Recent Progress in Optimizing Phase-Correcting Mirrors for a Multi-Frequency Gyrotron

X. Yang [1], A. Arnold [1,2], G. Dammertz [1], K. Koppenburg [1], M. Thumm [1,2]

[1] Forschungszentrum Karlsruhe, Association EURATOM-FZK, IHM, D-76021 Karlsruhe, Germany
[2] also Universitaet Karlsruhe, IHE, Kaiserstr. 12, D-76128 Karlsruhe, Germany
e-mail: xiaokang.yang@ihm.fzk.de . Tel: (49) 07247-822455

Abstract — **For a multi-frequency 1 MW short pulse gyrotron at Forschungszentrum Karlsruhe (FZK), the existing adapted phase-correcting mirrors (on the basis of plane mirror surfaces) of an internal beam-shaping mirror system have been modified in order to reduce potential diffraction losses, which may be introduced during the procedure of mirror fabrication, due to the requirement of very strong perturbations on the mirror surfaces in order to obtain a small beam radius at the gyrotron Brewster output window. This paper describes the steps to design two adapted phase-correcting mirrors on the basis of smooth elliptical mirrors with quadratic surface contour function. Simulation results show for these newly improved phase-correcting mirrors, that the perturbations on the surfaces of the elliptical mirrors are obviously reduced. For all nine operating modes from $TE_{17,6}$ at 105 GHz to $TE_{23,8}$ at 143.3 GHz, a nearly fundamental Gaussian distribution at the gyrotron output window is predicted.**

I. Introduction

In nuclear fusion devices, the availability of MW gyrotrons with fast frequency step tunability permits the use of a simple fixed, non-steerable mirror antennas for local electron cyclotron resonance heating and current drive at different magnetic fields, as well as gives more flexibility for the stabilization of neo-classical tearing modes (NTM) through the possibility of current drive without changing the magnetic field. For plasma stabilization in the ASDEX-Upgrade tokamak, there is great interest in step-tunable gyrotrons operating at frequencies between 105 GHz and 140 GHz [1]. For this purpose a multi-frequency test gyrotron is under construction at FZK in a cooperative parallel development with the Institute of Applied Physics in Nizhny Novgorod, Russia [2-4]. The complementary key tasks for FZK are the development of: a cavity operating in a wide range of magnetic fields and with proper choice of a set of operating modes with the same direction of rotation; a broadband quasi-optical mode converter transforming all operating modes into a fundamental Gaussian beam with low diffraction losses; an ultra-broadband CVD-diamond Brewster window and a low power cold test measurement set-up.

Due to the large Brewster angle of 67.2^o, the maximum effective window diameter for currently available CVD-diamond disks (140 mm diameter) is about 50 mm, and the length of the waveguide to house the disk is 149 mm [5]. This window configuration adds a strict requirement for the gyrotron output beams with different frequencies.

At the GeMic-2005 conference [6], we reported about how to design two adapted phase-correcting mirrors on the basis of plane mirror surfaces to match the requirement of the small effective diameter (50 mm) at the Brewster window. The surfaces of these adapted phase-correcting mirrors are shown in Fig.1. From theoretical view, this design is reasonable; a very good fundamental Gaussian output beam has been predicted. However, the adapted phase-correcting mirrors require accurate mirror fabrication and alignment. But in practice, diffraction losses may be introduced due to the procedure of mirror fabrication by a numerically controlled milling machine because of the tolerances of the very strong perturbations on the mirror surfaces. Preliminary cold measurements have shown higher sensitivity of the output beams on the alignment of the mirror system, and relatively high diffraction losses. In order to increase the tolerance of the adapted phase-correcting mirrors during the procedure of fabrication and alignment, it is necessary to re-design new phase-correcting mirrors on the basis of smooth mirrors with curved surfaces for our 1MW multi-frequency gyrotron.

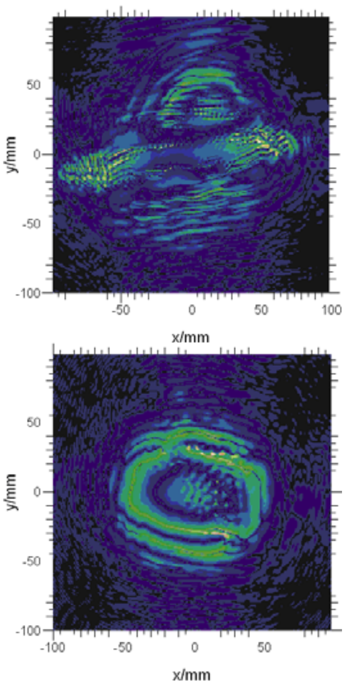


Fig. 1. Mirror surface of existing adapted phase-correcting mirror2 (upper) and phase-correcting mirror3 (lower).

