Contributed Paper

Alignment Method of ECH Transmission Lines Based on the Moment and Phase Retrieval Method Using IR Images

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(Received 26 November 2004 / Accepted 16 January 2005)

New alignment methods of millimeter-wave transmission lines for Electron Cyclotron resonance Heating are proposed and evaluated on a high power level. These methods are based on the measured data of infrared images on the target, which is irradiated by the high power millimeter-waves at several positions. The first and second moments and retrieved phase obtained from these data are used to determine the propagation direction of the millimeter-wave beam along the waveguide axis. It is demonstrated that these methods have sufficient resolution to discriminate 0.1 deg., which is required to restrict the transmission loss below 1% over the 100 GHz range.

Keywords:

electron cyclotron resonance heating, transmission line, alignment, phase retrieval method, moment method, infrared image

1. Introduction

Electron Cyclotron resonance Heating (ECH) is one of the most powerful heating methods for heating and current drive in fusion-oriented plasma devices. The high power millimeter-waves for ECH are usually transmitted by means of over-sized corrugated waveguides. The length of such transmission lines becomes longer and longer due to the huge size of plasma experimental devices. In the over-sized corrugated waveguides, the transmitted mode of the HE_{11} mode is easily converted to unwanted modes that are attenuated heavily by tilt and offset of the waveguide axis. Improvement of transmission efficiency is the essential in view not only of increase of usable power but reduction of heat load to the millimeter-wave components. For example, to maintain a mode conversion loss < 1%, tilt angle and offset of the beam center should be less than 0.1 deg. and 2.9 mm, respectively, for the 168 GHz transmission through the corrugated waveguide 88.9 mm in diameter [1].

Until now, millimeter-wave coupling to the corrugated waveguide and alignment have been performed with the aid of burning patterns on thermal recording papers that are stuck to the waveguide inlet and outlet. The propagation direction has been determined by the displacement of the beam center recorded on the thermal papers. On the occasion of alignment work, however, the finite size of the millimeter-wave beam and complex interference patterns on the thermal paper, resulting from binary-recording characteristics of the thermal papers, sometimes prevent identification of the beam center and its displacement.

We have been researching an alignment method of high power millimeter-waves based on infrared (IR) images on a target irradiated by high power millimeter-waves. In this paper, we propose a new alignment method of millimeter-wave transmission lines for ECH, and evaluate the method on the actual transmission system of the Large Helical Device [2] on a high power level. One method to identify the center of the beam is to calculate the first moment of the IR images, which corresponds to the center of the beam power. Another method is based on the phase information, which is sensitive for the wave characteristics and has the potential to determine the direction of propagation. Because the phase of high power millimeter-waves, however, cannot be measured directly, the phase retrieval method is used to obtain the phase information. The phase retrieval method has been used for design of the phase correction mirror in the matching optics unit (MOU), which converts an output mode of a gyrotron to the Gaussian mode to be coupled to the corrugated waveguide [3]. The retrieved phase information and the first and second order moments could be utilized on precise beam alignment even on a high power level.

This paper is organized as follows. In Sec. **2**, the ECH system for LHD and the transmission efficiency are briefly described. In Sec. **3**, the basic idea of the beam alignment method based on the moment and phase retrieval method is

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explained. Calibration of the system including the evaluation of target materials will be given in Sec. **4**. High power test results and evaluation as a beam alignment method are discussed in Sec. **5**. Finally, Sec. **6** will be devoted to a summary.

2. ECH System and Transmission Efficiency

The ECH system for LHD consists of eight gyrotrons (two 82.7 GHz / 0.5 MW / 2 sec, two 84 GHz / 0.8 MW / 3 sec and four 168 GHz / 0.5 MW / 1 sec), transmission lines, and quasi-optical antennas, which are shown in Fig. 1. The 84 GHz range gyrotrons, which are diode type tubes, are installed for fundamental EC resonance heating, and the 168 GHz gyrotrons with a depressed collector are for the second harmonic resonance heating at the magnetic field of 3T. Among eight transmission lines, six lines consist of corrugated waveguides with a diameter of 88.9 mm in atmospheric pressure. Two transmission lines are evacuated ones 31.75 mm in diameter.

