Contributed Paper

Quasi-Optical Beam Analysis Based on Direct Phase Measurement at Low Power Level

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Alignments of the beam size and position, and the tilt of the propagation axis, have been pointed out to be important in transmission lines for Electron Cyclotron Heating in order to achieve high transmission efficiency. Beam size evolution along the propagation of a Gaussian-like beam, and its beam tilt are analyzed with a quasi-optical moment theory by using measured intensity and phase patterns at a low power level. The Gaussian-like beam is coupled into a corrugated waveguide in the tilted injection. The desired Gaussian content after the coupling is also evaluated in terms of the measured phase as well as the intensity. It is indicated that the direct phase measurements are essential to evaluate the beam size evolution along the propagation, the tilt angle, and the Gaussian content of the beam, which are key issues in the alignment problem.

Keywords:
electron cyclotron resonance heating, transmission line, beam alignment, moment theory, phase measurement, millimeter wave

1. Introduction

Electron Cyclotron Heating (ECH) is currently an attractive method for plasma production, auxiliary heating, and current drive. ECH has been an effective tool for suppression of MHD activities and heat transport analysis because of its capacity for local heating. The output beam, from a gyrotron that is a high power mm-wave source for ECH, is led to a Matching Optics Unit (MOU) and coupled into oversized corrugated waveguides by means of a mirror array in the MOU. It is then transmitted to a launcher by the waveguide transmission line at an HE_{11} mode. In order to attain a high coupling efficiency between the MOU and the waveguide, the output beam from the gyrotron should be converted into a Gaussian beam.

An 84 GHz gyrotron with a single-stage depressed collector of the $TE_{15,3}$ oscillating mode was prepared for ECH on the Large Helical Device (LHD) at the National Institute for Fusion Science (NIFS) [1]. A geometric optics Vlasov converter was installed in the gyrotron to convert the oscillating mode into a quasi-optical beam [2]. The surface power density at the gyrotron output window was reduced by flattening the output profile for a longer pulse operation at the time. The output pattern from the gyrotron was flatter than that of the Gaussian beam, but was complicated due to diffraction at the converter. In order to couple the beam into the waveguide efficiently, a phase-correcting mirror array in the MOU was designed at the Massachusetts Institute of Technology (MIT) by the phase distributions calculated from the IR-imaging measurements along the propagation with the phase retrieval code [3]. The propagation axis was deduced from the evolution of the beam center position along the propagation in the design. The beam center position was evaluated as a first moment in the moment theory by using the measured IR-intensity patterns. The mirror array designed at MIT was evaluated to work correctly at a low power test facility [4].

In the first MOU for the gyrotron, conventional mirrors were designed based on only Gaussian optics. In the design, the intensity profiles of the gyrotron output measured as IR-images were only used in Gaussian beam analysis. The evolution of the phase profile along the propagation was calculated with the Gaussian parameters analyzed from the intensity measurement. However, because the Gaussian beam content in the gyrotron output was only 0.74 [3], a power level of 0.3 was lost at the MOU. The phase profile information calculated from the intensity measurement was not effective to achieve high coupling efficiency at the MOU. In this paper, a beam whose intensity profile is Gaussian-like, but not so complicated, is analyzed. The beam size evolution along the propagation even in the Gaussian-like beam cannot be explained with Gaussian optics, provided that the measured phase profiles are taken into consideration in the beam size

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analysis.

To obtain high transmission efficiency in the corrugated waveguide line, the beam position and tilt have to be also aligned within tolerable limits to provide coupling into the HE_{11} mode of the waveguide [5]. Precise quantifications of the beam position and the tilt angle of the beam are required in an order of the tolerable limits to investigate their effect on the transmission/coupling efficiency. The beam size is occasionally large in a beam expanding/focusing along the propagation strongly, and the evaluation of the beam center position from the intensity measurement becomes difficult in this case. The phase information directly shows how the beam strongly expands/focuses, and how it inclines for the measuring axis. The evaluation of the beam tilt from the phase as well as the intensity measurements is described in this paper. The beam tilt analyzed for the Gaussian-like beam is discussed together with the evolution of the beam center position along the propagation that is derived only from the intensity measurement.

