(R - \sin\theta E_{yX} / iE_{zX})}{E_{yO} / iE_{zO} - E_{yX} / iE_{zX}}, \quad (6.1)$$

$$E_{zX} = \frac{E_{\theta p}(-R + \sin\theta E_{yO} / iE_{zO})}{E_{yO} / iE_{zO} - E_{yX} / iE_{zX}}, \quad (6.2)$$

where, $R\ (= E_{\phi p} / iE_{\theta p})$ is the modified polarization ratio of the launched wave which derived from the ellipticity map. The suffix, O and X indicate O- and X-mode of the wave excited in plasma, respectively. The O- and X- mode purities are calculated by Eqs. (2)-(6). Figure 6 shows the contour plots of O-mode purity $(=S_O/(S_O+S_X))$ of the excited wave in the KSTAR plasma where the plasma density assumed to be 1 x 10^{20} m^{-3} and the toroidal magnetic field in the plasma center is 3.5 Tesla.

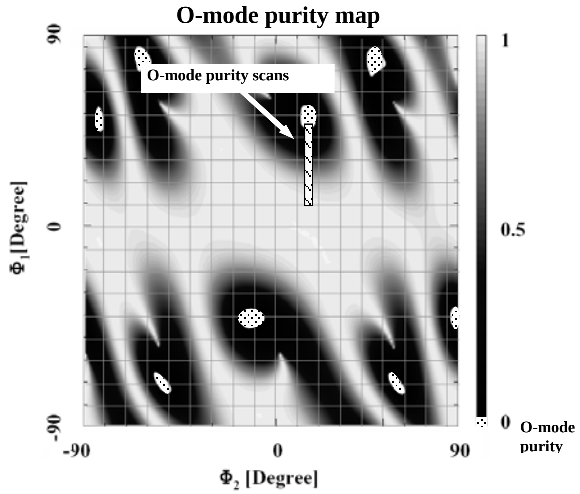

Fig. 6. The O-mode purity map of the exited wave in KSTAR plasma.

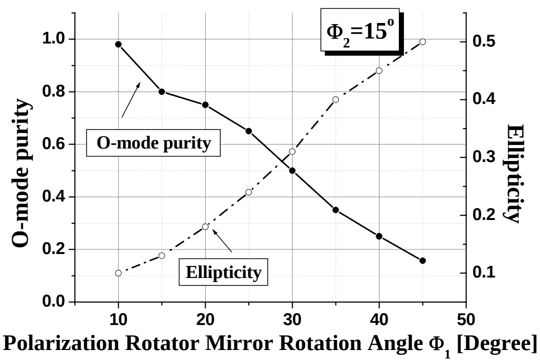

Fig. 7. The O-mode purity and ellipticity as a function of the mirror rotation angle of the polarization rotator miter bend, Φ_1 for Φ_2= 15 degrees. The cross structure has O-mode purity in the range of 0.15 (minimum) to 0.99 (maximum).

O-mode purity scans for ECH experiment are shown in Fig. 6 (hatched line). When Φ_2 are 15 degrees, the O-mode purity and ellipticity are plotted as a function of the mirror rotation angle Φ_1 as shown in Fig. 7. From this result, arbitrary values of O-mode purity can be obtained in the range of 0.15 to 0.99 as a function of mirror rotation angle.

3. Summary

In this paper, we calculated an ellipticity map with respect to the mirror rotation angles of the polarization rotator and circular polarizer. Also, the plasma mode purity map is investigated for the KSTAR. For the specific mode coupling of obliquely launched EC-wave in the KSTAR plasma, it is seen that the elliptical polarization is required. The ellipticity of 0.58 is required with τ_P = 28.9° at the plasma edge when rf wave is obliquely injected from the low field side with $n_{\|} = n \sin\theta = 0.5$. And arbitrary values of O-mode purity can be obtained in the range of 0.15 to 0.99 as a function of mirror rotation angle.

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