Matching of a non-Gaussian gyrotron output beam to an ECRH transmission line using thermographic measurements

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Abstract

Measurements of the power distribution of a 140 GHz gyrotron beam have been performed by recording the temperature profiles on a target plate by an infrared camera. On the basis of these measurements, a reconstruction of the phase distribution of the beam has been performed using an iterative technique. From the knowledge of the complete electric field distribution, phase-correcting mirrors have been designed in order to couple the beam to an HE_{11} mode in an oversized corrugated waveguide.

Introduction

At the stellarator experiment W7-AS of IPP Garching new gyrotrons operating at 140 GHz with an output power of 0.5 MW and a pulse length of up to 2 s have been installed. In these tubes the output power is coupled through a laterally mounted single disc boron nitride window which is circumferentially cooled. In order to reduce the thermal stress of this window during long pulse operation these gyrotrons have special mirrors inside the tube to produce a flattened power profile instead of a profile peaked in the centre of the window. This means that the emitted beam contains not only the fundamental free-space mode (Gaussian beam, TEM_{00}) but also higher order free-space modes. These modes are not useful for further transmission of the millimetre wave power in a corrugated waveguide system. To get optimum coupling to the HE_{11} mode of a corrugated waveguide, a transformation of the gyrotron output with two phase-correcting mirrors to a single-mode beam (fundamental Gaussian beam) is necessary. To calculate the surface of these mirrors, the amplitude and phase profiles of the output beams of the gyrotrons are required.

Experimental set-up

Figure 1 shows the experimental set-up for the measurement. A PVC-plate has been used as microwave target for the temperature measurement. This PVC-plate has a corrugated surface in order to minimise reflections back to the gyrotron. Four light emitting diodes serve as markers for the alignment of the pictures to each other and to be able to rectify the pictures from the oblique view of the camera. Since the microwave absorption of PVC depends on temperature, a calibration is required. The measurements of the beam profiles have been performed with a PtSi focal plane array camera with a thermal resolution of 0.1 °C and a spatial resolution of the order of 0.5 mm. The images have been recorded digitally (244 x 320 pixels, 12 bit). A typical gyrotron pulse with a reduced power of 200 kW and a length of 9 ms heats the target plate up to a maximum temperature of 70 °C. Thermal convection and cooling down of the target can be neglected during the frame time of the camera of 40 ms. The transmitted power of the gyrotron beam has been absorbed in a dummy load. At the end of the measurement procedure a series of 8 thermal images taken at different distances z from the gyrotron window were available for reconstruction of the phase and amplitude distribution of the beam (see Fig. 2).

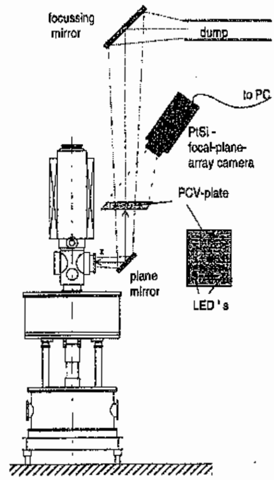

Fig. 1: Experimental set-up

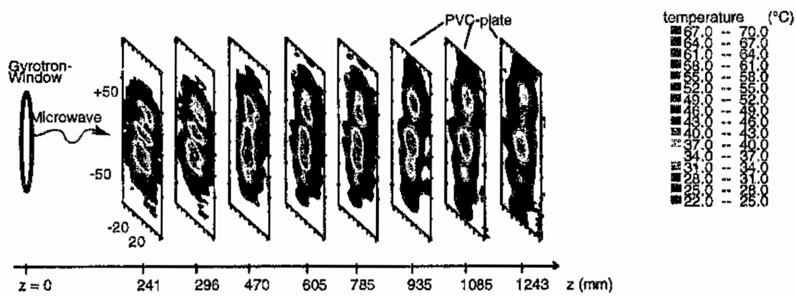

Fig. 2: Temperature profiles of the PVC-target, measured at different distances from the gyrotron window

Phase reconstruction

The reconstruction of the phase on the basis of the amplitude distribution at two different cross sections is possible with an iteration algorithm [1,2]. This algorithm is schematically shown in Fig. 3.