II. BEAM-FORMING MIRROR SYSTEM WITH SMOOTH CURVED SURFACES

Same as in the case of [6], we keep the launcher and the first quasi-elliptical mirror unchanged while modifying the last two mirrors in order to fit the requirements of the new CVD-diamond Brewster window. Conventional smooth mirrors with curved surfaces, such as toroidal or elliptical mirrors are widely used as beam-forming mirrors to obtain the desired fundamental Gaussian distribution at the gyrotron output window. These mirrors are inexpensive, easy to manufacture, and also relatively easy to align. In the case of toroidal mirrors, the positions and the orientations of the mirrors are found by evaluating the moments of the first and second order of the power distribution. This design technique requires knowledge of both the amplitude and the phase distribution of the input beam and the desired output beam. The design procedure is: (1) back propagate the desired beam onto the last mirror; (2) generate the resulting amplitude distribution with the first and second mirrors; (3) generate the resulting phase distribution with the last mirror. This design procedure incorporates a fast scalar diffraction code for nonparallel apertures, which allows a rapid synthesis of the mirror profiles. In the case of the $TE_{28,8}$ mode 140 GHz prototype gyrotron of FZK, two toroidal mirrors have been used as the beam-forming mirror system [7]. Both simulations and cold measurements have shown that an efficiency of more than 98% has been achieved to convert the $TE_{28,8}$ cavity mode at 140 GHz into a fundamental Gaussian beam.

Extensive calculations have been done to optimize the two elliptical mirrors. Results show that the optimized mirror surface contours depend strongly on frequency, beam radius at the window, distance between window and the last mirror, angle of incidence and quality of the RF beam from the launcher and the first quasi-elliptical mirror. Fig. 2 shows the surface contours of the two optimized elliptical mirrors.

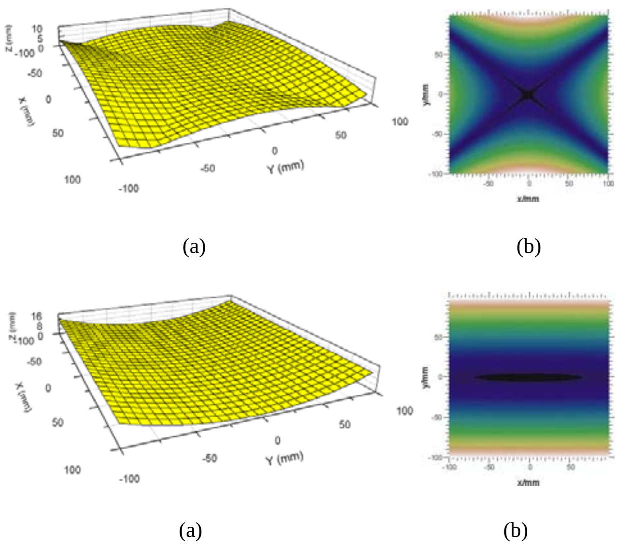
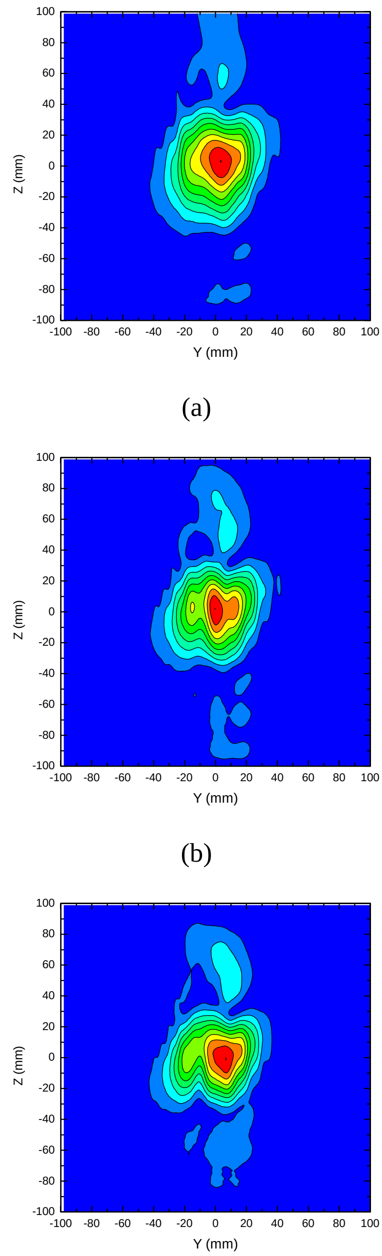


Fig. 2. Calculated mirror surface (a) and surface contour (b) of elliptical mirror 2 (upper) and elliptical mirror 3 (lower).