In LHD, each transmission line consists of matching optics units (MOUs), corrugated waveguides, miterbends, polarizers, arc detectors, power monitors, dummy loads, and injection windows. The MOU includes 2 or 4 mirrors. In the 4-mirror system, two are phase correcting mirrors and two are mirrors for beam alignment. High power millimeter-waves are transmitted through corrugated waveguides with diameters of 88.9 mm and 31.75 mm over a 100 m distance. The narrow waveguides are evacuated for higher power transmission capability.

Transmission efficiency for each line is evaluated by comparison with the measured powers at the gyrotron window, at the MOU output position, and at the corrugated waveguide near LHD. Figure 2 displays the transmission efficiency in percentage terms for each line, in which the gyrotron output power is divided into possible injection power, power loss in the MOU, and loss in the waveguide including miterbends.

The general aspects of the transmission efficiency can be deduced from the results as follows, though the optimization of beam alignment is not complete. 1) Transmission efficiencies from the waveguide inlet to LHD for the higher frequency lines of 168 GHz (#1–3, #7) are lower than those for the low frequency 84 GHz lines. And the conversion efficiency in the MOU is lower for the high frequency lines. 2) The narrow evacuated line (84 GHz #4, 5) does not have similarly good efficiency, even though it has fewer miterbends and a shorter length. 3) The coupling efficiency from gyrotrons to the corrugated waveguide is almost 80% including the conversion efficiency in the MOU. 4) The lower frequency and fat waveguide lines (82.7 GHz #11, 12) have better coupling and transmission efficiencies. 5) More miterbends and longer length of the lines degrade the efficiency, though the number of miterbends and the length of the lines are not shown here. The loss per miterbend is estimated to be 1.5% on average.

Total transmission efficiency is divided into three parts when considering total transmission from a gyrotron window to an antenna. The first part is what we call the conversion efficiency of the gyrotron output to the best coupled Gaussian beam, which has a waist diameter of 0.643 $\times$ (waveguide inner diameter) at the waveguide inlet [1]. The second part is the coupling efficiency of the best coupled Gaussian beam in free space to the corrugated waveguide. This includes not only the spill-over loss of the Gaussian beam at the waveguide mouth but also the mode conversion loss due to beam tilting, offset, and mismatched beam waist size. The third part is the pure transmission loss along the transmission line. This is induced by the Ohmic loss on the waveguide wall and miterbend mirrors, and the mode conversion loss due to waveguide deflection and discontinuity. The second part is closely related to the third one, because the mode conversion to the spurious modes is spoiled by the waveguide misalignment, and probably causes arcings in the waveguide. The new alignment method that we propose here is mainly related to improvement of the second part. The power loss in the second part cannot be discriminated in the data shown in Fig. 2, but the improvement by this method affects losses both in the MOU and in the waveguide indicated in Fig. 2.

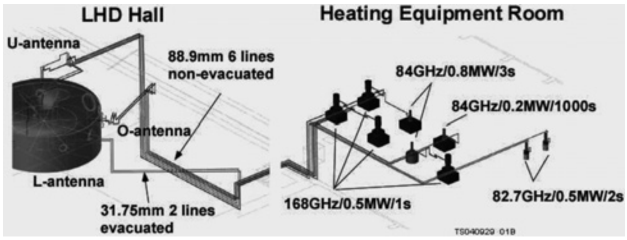

Fig. 1 ECH system in LHD, which consists of 82.7 GHz, 84 GHz, 168 GHz gyrotrons, transmission lines and antennas.

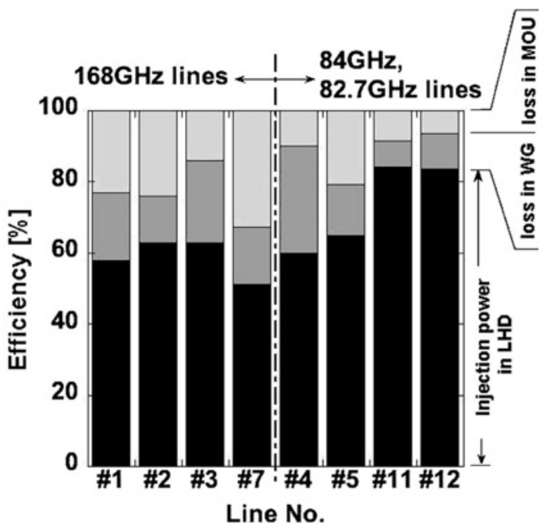

Fig. 2 Transmission efficiency in each line. Black, dark gray and light gray bars show the percentage of injection power into LHD, power loss in the waveguide (WG) and loss in the MOU, respectively.