The Gaussian-like beam is coupled into a corrugated waveguide in the tilted injection. Unwanted modes that are excited in the coupling by the tilted injection cause high transmission losses and arcing events in the transmission line. The HE_{11} mode coupled into the waveguide correctly is mostly radiated from the waveguide as the Gaussian-mode. The desired Gaussian content in the beam after coupling is evaluated with the matching coefficient method by using the measured intensity and phase patterns.

The contents in this paper are as follows. In Sec. **2**, basic equations in a quasi-optical moment theory are introduced to analyze a Gaussian-like beam. The low power test facility is explained in Sec. **3**, and the obtained experimental results are discussed in Sec. **4**. Finally, a summary is given in Sec. **5**.

2. Basic Equations

The arbitrarily shaped quasi-optical beam propagates according to the moment theory of quasi-optical beams [6]. Here, the n-th moment is defined with the amplitude distribution $A(x, y)$, as

$$\langle x^n \rangle = \int x^n A^2 \mathrm{d}x\mathrm{d}y \,/ \int A^2 \mathrm{d}x\mathrm{d}y \,, \tag{1}$$

where the x and y axes are in a perpendicular plane to the propagating z axis. The beam power density center positions are expressed with the first moments ($\langle x \rangle$ and $\langle y \rangle$) in both of the coordinates. The effective radii $a^{\mathrm{eff}}_{x,y}$ in the x and y directions are described, as

$$a^{\mathrm{eff}}_x = \sqrt{\langle x^2 \rangle - \langle x \rangle^2},\ a^{\mathrm{eff}}_y = \sqrt{\langle y^2 \rangle - \langle y \rangle^2}\,, \tag{2}$$

by using the 2nd moments. $2a^{\mathrm{eff}}_{x,y}$ correspond to the beam sizes $w_{x,y}$ in a Gaussian beam. The dependence of the beam power density center on the propagating position z can be written in terms of the quasi-optical moment theory in the x and y directions, as

$$\langle x(z) \rangle = \langle x(0) \rangle - z \frac{\int A^2 (\partial\Phi/\partial x)\mathrm{d}x\mathrm{d}y}{k\int A^2 \mathrm{d}x\mathrm{d}y}\,, \tag{3}$$

and

$$\langle y(z) \rangle = \langle y(0) \rangle - z \frac{\int A^2 (\partial\Phi/\partial y)\mathrm{d}x\mathrm{d}y}{k\int A^2 \mathrm{d}x\mathrm{d}y}\,, \tag{4}$$

where k and Φ are the wave number and the phase distribution, respectively. The amplitude $A(x, y)$ and phase $\Phi(x, y)$ in Eqs. (3) and (4) are taken at $z = 0$ here. The beam center and/or the effective radius are analyzed by using the moment theory.

The Gaussian content is evaluated as a matching coefficient, defined as

$$\left| \int f g^* \mathrm{d}x\mathrm{d}y \right|^2 / \int |f|^2 \mathrm{d}x\mathrm{d}y \,/ \int |g|^2 \mathrm{d}x\mathrm{d}y \,. \tag{5}$$

In order to evaluate the coefficient, the complex amplitude, f and g, which are deduced from the amplitude and phase distributions in the measurement and in the calculation with Gaussian optics, are used. The asterisk [*] represents the complex conjugate here.

3. Low Power Test Facility

The low power test facility to measure directly the phase profiles of the propagating wave as well as the intensity profiles has been prepared in the frequency range up to 180 GHz at NIFS. In the LHD project at NIFS, the ECH systems at 82.7/84 GHz and 168 GHz are used in the experiment. The subject in this paper is related to the beam alignment in the ECH transmission on LHD.

In the mm-wave range measurement, the phase information, relative to the intensity in general, is very sensitive to the measuring position. Accuracy of setting position of the detector stage should be in the order of 1/100 for the wavelength in the frequency range. The three-dimensional stage control system is prepared to set the detector stage precisely. The accuracy in the position setting along two directions perpendicular to the propagating axis is 0.010 mm, and the resolution for the axis is 0.025 mm. The experimental equipment and the test components are set up on the basis of the position control in the three-dimensional stage. The He-Ne laser is also used to align the components. In the low power test facility, a setting accuracy of less than 1 mm is realized for all components.

