Proceedings of ITC18, 2008

Analysis of Propagating Mode Contents in the Corrugated Waveguides of ECH System for Precise Alignment

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A new method is proposed to analyze mode contents of high power electromagnetic waves that are propagating through corrugated waveguides in the electron cyclotron resonance heating (ECH) system for nuclear fusion devices. The method was applied to a 168GHz transmission line of the ECH system in Large Helical Device (LHD) to evaluate the waveguide alignment. Mode contents of the propagating wave could be well analyzed using this method. Furthermore, the wave field in the waveguide was reconstructed using the obtained information of the each mode content.

Keywords: ECH, gyrotron, corrugated waveguide, mode analysis, phase retrieval

1 Introduction

Electron Cyclotron resonance Heating (ECH) is one of the most powerful heating methods for plasma heating and current drive in fusion-oriented plasma devices. The high power millimeter-waves for ECH are usually transmitted by over-sized circular corrugated waveguides. The length of such transmission lines becomes longer and longer due to the huge size of plasma confinement devices. In the over-sized corrugated waveguides, tilt and offset of the waveguide axis easily cause conversion of the transmitted mode of HE_{11} to unwanted modes. Improvement of transmission efficiency is essential in view not only of increase of usable power but reduction of heat load to the millimeter-wave components by Ohmic loss. For example, to suppress a mode conversion loss $< 1\%$, tilt angle and offset of the beam center should be less than 0.1 deg. and 2.9mm, respectively, for the 168GHz transmission through the corrugated waveguide 88.9mm in diameter [1]. We already proposed an alignment method of transmission lines based on infrared (IR) images on a target irradiated by high power millimeter-waves [2].

As a next step, it is important to identify propagating mode contents in the corrugated waveguides for clarifying what kind of misalignment induces such mode conversion. One method of the mode-content analysis has been already proposed by using the irradiant waveguide modes [3]. We will report another method of mode-content analysis and reconstruction of the wave field in the corrugated waveguide. Figure 1 illustrates a flow chart of the mode-content analysis. At first, a target plate, which is set several tens centimeter away from the open edge of the corrugated waveguide, is irradiated by a high power millimeter-wave. The temperature rise of the target plate is measured by IR camera precisely for several target positions. Next, the phase information is retrieved by the phase retrieval method [4]. In parallel with this, the first and second moments of the radiation pattern are calculated to evaluate the position of the power center and the waist size of the beam. Once the information of the amplitude and phase at the exit of the waveguide is determined, mode contents can be analyzed by orthogonal-mode expansion in the corrugated waveguide. Finally, the electric field in the waveguide can be reconstructed up to its entrance using the obtained mode contents and the phase factor of each constituent mode.

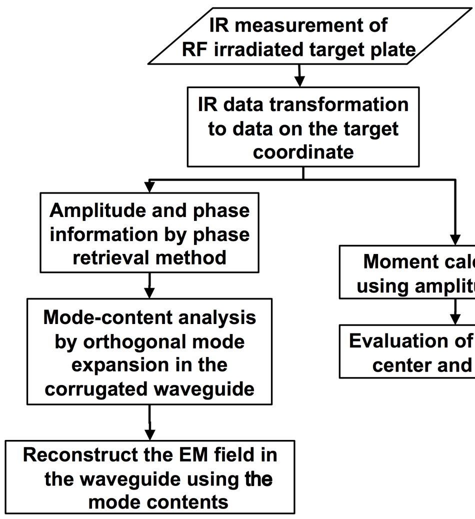

Fig. 1 A flow chart of the mode-content analysis and electric field reconstruction in the corrugated waveguide.

This paper is organized as follows. In Sec. 2, the

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method of mode-content analysis is described, and the results of its application to a 168GHz transmission line in LHD ECH system are given. In Sec. 3, a method and calculated results of the electric field reconstruction in the corrugated waveguide are described using the information of analyzed mode contents in Sec. 2, Finally, Section 4 will be devoted to a conclusion.

2 Method and Results of Mode-Content Analysis

In the process of designing phase correcting mirrors and performing waveguide alignment, the phase retrieval method was successfully used to reconstruct the phase information of the radiated waves using only measured intensity profiles at several positions [4]. By using the phase retrieval method, we can find the complex amplitude at radiating edge of the corrugated waveguide. It can be decomposed by the eigen modes in the corrugated waveguide. The expansion coefficients by the eigen modes give the mode contents of the corresponding eigen modes.

