Design of a step-tunable 105-140 GHz, 1 MW gyrotron at FZK

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Abstract

A prototype of a multifrequency step-tunable 1MW gyrotron for controlling plasma instabilities in fusion tokamaks has been designed. It operates in the $\mathsf{TE}_{22,8}$ mode at 140 GHz, the $\mathsf{TE}_{17,6}$ mode at 105 GHz and 7 other modes in between. The last design results of the Brewster window design and experimental results of the cold measurements are presented.

1. Introduction

For plasma stabilization in nuclear fusion devices such as the ASDEX-Upgrade tokamak, there is an interest in step-tunable gyrotrons operating at frequencies between 105 GHz and 140 GHz [1]. For this purpose a multifrequency gyrotron is under investigation at Forschungszentrum Karlsruhe (FZK) in a cooperative development with the Institute of Applied Physics in Nizhny Novgorod, Russia [2]. A prototype of the multifrequency step-tunable 1MW gyrotron for controlling plasma instabilities in fusion tokamaks has been designed.

Calculations for the cavity design were performed with the numerical codes BFCRAY and ESRAY including constraints which results from use of the present electron gun and cryomagnetic system. The cavity has quadratic roundings on the input and output taper. Lengths and angles are similar to the geometry which is used in the W7-X gyrotron [8]. The cavity radius is 17.96mm.

The quasi-optical mode converter of the gyrotron consists of a dimpled-wall antenna and a beamforming mirror system optimized for 9 modes from $\mathsf{TE}_{17,6}$ to $\mathsf{TE}_{23,8}$. For these modes the dimpled-wall antenna shows a well focused beam with low diffraction of the radiation pattern compared to a simple waveguide cut antenna. The first mirror is a large quasi-elliptical one, the second and third are phase correcting mirrors with a non-quadratic shape of the surface. These two mirrors were also optimized for broadband operation in the design modes.

To check the new design of the quasi-optical mode converter, cold test measurements have been performed recently. For this purpose a quasi-optical high-order mode generator was used. To improve the mode selection, the generator contains an inner central rod, like it is also done in a coaxial cavity.

Efficient operation for the large number of operating modes at different frequencies is possible by using a broadband chemical vapor deposited (CVD) diamond Brewster window. First measurements on a 1.923mm thick, 120mm diameter disc from Element Six (former DeBeers) showed a homogeneous distribution of the loss tangent in an area, which can be used for the elliptic shape of a Brewster window.

2. Cavity design

Calculations for the cavity design were performed with the numerical codes BFCRAY [3] and ESRAY which includes constraints which results from use of the present electron gun and cryomagnetic system. The possible cavity modes are shown in Fig. 1. For these modes a cavity with quadratic roundings on the input and output taper was designed [3]. Lengths and angles are similar to the geometry which is used in the W7-X gyrotron [1]. The cavity radius is 17.96mm. Table 1 gives the resonant frequencies, beam radius and the quality factors for the modes of interest.

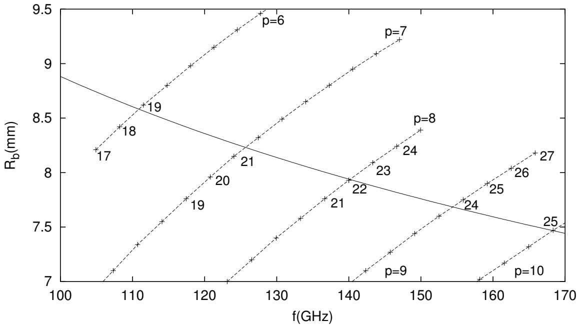

Figure 1: Beam radius R_b as a function of possible output frequencies ($TE_{m,p}$modes). Also shown is the curve $R_b = R_{b0}(140/f)^{1/3}$ for diode guns.

TE-mode	frequency [GHz]	R_b [mm]	Q
17,6	105.0	8.21	551
18,6	108.4	8.42	586
19,6	111.6	8.62	620
19,7	120.9	7.96	714
20,7	124.2	8.15	744
21,7	127.4	8.32	773
21,8	136.7	7.76	851
22,8	140.0	7.93	881
23,8	143.4	8.09	915

Table 1: Cavity modes with resonant frequency, beam radius and quality factor.