Two synthesizers are prepared to obtain high resolution and stability on the measuring frequency. One synthesizer is used as a radio-frequency source for a multiplier to generate the millimeter wave, and the other is a local oscillator of harmonic mixers on both the launcher and receiver sides. Because the conversion losses in the harmonic mixers are not so low (typically, 35 dB), additional Intermediate Frequency (IF) amplifiers are prepared. The frequency of the IF signal is 20 MHz. The intensity ratio and the phase difference between the IF signals on the two sides are detected at the vector network analyzer. In this system, a dynamic range is more than 90 dB for the intensity measurement. The error in the phase measurement is about ±5 degrees at a power level of –80 dBm [7].

4. Experimental Results and Discussion

4.1 Gaussian-like beam

First, propagation of the Gaussian-like beam is investigated. In order to prepare a beam in the low power test facility, a scalar horn antenna and two coupling mirrors are used. The Gaussian beam is modified using additional quasi-optical mirrors. The prepared Gaussian beam was used to evaluate the mirror array designed at MIT [4]. The Gaussian-like beam is produced by a shift of the coupling mirror position in the aligned-axis of the beam. The intensity and phase distributions are measured in the x–y plane. Here, the wave frequency of the beam is 82.7 GHz. Figure 1 shows measured intensity and phase profiles in the x direction at the propagating position z = 0 mm. Here, the origin of the z coordinate is artificial and has no meaning. The intensity profile is Gaussian-like, though, there is a shoulder in the peripheral region. The fitted curve as a Gaussian profile is also plotted in the figure. The measured peaked-profile cannot be expressed by the fitted Gaussian profile even in the main lobe. The phase is flat with a small tilt angle in the central region. Figure 2 shows the evolutions of the beam power density center positions ($\langle x\rangle$ and $\langle y\rangle$) and the tilt angles along the propagating z direction. The tilt angles in the x and y directions, $t_{x,y}$, are derived from

$$\frac{\int A^2(\partial\Phi/\partial x, \partial y)\mathrm{d}x\mathrm{d}y}{k\int A^2\mathrm{d}x\mathrm{d}y}$$

in Eqs. (3) and (4). Similar tilt angles are evaluated at various z positions, as shown in the figure. The slope lines in the figure are from the tilt angles evaluated at z = 0 mm in both the x and y directions. The evolution of the beam center position is well explained with the slopes based on the quasi-optical moment theory.

Figure 3 shows the evolution of beam sizes in the x and y directions along the propagating z direction. In Gaussian optics, the beam sizes, w_x and w_y, are derived from the intensity data in the cross-cut at the beam center positions, $\langle x\rangle$ and $\langle y\rangle$. The effective beam sizes, $2a_x^{\mathrm{eff}}$ and $2a_y^{\mathrm{eff}}$, based on the moments are also shown in the figure. The evolution of the beam sizes based on Gaussian optics can be calculated, provided that the waist sizes and positions are given. The waist sizes and positions are derived from the beam sizes and the phase curvatures at z = 500 mm. The phase profiles in the x and y directions are approximately parabolic in the beam sizes there. The calculated evolution of the beam sizes is not consistent with the measured beam sizes in Gaussian optics. The calculated beam sizes are in the middle between those evaluated from Gaussian optics and the moment theory.

The conventional mirrors have been designed based on Gaussian optics. Gaussian parameters, which are the waist size and position, are deduced from the evolution of the beam size along beam propagation. The phase profiles are calculated with the Gaussian parameters obtained from the intensity measurement. In the analysis of the Gaussian-like beam, as shown in Fig. 3, the phase profile measured at z = 500 mm is different from that evaluated by using the beam size evolution from z = 0 mm to 500 mm. The direct phase measurement is required in the development of millimeter wave components even for Gaussian-like beams.

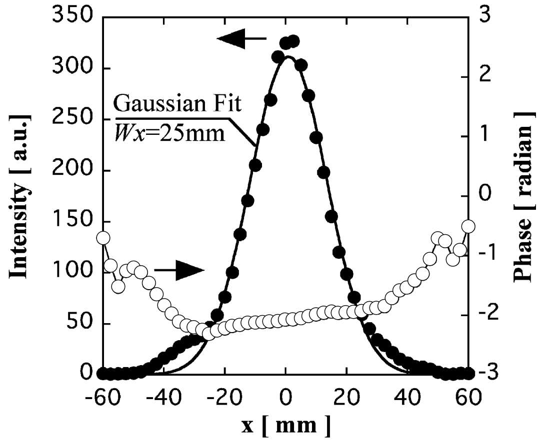

Fig. 1 Intensity and phase profiles of the Gaussian-like beam in the x direction at z = 0 mm.