3. Millimeter-Wave Beam Alignment by Moment and Phase Retrieval Method

The basic idea of millimeter-wave-beam alignment by the moment and phase retrieval methods is as follows. The schematic is illustrated in Fig. 3. The transmission line consisting of corrugated waveguides should be initially aligned by a visible laser beam. After the millimeter-wave beam is coupled into the corrugated waveguide and propagated through the guide, it is irradiated to a target plate which is set at several locations away from the waveguide exit. The temperature rise of the target is recorded by an IR camera. The first and second moments are calculated from the data to find the beam center and effective beam radius. Together with this procedure, the phase information could be retrieved from these data [3], which gives the precise information of propagation direction. Then the beam will be re-aligned according to the obtained information, and re-alignment is performed by adjustment of the final flat mirror in front of the waveguide inlet, which can determine only the tilt of the beam axis with respect to the waveguide axis (Fig. 3).

Here the moment and phase retrieval methods are overviewed briefly. The n-th moment in the x-direction 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 plane perpendicular to the propagating axis z. The first moment represents the power center of the millimeter-wave beam. The effective radii $a^{\mathrm{eff}}_{x,y}$ in the x- and y-direction are described in terms of the first and second moment.

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

$$a^{\mathrm{eff}}_y = \sqrt{\langle y^2 \rangle - \langle y \rangle^2} \,. \tag{3}$$

These values are indicators to find the center of the millimeter-wave beam and its waist radius.

Another piece of information on propagation direction can be obtained from the phase information of the millimeter-wave beams. This, however, is impossible to obtain on the Megawatt power level. The phase retrieval method is the one by which the phase information is reconstructed iteratively from only amplitude values acquired at several positions [4]. This method has been successfully used to design phase correction mirrors in the MOU.

The phase retrieval method is outlined briefly as follows. The field component of the millimeter-wave on j-th plane can be expressed by

$$u_j(x,y,z_j) = A_j(x,y) \exp[i\phi_j(x,y)] \,, \tag{4}$$

where $A_j(x,y)$ and $\phi_j(x,y)$ denote the wave amplitude and the phase on the j-th plane, respectively. The field components on the j-th and i-th planes are related by the plane wave expansion as

$$u_j(x,\, y,\, z_j) = \mathrm{F}^{-1}\left\{ \exp\left[i\,(z_j - z_i)\sqrt{k^2 - k_x^2 - k_y^2}\,\right] \times \mathrm{F}\{u_i(x,\, y,\, z_i)\} \right\}, \tag{5}$$

where F is the Fourier transform and F^{-1} is its inverse transform. The phase is retrieved by iteratively solving Eq. (5) for the phase functions ϕ_j, ϕ_i with the measured amplitudes as weights. The algorithm of the calculation is illustrated in Fig. 4. Beginning with an initial phase guess ϕ_0, the field component u_1 is calculated. Then the obtained amplitude is replaced by the measured amplitude. The calculation with this replacement procedure will be continued in the order denoted in the figure. The criterion to stop the iteration is expressed as

$$E_j^{(n)} = \int_{S_j} \left| A_j - A_j^{(n)} \right|^2 \mathrm{d}S_j < \varepsilon_j \,, \tag{6}$$

where the superscript means the value after the n-th iteration and ε_j is a set of given small values. The integral is performed on the surface of S_j.

The issues of attainability, uniqueness, and convergence of the solution of this inverse problem have been the subject of much study. Therefore, in advance of the high power test, the retrieved phase has been compared with directly measured phase information on the low power level by using a vector network analyzer. Good agreement was obtained between the directly measured phase and the retrieved phase [5-7].