3. Quasi-optical mode generator

Very good performance of high-order mode generators for cold tests has been found by using a quasi-optical design [4]. A Gaussian-like beam is coupled via two cylindrical lenses and a quasi-parabolic caustic mirror into a perforated gyrotron-like coaxial resonator (Fig. 2). The caustic mirror is shaped in a way, that all waves are tangent to the so-called caustic of the mode. As the eigenvalues of an overmoded resonator are very close to each other, an inner rod is used to improve the mode selection (coaxial resonator). A more detailed description of the setup and the performed measurements will be given in [5].

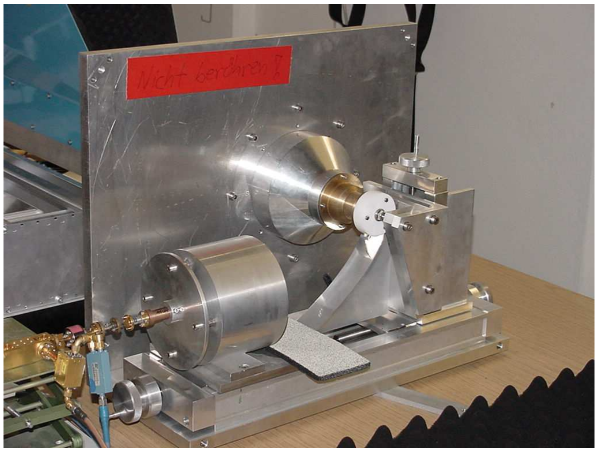

Figure 2: High-order mode generator with quasi-optical design.

4. Quasi-optical mode converter

For the quarz glas Brewster window the quasi-optical mode converter of the gyrotron consists of a dimpled wall antenna and a beamforming mirror system optimized for the modes given in Table 1. For these modes the dimpled wall antenna shows a well focused beam with low diffraction of the radiation pattern compared to a simple waveguide cut antenna. The first mirror is a large quasi-elliptical one, the second and third are phase correcting mirrors with a non-quadratic shape of the surface. These two mirrors were also optimized for broadband operation in the 9 design modes [6].

At present for the new design of a CVD-diamond Brewster window a modified quasi-optical mode converter is under development.

5. Low power measurements

To check the design of the quasi-optical mode converter, cold test measurements have been performed recently [5]. For the $\mathsf{TE}_{22,8}$-mode the calculated field pattern (Fig. 3) showed a good agreement with the measured output beam at the position of the window (Fig. 4). Since two sets of quasi-optical output systems have been machined and a comparison of both sets showed practically the same results one set can be used to continue the low power measurements while the other set is used in the gyrotron.

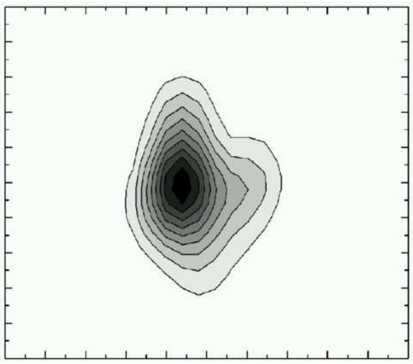

Figure 3: Calculated field pattern of the $\mathsf{TE}_{22,8}$-mode at window position.

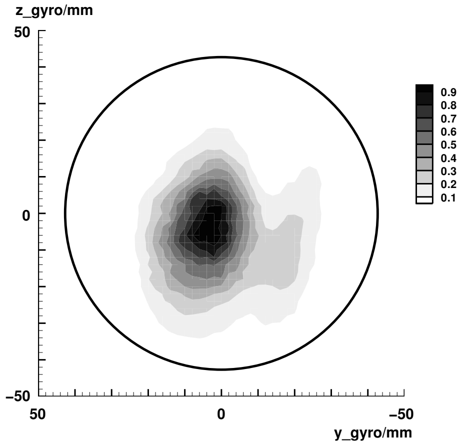

Figure 4: Measured field pattern of the $\mathsf{TE}_{22,8}$-mode at window position.