At the waveguide exit (z=0), the phase can be retrieved by the phase retrieval method. Such amplitude $A(x, y, 0)$ and phase $\varphi(x, y, 0)$ can be expanded by the orthogonal functions in the waveguide as,

$$A(x, y, 0)e^{j\varphi(x,y,0)} = \sum_{n=1}^{N} C_n e^{j\varphi_n} \phi_n(x, y) \quad (1)$$

, where C_n is the amplitude and φ_n is the phase of a mode n. On the contrary, the expansion coefficients are represented by

$$C_n e^{j\varphi_n} = \frac{\int_S A(x, y, 0)e^{j\varphi(x,y,0)} \cdot \phi_n^*(x, y)ds}{\int_S |\phi_n(x, y)|^2 ds}. \quad (2)$$

So, a fraction of the mode n, p_n, is calculated as,

$$p_n = \frac{|C_n|^2 \cdot \int_s |\phi_n|^2 ds}{\int_S |A|^2 ds} = \frac{|\int_S A(x, y, 0)e^{j\varphi(x,y,0)} \cdot \phi_n^* ds|^2}{\int_S |\phi_n|^2 ds \cdot \int_S |A|^2 ds}. \quad (3)$$

The eigen functions in an over-sized corrugated waveguide with the radius of a are approximately given by [5]

$$\phi_{n,m}^{even} = J_{n-1}(X_{n-1,m}\frac{r}{a}) \cdot \cos(n-1)\phi$$

$$\text{for } n, m = 1, 2, \cdots$$

$$\phi_{n,m}^{odd} = J_{n-1}(X_{n-1,m}\frac{r}{a}) \cdot \sin(n-1)\phi \quad (4)$$

$$\text{for } n = 2, 3, \cdots, m = 1, 2, \cdots$$

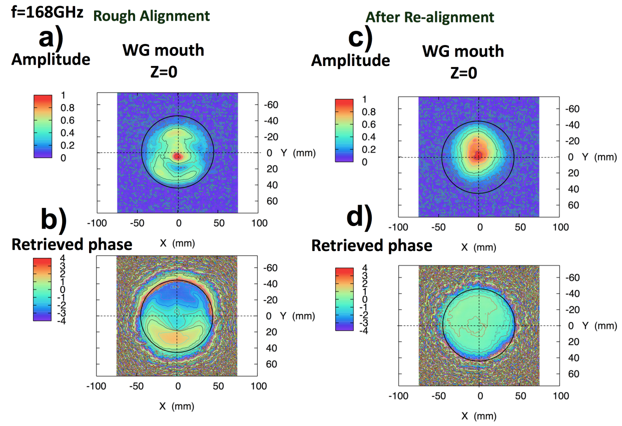

Fig. 2 Measured amplitude and retrieved phase at the radiating edge of the corrugated waveguide. The amplitude in a) and phase profile in b) for the rough alignment case. The amplitude in c) and phase profile in d) for the case after realignment.

Here, $X_{n-1,m}$ are m-th roots of Bessel function $J_{n-1}(X_{n-1,m}) = 0$ and $r = \sqrt{x^2 + y^2}, \phi = \tan^{-1}(y/x)$.

This method was applied to the 168GHz transmission line in the ECH system of LHD. Figure 2 shows measured amplitude and retrieved phase at the radiating edge of the circular corrugated waveguide. Figs. a) and b) correspond to the amplitude and phase profiles for the rough alignment case, respectively. Figs. c) and d) are the amplitude and phase profiles for the case after realignment of the waveguide. In the rough alignment case, the intensity pattern breaks into several peaks and the phase in the lower part is reverse to that in the upper part on the waveguide cross section. After realignment, the intensity profile was improved to be a Gaussian-like one and the phase distribution was almost constant.

These data were used for mode-content analyses. Figure 3 shows the analyzed mode contents of both cases in Fig. 2 for the orthogonal even- and odd-modes in the corrugated waveguide. In the rough alignment case, HE_{11} main propagating mode is only 13%. The major component is HE_{21} odd mode, which stems from the profile asymmetry with respect to x-axis as shown in Fig. 2 a) and b). HE_{12} mode of 18.5% is caused by a part of off-axis components in the amplitude profile. In the case after realignment, HE_{11} main propagating mode is recovered to dominate 89% and the other unwanted modes are HE_{21}/1.1%, HE_{12}/0.9% (even-mode) and HE_{21}/5.4% (odd-mode). The small fraction of HE_{21} odd mode attributes to the small offset of the intensity center from the waveguide axis in y-direction.