The alignment system of millimeter-wave beams consists of an IR camera, a millimeter-wave target, and an optical

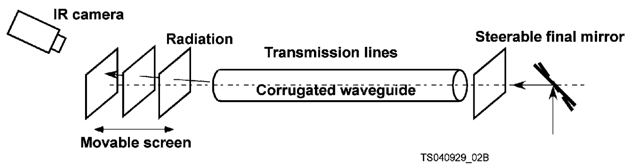

Fig. 3 Basic idea of the alignment method of transmission lines by means of IR images on the millimeter-wave target.

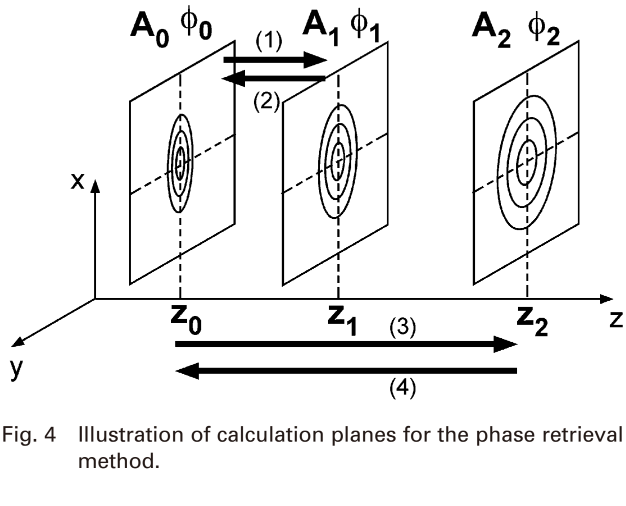

Fig. 4 Illustration of calculation planes for the phase retrieval method.

bench to support the IR camera. Prior to the installation of the system into the transmission line, calibrations of the IR camera and the target, such as correction of viewing angle and of their relative positions, sizes and temperatures, were performed. Figure 5 shows the test setup for calibration. The IR camera is fixed at an angle of about 20 deg. to the waveguide axis. Distance between the camera and the target is adjusted at 705 mm. The IR camera and target can always be moved together, keeping the distance and angle constant. The optical bench is fixed on the waveguide to match the waveguide axis with the center of the target. For calibration of the position and size of the IR images, a tenuous heating element is mounted on the Poly-Vinyl chloride (PVC) target. The IR camera data have 12-bit resolution, which means that the temperature resolution is about 0.1 deg. For data conversion, the tilt, rotation, and translation of the target are taken into account together with viewing angles of the IR camera. Obtained data were analyzed. The relation for data conversion to the real coordinate was established. Hereafter, this relation will be used to obtain the real size of the temperature profiles.

One of the most important issues to be resolved is the temperature linearity of the target material to the absorbed millimeter-wave power. This calibration was performed by means of a grid polarizer as shown in Fig. 6 (a). The irradiated millimeter-wave is transmitted partially through the grid polarizer at a rate determined by the polarizer angle relative to the wave polarization. Measured temperature increase ΔT is plotted as a function of the polarizer angle θ in Fig. 6 (b). In the figure, the solid line indicates the fitted ΔT, which is deduced from the power fraction expected to penetrate the polarizer. In Fig. 6 (c), the measured ΔT is plotted to the fitted temperature increase ΔT_{fit} that is in proportion to the irradiated power to the target. Good agreement implies good temperature linearity of the PVC plate to the absorbed millimeter-wave power within this temperature range.

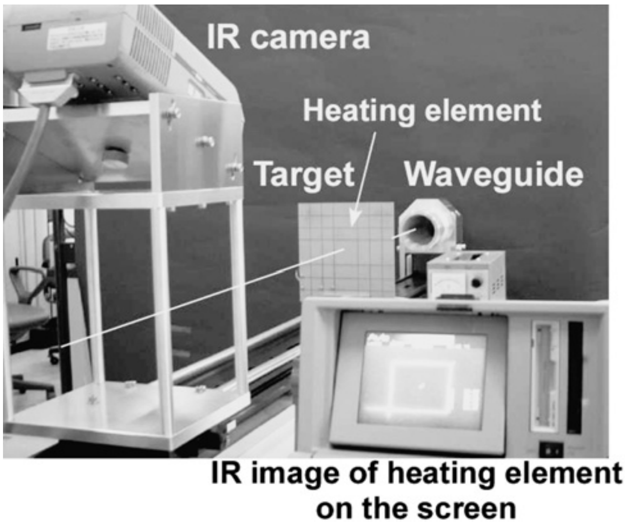

Fig. 5 Setup of beam alignment system for calibration of IR camera and millimeter-wave target.