6. CVD-diamond Brewster window

Efficient operation for a large number of operating modes at different frequencies is possible by using a broadband chemical vapor deposited (CVD) diamond Brewster window. But even tough the manufacturing of 100mm diameter discs seems to be no problem for the industry, an order of two 140mm diameter discs, one at the Fraunhofer Institute in Freiburg, Germany and one at Element Six (former Debeers), reveals many difficulties in the production process of large CVD-discs. CVD-diamond has a large value of $\epsilon_{\mathsf{r}} = 5,67$, thus the Brewster angle of 67,22° is also very large. This has two effects: A large CVD-diamond disc window is necessary and the waveguide for output beam in which the disc is mounted is getting longer compared to other window materials. For these reasons it is an important task to minimize the demands of window size by optimizing the Gaussian beam parameters. That is to choose the minimum RF beam radius at the input and output of the waveguide.

To get the minimum beam radius $\mathsf{R}_{\mathsf{min}}$ of a Gaussian beam at a distance of z (z=0 describes the position of the beam waist) we take the partial derivative with respect to r_0 of the well known formula for a Gaussian beam radius $\mathsf{r(z)}$ (1) and equate it to zero (2). This yields the waist of the beam (3), which gives a minimum beam radius at the position z. For this minimum beam radius $\mathsf{R_{min}(z)}$ the beam waist calculates as the beam radius divided by $\sqrt{2}$ (4).

$$r(z) = r_0 \cdot \sqrt{1 + \frac{\lambda \cdot z}{\pi \cdot {r_0}^2}} \tag{1}$$

$$\frac{\partial r(z)}{\partial r_0} = 2 \cdot r_0 - 2 \cdot \frac{\lambda^2 \cdot z^2}{\pi^2 \cdot {r_0}^3} = 0 \tag{2}$$

$${r_0}^2 = \frac{\lambda \cdot z}{\pi} \tag{3}$$

$$R_{min}(z) = \sqrt{2} \cdot r_0 \tag{4}$$

Assuming that a brazed 140mm disc under the Brewster angle has an effective waveguide diameter of 50mm and half of the effective length is 74,5mm one can calculate by using formula (3) if it is possible to generate a suitable Gaussian beam for the window mounting. Using the effective half length l of the window, the minimum RF-output beam radius $\mathsf{R_{min}(l)}$ at the end of the window housing for 140 GHz is calculated to 10,1mm and for 105 GHz it is 11,6mm. Considering, that the horizontal position of the beam at the center of the window changes for different modes one has to calculate which deviation v of the beam in the output waveguide can be allowed. The part $\mathsf{P_{outer}}$ of a Gaussian beam with the radius of $\mathsf{R_{min}}$ which is cut at an aperture of $\mathsf{r_{eff}}$ is calculated by (5). For a part of 0.1% outside the aperture one obtains a ratio of $\mathsf{r_{eff}} = 1,858 \cdot \mathsf{R_{min}}$.

$$P_{outer} = e^{-\frac{2 \cdot r_{eff}^2}{R_{min}^2}} \tag{5}$$

From this, one can give an upper estimation for the beam losses. For the calculation according to (5 a concentric arrangement is used but the radius of the aperture is reduced by the deviation (Fig. 5). At the frequency of 105 GHz and a beam deviation of 3.5mm, the reflected power is obout 0.1% of the output power. This has to be taken into account for the new design of the quasi-optical mode converter system for a CVD-diamond Brewster window.

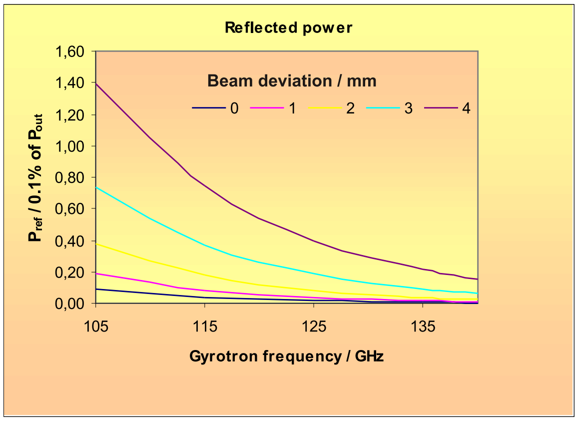

Figure 5: Calculated power losses versus output frequency at different beam deviations for a 140 mm CVD-diamond Brewster window.

A 1.923mm thick with 120mm diameter disc from Element Six is available at FZK. It shows a homogeneous distribution of the loss tangent in an elliptic area, which can be used for the elliptic shape of a Brewster window [7]. The measured values of the complete disc are between about $2 \cdot 10^{-5}$ and $8 \cdot 10^{-5}$. The meridian of the loss tangent is $3.6 \cdot 10^{-5}$.