The amplitude distributions $|E_1(x,y)|^2$ at z_1 and $|E_2(x,y)|^2$ at z_2 are given by measurements. E_1 is multiplied with a complex phasor, $u_1 = E_1 e^{i\varphi_1}$, which is arbitrary in the first step, and the free space propagation of this field to $z = z_2$ is calculated, resulting in $\tilde{u}_2 = \tilde{E}_2 e^{i\varphi_2}$. Replacing $\tilde{E}_2$ by the measured amplitude E_2 ($u_2 = E_2 e^{i\varphi_2}$) and calculating the free-space propagation back to z_1 yields $\tilde{u}_1 = \tilde{E}_1 e^{i\varphi_1}$. This procedure is repeated several times. In each step one combines the phase factor with the measured amplitude pattern and neglects the calculated amplitude pattern. The convergence is defined by means of a matching coefficient

$$\eta_k = \frac{\left[\int \tilde{E}_k \cdot E_k \, dx dy\right]^2}{\int \left|\tilde{E}_k\right|^2 dx\, dy \cdot \int \left|E_k\right|^2 dx\, dy}.$$

A typical value for η_k of 97-98 % is achieved.

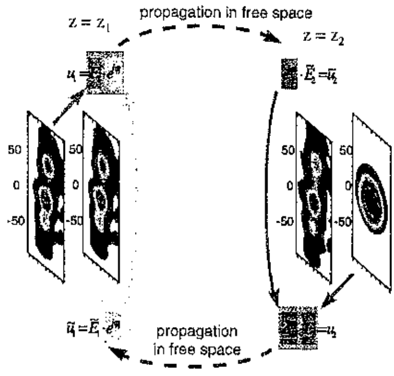

Fig. 3: Phase Reconstruction algorithm

Figure 4 shows the comparison of two measured amplitude distributions with the corresponding patterns resulting from the reconstruction.

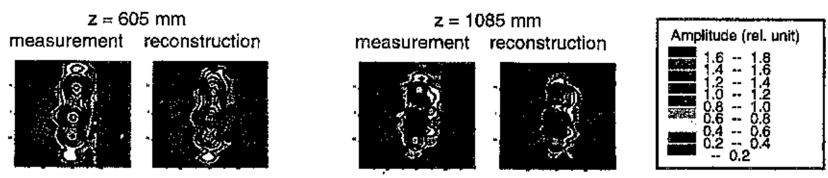

Fig. 4: Comparison of two measured amplitude distributions with the corresponding patterns resulting from the beam reconstruction

Design of the matching mirrors

The reconstruction algorithm has been also used to find the distribution of phase shift for the two matching mirrors with given field at the position of the first mirror and the wanted field (TEM_{00}) at the position of the waveguide input after the second mirror. From the phase $\varphi(x,y)$ the mirror surface $z(x,y)$ is given by

$$z_{mirror}(x,y) = \frac{\lambda}{4\pi} \cdot \frac{1}{\cos(\alpha)} \cdot \varphi\left(x, \frac{y}{\cos(\alpha)}\right)$$

where α is the angle of incident. To get a smooth surface without steps it is possible to add multiples of 2π. Since the amplitude measurement is not perfect and since we work in two dimensions it can happen that the reconstruction leads to a continuous complex phase factor that can not be transformed to a real continuous phase shift. This may lead to steps which cannot be smoothed afterwards. However, by filtering of high Fourier components during the free space propagation it is possible to avoid these steps.

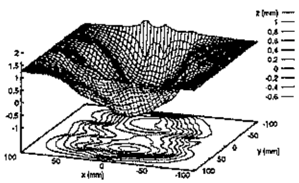

Fig. 5a: Surface of phase correcting mirror M1

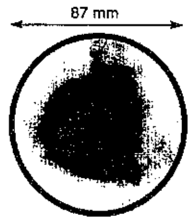

Fig. 5b: Burn pattern at the waveguide entrance

Results

Since the measured temperature pattern is changing its structure with increasing distance z from the output window due to enhanced divergence of the higher order modes it is most advantageous to evaluate pictures taken as close as possible to the window flange. The calculations showed that the Gaussian content of the gyrotron output beam is 78 %, this value has been theoretically increased up to 96 % with the technique described above. Figure 5a shows the contour of the first phase correcting mirror installed in the system. The burn pattern at the entrance of the corrugated waveguide is given and in Fig. 5b. Up to now the system has been tested with a power of up to 680 kW and a pulse length of up to 2 s with 500 kW using mirrors designed on the basis of these measurements by the Institute of Applied Physics, Nizhny Novgorod.

Summary

Thermographic measurements with high dynamic range allow a precise reconstruction of the complex field of a gyrotron beam. Based on this field, mirrors have been designed to convert the multi-mode output beam to a nearly Gaussian mode.

References

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