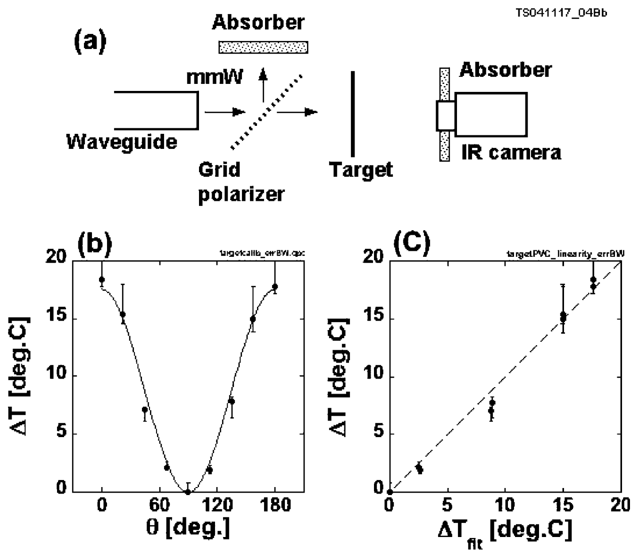

Fig. 6 (a) Schematic diagram of a test setup for the millimeter-wave absorption in the target to assure the linearity of the temperature rise on irradiated power. Measured temperature increase ΔT is plotted as a function of the polarizer angle θ in (b). In (c) the measured ΔT is plotted versus the fitted temperature increase ΔT_{fit} that is in proportion to the irradiated power on the target.

4. Results of High Power Transmission Test

The test set was installed to one of the 168 GHz transmission lines of the LHD heating system. At a position about 10 m apart from the waveguide inlet, one section of corrugated waveguide (1m-long section) was taken off, and the test set including the IR camera, the target, and the optical bench was precisely adjusted so that the waveguide axis coincided with the center of the target along the optical bench by visible lasers, which is shown in Fig. 7.

The generated millimeter-wave power of about 0.2 MW/ 4 ms in the 168 GHz gyrotron was coupled to the corrugated waveguide by the 4-mirror MOU. After 10 m propagation through the waveguide, the wave beam was irradiated from the waveguide again. The irradiated patterns on the target were obtained at several target positions. Figure 8 (a) shows the temperature increment of the target at L = 0, 200, 400 mm from the waveguide mouth. The dashed-line circle indicates the inner diameter of the waveguide. The complicated patterns imply bad matching of the beam to the waveguide. Because the beam center is not clear, the first and second moments are calculated; they are plotted in Fig. 8 (b) for the first and (c) the second moments. With rough alignment, the millimeter-wave beam had a big tilt along the y-direction (the tilt angle is about 0.29 deg.), which implied multiple reflection in the waveguide. The expansion of the beam waist deviated from the expected waist radii of the Gaussian beam shown in Fig. 8 (c).

After realignment of the millimeter-wave beam by readjustment of the steerable final mirror shown in Fig. 3,

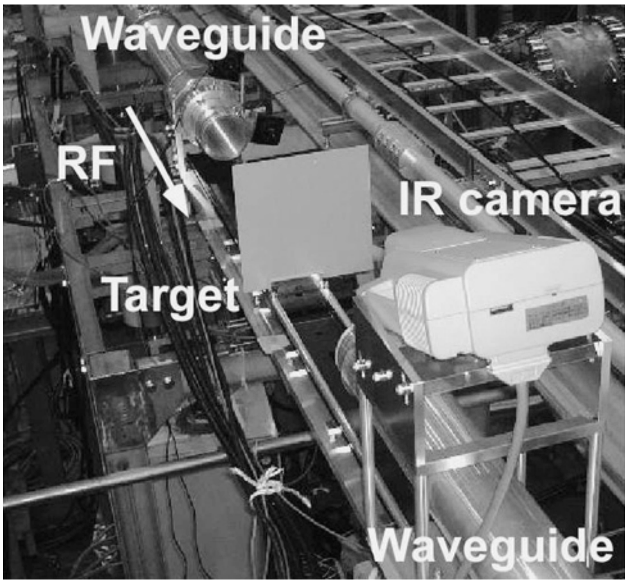

Fig. 7 Configuration of IR pattern measurement system mounted in the transmission line. Waveguide axis is adjusted to coincide with the target center by visible lasers.