3 Field Reconstruction

On the contrary, the electromagnetic field at the arbitrary position, z, in the waveguide can be reconstructed by using the expansion coefficients of each eigen mode, $C_n e^{j\varphi_n}$, and

a) Rough Alignment Case

Mode	Even (%)	Odd (%)
HE11	**13.289**	**-**
HE12	**18.499**	-
HE13	0.337	-
HE14	0.584	-
HE15	0.173	-
HE21	0.440	**35.709**
HE22	0.213	**5.897**
HE23	0.020	0.451
HE24	0.064	0.986
HE25	0.022	0.218
HE31	**13.741**	0.723
HE41	0.465	**2.542**

b) After Re-alignment Case

Mode	Even (%)	Odd (%)
HE11	**88.841**	**-**
HE12	**0.910**	-
HE13	0158	-
HE14	0.118	-
HE15	0.161	-
HE21	**1.149**	**5.357**
HE22	0.140	**0.684**
HE23	0.079	0.131
HE24	0.012	0.086
HE25	0.036	0.177
HE31	**0.432**	0.048
HE41	0.147	0.021

Fig. 3 Results of mode-content analysis for even and odd modes in the corrugated waveguide.

propagation phase factor, $e^{(-j\beta_n z)}$, where β_n is a propagation constant of the mode n in the z-direction.

The amplitude and phase at the arbitrary z position in the corrugated waveguide are generally represented as follows,

$$A(x,y,z)e^{j\varphi(x,y,z)} = A_r(x,y,z) + jA_i(x,y,z) \quad (5)$$

$$= \sum_{n=1}^{N} C_n e^{j\varphi_n} \phi_n(x,y) \exp(-j\beta_n z) \quad (6)$$

, where

$$\beta_n = \sqrt{k^2 - \left(\frac{X_n}{a}\right)^2} \quad (7)$$

$$k = \frac{\omega}{c} = \frac{2\pi}{\lambda} \quad (8)$$

ω and λ are the angular frequency and wave length of a propagating wave, respectively. c is the speed of light. Finally the real and imaginary parts of the wave field, A_r and A_i, are expressed as follows,

$$A_r(x,y,z) = \sum_{n=1}^{N} \Big\{ C_n \cos\varphi_n \cos(\beta_n z) + C_n \sin\varphi_n \sin(\beta_n z) \Big\} \phi_n(x,y) \quad (9)$$

$$A_i(x,y,z) = \sum_{n=1}^{N} \Big\{ -C_n \cos\varphi_n \sin(\beta_n z) + C_n \sin\varphi_n \cos(\beta_n z) \Big\} \phi_n(x,y) \quad (10)$$

Figure 4 a) shows the intensity and phase profiles of the reconstructed field for the rough alignment case at several positions (z=0, -1.6m and -3.2m) as indicated in the illustration. The positions of z =-3.2m and z=0 correspond to the entrance and exit of a corrugated waveguide under test, respectively. In general, the n-th moment in the x-direction weighted by the intensity $A(x,y,z)^2$ can be defined as,

$$< x^n > (z) = \int x^n A^2(x,y,z) \mathrm{d}x\mathrm{d}y \Big/ \int A^2(x,y,z) \mathrm{d}x\mathrm{d}y \quad (11)$$

As a representative of the power density center, the first moment was calculated. The results are shown in Fig. 4 b). Since the beat wavelength between HE_{11} and HE_{21} (odd-mode), which is the most dominant mode among the unwanted modes, is about 9.8m, this results in a periodic change of the first moment $< y >$ of which period corresponds to about a beat wavelength. In x-direction, the non-axisymmetric unwanted even-mode of HE_{21} affects the value of $< x >$ and shows the same periodic change. Because HE_{12} is an axisymmetric mode, the first moment calculation is not affected by this mode.

Figure 5 a) shows the same intensity and phase profiles of the reconstructed field for the case after re-alignment. The peak position in the amplitude profile moves slightly in y-direction. This is due to the existence of the same dominant mode, HE_{21} (odd-mode). The phase pattern, however, keeps almost uniform along the waveguide axis. The first moment of the intensity profile are shown in Fig. 5 b). The changes of $< x >$ and $< y >$ show the same periodic change, and their periods correspond to the beat wave length between HE_{11} and HE_{21} (odd-mode). Although the center of intensity locates around the waveguide axis at the entrance, the calculated phase indicates an little inclined phase profile in the y-direction, which is about 0.3 degree. This caused a generation of the dominant unwanted mode of HE_{21} (odd-mode).