A disc with a diameter of 140mm has been grown at Element Six. The disc has two small cracks so that only an elliptic area of about 140x75mm can be used. In the near future there will be a measurement of the loss tangent at FZK.

The details of the planned brazing process of the diamond disc are similar to them for W7-X [8]. The window housing is shown in (Fig. 6). First the diamond disc will be brazed on a copper tube. The thickness of this tube is very thin so that an introduction of mechanical stresses will be avoided. The copper tube will then be brazed on a nickel part and this construction again on the stainless steel housing.

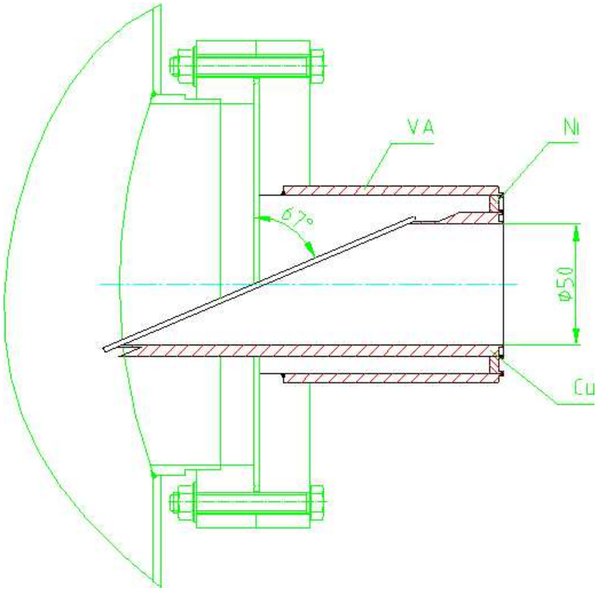

Figure 6: Technical drawing of a planned arrangement of the new CVD-diamond Brewster window.

7. Present state of project

For the tunable short-pulse gyrotron some major parts of our $\mathsf{TE}_{22,6}$-mode gyrotron [8], especially the electron gun, the beam tunnel, the mirror box, the collector and the housing will be re-used. The cavity, the dimpled wall launcher and the three beam-forming mirrors were newly designed. A new frequency tunable mode generator has been constructed to realize low power measurements of the quasi-optical output system. First measurements have been successfully performed. Also a 120 diameter CVD diamond disc for the Brewster window is available at FZK. A second disc with a diameter of 140mm will hopefully be available in the near future. At present a new quasi-optical mode converter for a CVD-diamond Brewster window is under development.

References

[1] G. Dammertz et al.: *Development of a 140 GHz, 1 MW, continous wave gyrotron for the W7-X stellarator*, Frequenz, Zeitschrift für Telekommunikation, Band 55, pp. 270-275, (2001).

[2] V.E. Zapevalov et al.: *Test results of the prototype for frequency step tunable 105-170 GHz 1MW gyrotron*, 12th Joint Workshop on ECE and ECRH, Aix-en-Provence, (France), pp. 523-528, (2002).

[3] E. Borie et al.: *Possibilities for multifrequency operation of a gyrotron at FZK*, IEEE Trans. on Plasma Science, Vol 30, No. 3, pp. 828-835, (2002).

[4] N.L. Alexandrov et al.: *Selective excitation of high-order modes in circular waveguides*, Int. Journal of Infrared and Millimeter Waves, **13**, pp. 1369–1385, (1992).

[5] A. Arnold et al.: *Low power measurements on a mode converter system of step-tunable gyrotrons*, This conference (2003).

[6] O. Drumm et al.: *Design methods for mirrors in a quasi-optical mode converter for a frequency step-tunable gyrotron*, 27th Int. Conf. on Infrared and Millimeter Waves, San Diego, (USA), Conf. Digest, pp. 191-192, (2003).

[7] K. Koppenburg et al.: Design of a multi-frequency high power gyrotron at FZK , 27th Int. Conf. on Infrared and Millimeter Waves, San Diego, (USA), Conf. Digest, pp. 153-154, (2003).

[8] G. Dammertz et al.: *Recent results of the 1 MW 140 GHz,* $\mathsf{TE}_{22,6}$*-mode gyrotron*, IEEE Trans. on Plasma Science, Vol 27, No. 2, pp. 330-339, (1999).