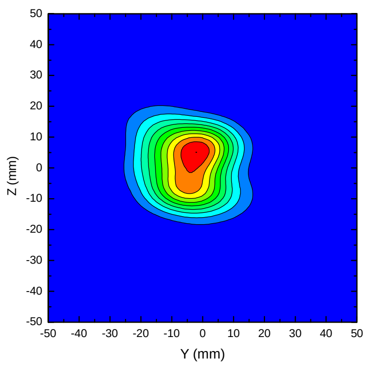
(c)

Fig. 3. Calculated field distribution on the last mirror. Normalized field contours are shown in linear scale with 0.1 increments from the peak: (a) $TE_{17,6}$ mode, (b) $TE_{20,7}$ mode, (c) $TE_{22,8}$ mode.

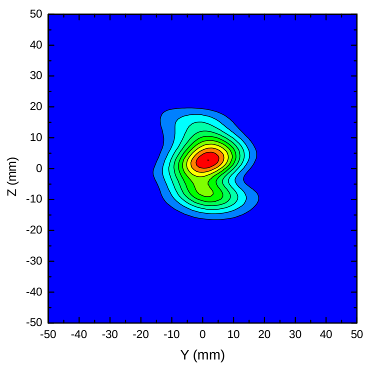
On the basis of the two smooth surface elliptical mirrors shown in Fig.2, we can calculate the field and power distributions on the last mirror and at the middle position of the Brewster window. Fig. 3 shows some examples of field distributions on the last mirror for the modes $TE_{17,6}$ at 105 GHz, $TE_{20,7}$ at 124.1 GHz and $TE_{22,8}$ at 140 GHz respectively. All other operating modes present nearly same beam patterns as shown in Fig.3.

From Fig. 3 one can see that all beams have a near Gaussian-like distribution; but due to the non-optimized launcher the beam quality is not good and there are sidelobes around the main beam. Thus diffraction losses would be introduced. In order to reduce diffraction losses, the launcher should be redesigned (with lower overmode factor of 1.07 instead of 1.17). Highly efficient quasi-optical mode converters should have both an optimized launcher and an optimized beam-forming mirror system.

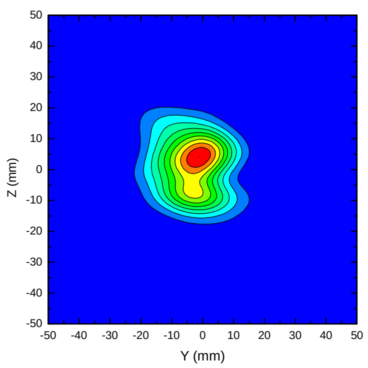
The third elliptical mirror adjusts the beam patterns to the output window. Fig. 4 shows power distributions at the middle position of the CVD-diamond Brewster window. The beams shift by ±5 mm in horizontal direction around the center of the window plane. Unfortunately this beam-forming mirror system has no broadband characteristics; it can not match the requirement of small effective window diameter for all nine operating modes.



(a)



(b)



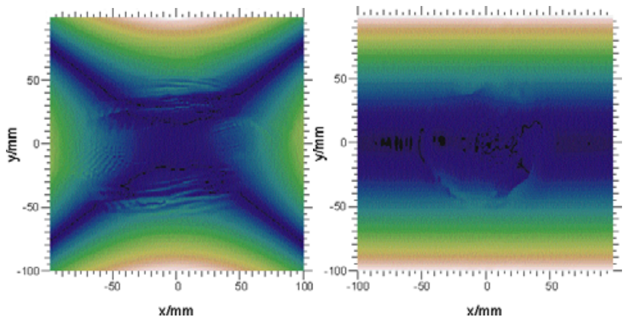
(c)

Fig. 4. Calculated power distribution at the middle position of the Brewster window. Normalized power contours are shown in linear scale with 0.1 increments from the peak: (a) $TE_{17,6}$ mode, (b) $TE_{20,7}$ mode, (c) $TE_{22,8}$ mode.

III. BEAM-FORMING MIRROR SYSTEM WITH ADAPTED PHASE-CORRECTING SURFACES

On the basis of the mirror system with two smooth elliptical mirrors described in section II, we can further optimize this system employing a numerical procedure such as the extended Katsenelenbaum-Semenov algorithm [8] to obtain adapted phase-correcting mirrors which have broadband characteristics. The optimization process is nearly in the same way as what we used in [6], the only difference is that we set conventional elliptical mirrors as the initial mirror surfaces for the optimization rather than plane mirror surfaces.