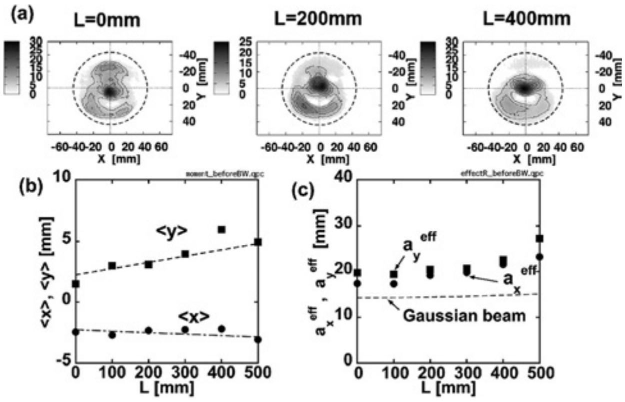

Fig. 8 (a) Radiation patterns as temperature rise of the target that were taken at the position of L = 0, 200, 400 mm before precise alignment of the transmission line. Contours of constant temperature are at 5 deg. intervals. (b) The first and (c) second moments of the radiation patterns.

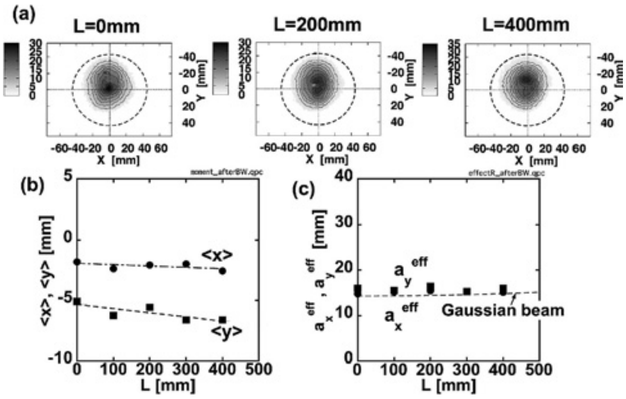

Fig. 9 (a) Radiation patterns as temperature rise of the target that were taken at the position of L = 0, 200, 400 mm after precise alignment of the transmission line. Contours of constant temperature are at 5 deg. intervals. (b) The first and (c) second moments of the radiation patterns.

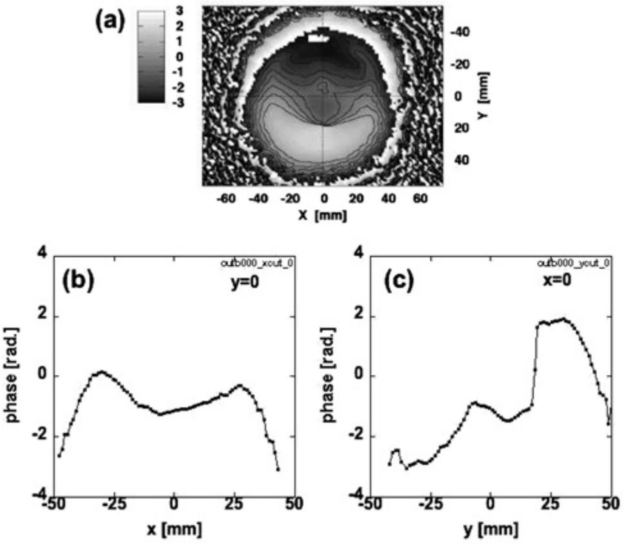

Fig. 10 (a) Contour plot of the retrieved phase for before precise alignment. Contours of constant phase are 1 rad. interval. The phase profiles along x axis and y axis are plotted in (b) and (c), respectively.

radiation patterns were acquired again in the same manner. The results are shown in Fig. 9 (a). In this case, the radiation patterns form Gaussian like profiles. The first and the second moments are plotted in Fig. 9 (b) and (c), respectively. The tilt angle is about 0.09 deg. in the x-direction and 0.2 deg. in the y-direction. The beam waist size is in good agreement with one expected as the Gaussian beam.