4 Conclusion

Mode contents of high power electromagnetic waves that are propagating through corrugated waveguide in ECH

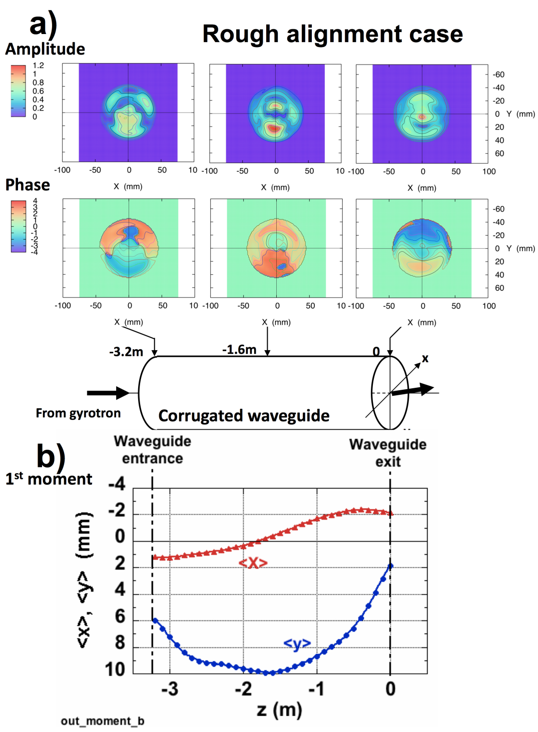

Fig. 4 For the rough alignment case, a) contour plot of amplitude and phase of reconstructed electric field at several positions (z=0, -1.6m and -3.2m) in the corrugated waveguide and b) the first moment calculation for x- and y- direction are given.

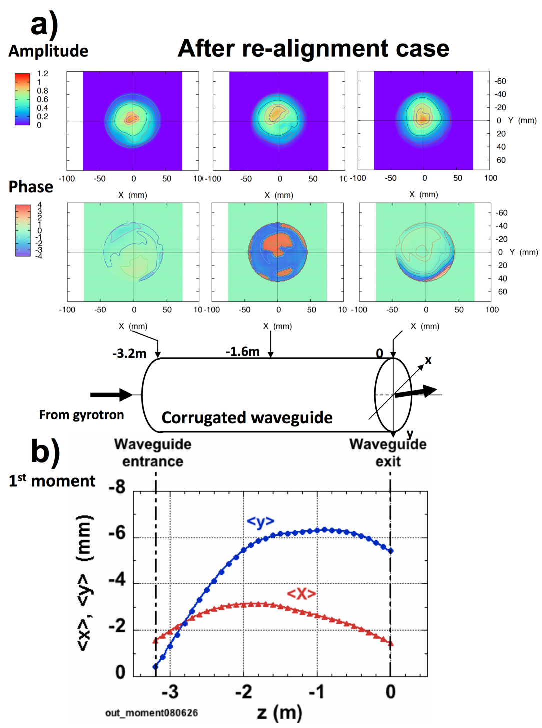

Fig. 5 For the case after re-alignment, a) contour plot of amplitude and phase of reconstructed electric field at several positions (z=0, -1.6m and -3.2m) in the corrugated waveguide and b) the first moment calculation for x- and y- direction are given.

system could be well analyzed using retrieved phase information, and the wave field in the waveguide was reconstructed on the basis of the complex amplitude of each eigen mode. The advantage of this method is that the used data are measured in the same configuration as the actual transmission system and as the same high power level. The obtained results can be useful to analyze the possible cause of degradation of transmission efficiency.

Two cases of the rough alignment and after realignment of the wave coupling were analyzed using this method as examples. The results of mode-content analysis clearly give the cause of misalignment between the incident beam axis and the waveguide axis. Subsequent field reconstruction in the waveguide gives the change of the field propagating through the waveguide and an unobservable phase information of the incident wave at the waveguide entrance. In special, the phase information at the waveguide entrance gives a good guidance for alignment. It was found that a burn-pattern measurement at two positions was insufficient for the beam alignment, because the center of measurable intensity distribution changes with a period of beat wavelength between the related modes. This suggest that burn-pattern measurement should be performed at several positions, quarter beat wave length between the main mode and unwanted modes, in special.

Acknowledgment

The authors gratefully acknowledge Professors A. Komori, S. Sudo and O. Motojima for their continuous guidance and encouragement. This work has been supported by NIFS under NIFS08ULRR501, 502, 503, and was partly performed under the collaboration organized by NIFS(NIFS08KCRR004). This work was also supported by Grant-in-Aid for Scientific Research from Ministry of Education, Science and Culture of Japan (19560051).

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