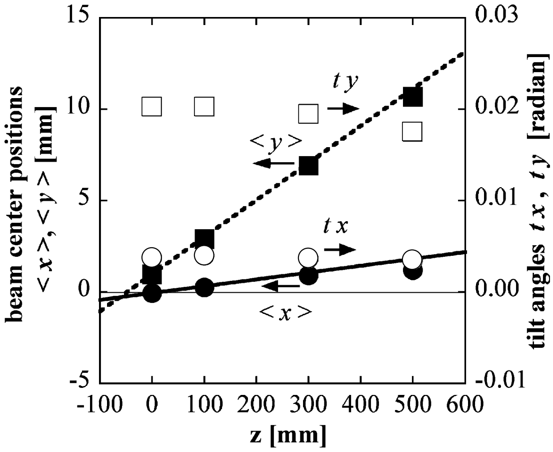

Fig. 2 Beam center positions and tilt angles in Moment Analysis for Gaussian-like beam.

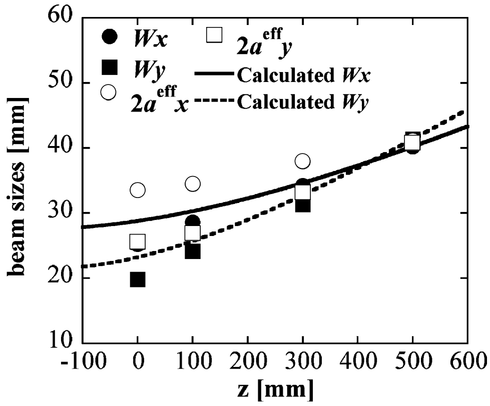

Fig. 3 Evolution of beam sizes of the Gaussian-like beam along the propagation.

4.2 Coupling to corrugated waveguide

The beam center and tilt angle of the beam can be evaluated from the measured intensity and phase

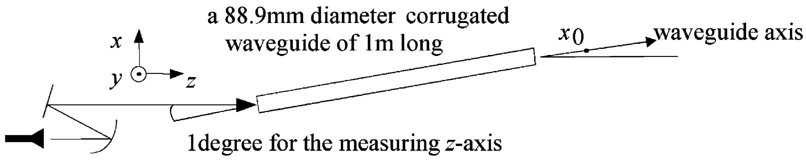

Fig. 4 Schematic of experimental setup in the tilted injection experiment.

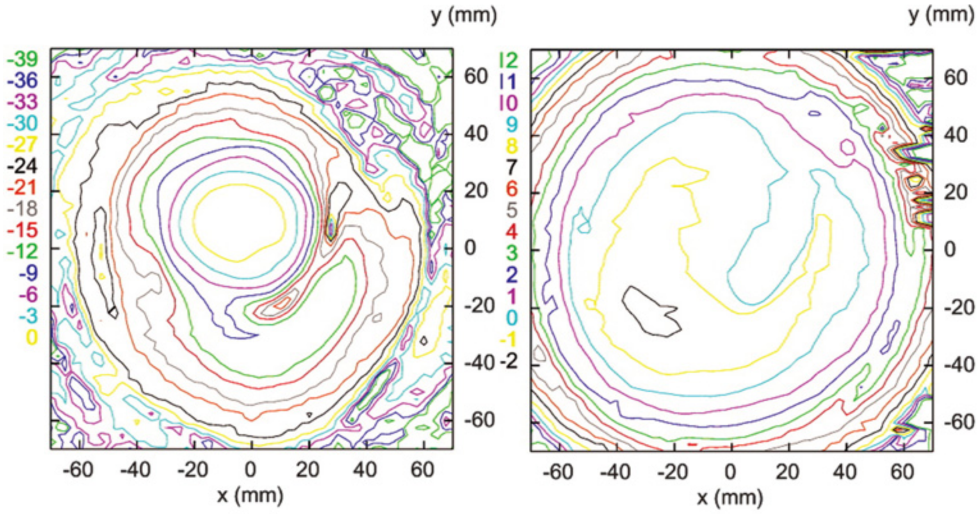

Fig. 5 Contour plots of (a) measured Intensity distribution [in dB] by 3 dB step and (b) phase distribution [in radian] by 1 radian step of the output beam after coupling to a corrugated waveguide.