Along with these moment analyses, retrieval of the millimeter-wave phase was performed by using obtained radiation pattern data. For the initial state corresponding to Fig. 8, a contour plot of the retrieved phase at the waveguide mouth is given in Fig. 10 (a) together with profiles at the (b) y = 0 and (c) x = 0 cross section. The large phase jump at $y \simeq +20$ mm in (c) clearly means that reflections on the waveguide wall occurred in the waveguide. The same plots are shown after precise alignment corresponding to Fig. 9, in Fig. 11 (a), (b), and (c). The flat phase profile is obtained in this case. The inclination of the beam propagation is calculated to be only 0.1 and 0.17 deg. in x- and y-directions, respectively. Fairly good agreement is attained between the tilt angles obtained from the moment method and those from the phase retrieval method in both directions.

5. Summary

The IR measurement system was accomplished for the alignment of transmission lines based on the moment and phase retrieval methods. Power linearity with respect to the temperature rise of the target plate was checked for target

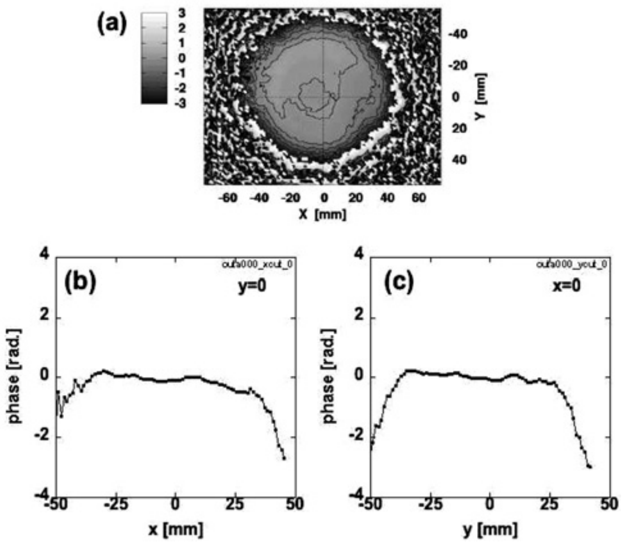

Fig. 11 (a) Contour plot of the retrieved phase for after precise alignment. Contours of constant phase are 1 rad. interval. The phase profiles along *x* axis and *y* axis are plotted in (b) and (c), respectively.

material. Preliminary measurement shows that calculated moments of the obtained IR images give sufficient information to adjust millimeter-wave beams to the waveguide. Phase reconstruction by using the IR data was performed and comparatively evaluated. Fairly good agreement was obtained between the results from the moment and those from the phase retrieval method. The effectiveness of these methods is demonstrated for the transmission alignment.

In the test, high power but short pulse millimeter-wave was used. The oscillation frequency of the gyrotron could be changed for long pulse operation (over hundreds of milliseconds), which is caused by the thermal expansion of the gyrotron cavity. The frequency change results in the change of beam direction from the output window. This leads to the setting error of the final mirror adjustment, and is a serious problem in this alignment method. One possible candidate solution to the problem is to use a low-loss material, such as, Teflon or alumina ceramics and low-loss silicon-nitride, for the target to withstand long pulse irradiation. Evaluation and modification of the IR image measurement used in the waveguide alignment method have to be continued.

The main issues remaining are miniaturization of the system and establishment of the algorithm to adjust the final mirror by the information from the analyzed data via feedback loop. The phase retrieval method has the potential to analyze mode purity and mode contents in the waveguide. Investigation of these aspects will be the subject of future work.

Acknowledgements

The authors gratefully acknowledge Prof. M. Sato and Prof. T. Watari at the National Institute for Fusion Science for useful discussion and continuous encouragement, and Prof. N. Noda and Prof. O. Motojima for promotion of the Japan-US collaboration.

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