Fig.5 shows the surface contours of the two optimized adapted phase-correcting mirrors. A comparison with Fig.2 shows clearly that there are only small perturbations on the mirror surfaces. This may reduce the diffraction losses introduced by tolerances in mirror fabrication, and also reduce the sensitivity of mirror alignment.



(a) (b)

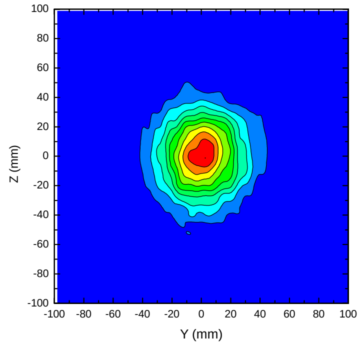
Fig. 5. Calculated surface contour of adapted phase-correcting mirror 2 (upper) and phase-correcting mirror 3 (lower).

Fig. 6 shows field distributions on the surface of the last phase-correcting mirror. It is very clear that after the adjustment of the second phase-correcting mirror, all the beams present near fundamental Gaussian distribution.

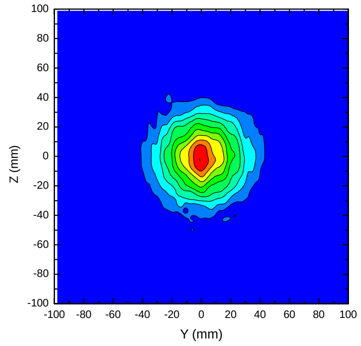
The third phase-correcting mirror adjusts the beam patterns to the gyrotron output window. Fig. 7 shows the power distributions. In comparison to the beam patterns in Fig.4, adapted phase-correcting mirrors can be used for gyrotron broadband operation and give much better fundamental Gaussian pattern than elliptical mirrors do.

IV. CONCLUSIONS

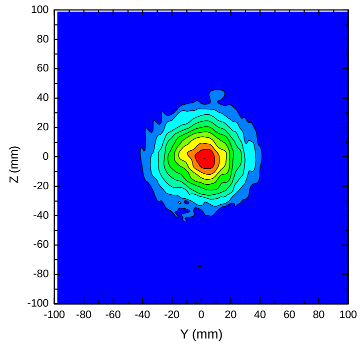
Two adapted phase-correcting mirrors have been redesigned on the basis of two elliptical mirrors with smooth surfaces. There are only small perturbations on the mirror surfaces, and near fundamental Gaussian distribution for all nine operating gyrotron modes is predicted by the simulations. This design may reduce the diffraction losses introduced during mirror fabrication and make the alignment of mirror system less sensitive.



(a)

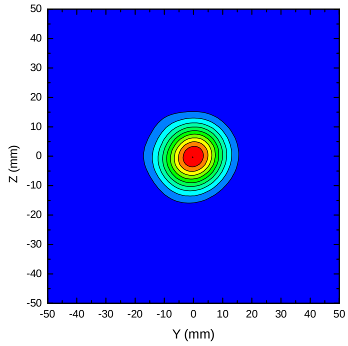


(b)

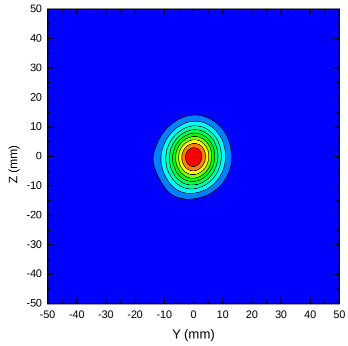


(c)

Fig. 6. Calculated field distribution on last mirror. Normalized field contours are shown in linear scale with 0.1 increments from the peak: (a) $TE_{17,6}$ mode (105 GHz), (b) $TE_{20,7}$ mode (124.1 GHz), (c) $TE_{22,8}$ mode (140 GHz).



(a)



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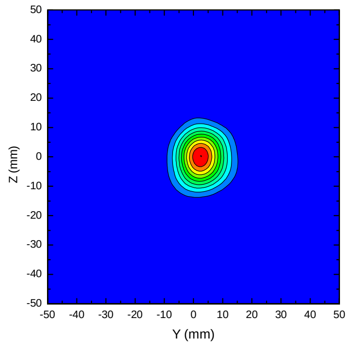

(c)

Fig. 7. Calculated power distribution at middle position of the Brewster window. Normalized power contours are shown in linear scale with 0.1 increments from the peak: (a) $TE_{17,6}$ mode, (b) $TE_{20,7}$ mode, (c) $TE_{22,8}$ mode.

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