measurements by using the moment theory. In order to obtain high transmission efficiency in the waveguide line, these parameters should be aligned within the tolerable limits. In relation to the alignment problem, the beam is coupled into a corrugated waveguide with a length of 1m and a diameter of 88.9 mm with the tilt angle, as shown in Fig. 4. The beam size at the input of the waveguide is about 30 mm. The input aperture is located at z = 225 mm in Fig. 3. The offset, between the beam center and the waveguide center, is aligned to be less than 1 mm (with an accuracy of ±0.5 mm), based on the first moment analysis. The incident angle of the beam can be adjusted by moving the position of the output waveguide aperture. Here, the waveguide is set with a tilt angle of –1.0 degrees for the measuring axis in the x direction. The sign of the tilt angle is defined as plus when the beam is inclined to the positive x direction. The waveguide is aligned under the position control of the three-dimensional stage. The tilt angles of the Gaussian-like beam for the measuring axis are +0.2 and +1.2 degrees in the x and y directions, as shown in Fig. 2. The input angles to the waveguide in the x and y directions, θ_x and θ_y, therefore, become –0.8 and +1.2 degrees, respectively.

Figures 5 (a) and (b) show the measured intensity [in dB] and phase distributions [in radian] at the propagating position of 200 mm from the output waveguide aperture in the case of the incident angles θ_x = –0.8 and θ_y = +1.2 degrees, respectively. There are side-lobes in the intensity distribution, and the phase distribution is distorted from a paraboloid. The beam centers are evaluated as $\langle x\rangle$ = –7.6 mm and $\langle y\rangle$ = +6.4 mm with the first-order moment analysis by Eq. (1). The Gaussian content in the output beam from the waveguide after the coupling can be calculated with Eq. (5). The output beam from the waveguide is normally coupled into a mirror array in the launcher system. In this case, a Gaussian beam that is used to design the mirror array has a circular waist size of 28.9 mm and a waist position at the waveguide aperture. The matching coefficient in Eq. (5) between the desired Gaussian beam and that in Fig. 5 is evaluated as 0.39. The HE_{11} mode coupled into the waveguide is mostly radiated from the waveguide as the Gaussian-mode. The coupling content of the HE_{11} mode was calculated in the tilted injection, but using a pure ideal Gaussian beam input [5]. The obtained matching coefficient is consistent with the theoretical prediction, taking the tilted angles for the input into account. In order to evaluate the mode content in the beam, the phase information is also required, and is essential in the evaluation.

5. Summary

The low power test facility has been prepared to measure the phase profile as well as the intensity profile of the propagating beam in the high frequency mm-wave range. The beam size of the quasi-optical beam is derived as the second moment from the intensity measurement, and compared to those in Gaussian optics. If the beam is not a pure Gaussian beam, the phase profile evaluated from the intensity measurement is not consistent with that measured directly. The beam tilt angle of the beam determined from both the intensity and phase measurements can well explain the evolution of the beam center (*i.e.*, the first moment) determined from intensity measurement. The phase profile directly shows how the beam is expanding/focusing and inclining. Intensity and phase patterns in the output beam from the waveguide after the coupling in the tilted injection are measured. There are the beam center offsets and the side-lobes in the intensity distribution, and the phase distribution is distorted from a paraboloid. The mode purity for the desired Gaussian content is analyzed from the measured intensity and phase information. It should be noted that the direct phase measurement is very important to analyze the beam property of the quasi-optical beam.

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References

[1] T. Shimozuma *et al.*, *Proc. of the 22nd IRMMW Conference*, 194 (1997).
[2] M. Sato *et al.*, Fusion Eng. Des. **26**, 287 (1995).
[3] M.A. Shapiro *et al.*, Fusion Eng. Des. **53**, 537 (2001).
[4] H. Idei *et al.*, *Proc. of the 26th IRMMW Conference*, 208 (2001).
[5] K. Ohkubo *et al.*, Int. J. Infrared Millim. Waves **18**, 23 (1997).
[6] S.N. Vlasov *et al.*, Izv, vuz Radiofizika **14**, no.9, 1353 (1971).
[7] T. Notake *et al.*, Rev. Sci. Instrum. **76**, 023504 (2005).