Investigation of a Broadband Quasi -Optical Mode Converter for a Multi-frequency 1 MW Gyrotron

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Abstract

A broadband quasi-optical (QO) mode converter for a multi-frequency gyrotron has been designed and tested at Forschungszentrum Karlsruhe (FZK). The launcher is optimized for the $TE_{22,8}$ mode at 140 GHz, but the radiated beams present an almost identically focused pattern for all 9 considered modes between 105 GHz ($TE_{17,6}$) and 143 GHz ($TE_{23,8}$). Combining with a beam-forming mirror system, which consists of a quasi-elliptical mirror and two phase-correcting mirrors, further calculations show that efficiencies of more than 94% have been achieved for converting the rotating high-order cylindrical cavity modes into the usable fundamental Gaussian mode. Low power (cold) measurements show a good agreement with theoretical predictions. This QO mode converter can be used for the broadband operation of a multi-frequency 1 MW gyrotron.

1. Introduction

The availability of MW gyrotrons with fast frequency step tunability permits the use of a simple fixed, non-steerable mirror antenna 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 gyrotron is under construction at Forschungszentrum Karlsruhe (FZK) in a cooperative parallel development with the Institute of Applied Physics in Nizhny Novgorod [2-4]. The complementary key tasks for FZK are: a cavity operating in wide range of magnetic fields and with proper choice of a set of operating modes with the same direction of rotation; a broadband QO mode converter transforming all operating modes into fundamental Gaussian beam with low diffraction losses; development of ultra-broadband CVD-diamond Brewster window; a low power measurement set-up. This paper reports about the investigation of a broadband QO mode converter, focusing on how to achieve a fundamental Gaussian distribution of the output beam with low diffraction losses and minimal frequency dependence for all the designed frequencies.

2. General consideration of the QO mode converter

In the case of a dimpled-wall launcher with a helical cut for a frequency step-tunable gyrotron, the different working modes should have approximately the same caustic radius $R_C = (m/ X_{mn})R_{cav}$, here R_{cav} is the cavity radius, X_{mn} is the root of Bessel function (or derivative), so that the coupling of the electron beam to the RF electric field is comparably good. The different operating modes also must have the same sense of rotation since the direction of the helical cut of the q.o. launcher fixes its applicability to either right-hand (co-rotating with the electrons "-") or left-hand rotating (counter-rotating "+") waves. The cut length of the launcher and the angles of divergence of the output beam, are determined by the Brillouin angle and the ratio m/X_{mn} of the gyrotron cavity mode. The operating mode in a gyrotron cavity is very close to cut-off $(X_{mn}/ kR_{cav} \approx 1)$. Therefore all operating modes have the same Brillouin angle, independent of the frequency. These common features support the possibility that a few selected cavity modes can be converted into a fundamental Gaussian beam by a broadband QO mode converter.

3. Design and simulation results

Our current analysis method for these launcher systems is performed in two steps. First, the waveguide mode converter is analysed by using the coupled mode theory. Then, the radiated fields are calculated from the launcher cut by using the scalar diffraction integral. The launcher employs an irregular cylindrical waveguide section (pre-bunching section) followed by a helical-cut launching aperture, as shown in Fig.1. There are two principal design criteria for the dimpled-wall waveguide section. First, the section must convert the main mode to a mixture of modes such that 100% of the power in the waveguide is contained in a bundle with a Gaussian-like amplitude profile. Second, this profile must be achieved in a short distance, typically less than 200 mm, so that the launcher is short enough to avoid interception of the expanding spent electron beam. On the other hand, in order to assure that radiation is emitted only over a small part of the helical cut, the designed cut length L_d should be at least as long as the longest cut length of all modes under consideration. For this dimpled-wall launcher, a Gaussian-like profile of the field intensity on the waveguide wall can be achieved by specific periodic wall deformations $\Delta m_1 = 1$ and $\Delta m_2 = 3$. The design parameters for this launcher are: the input radius of the waveguide section 21.0 mm, the $\Delta m_1 = 1$ and $\Delta m_2 = 3$ wall perturbations for the longitudinal and azimuthal field bunching, respectively, use the same amplitude of 0.05 mm and perturbation length of 183 mm (with 10 mm tapers), they start at z = 0 mm along the z-axis of the launcher. The helical cut of the antenna is located at 1.0 rad and begins at z = 115 mm, cut length 68 mm, Brillouin angle 1.025 rad. In addition, the radius of the launcher section is slightly tapered ($R = a_0 + 0.002\ z$). This configuration reduces the Q factor of the section between the cavity and the helical cut, and suppresses spurious oscillations generated by the spent electron beam of the gyrotron in the launcher section. Fig 2 shows an example of the field distribution on the aperture of the launcher. Due to the tapering of the waveguide section, and the short launcher length (because of the limited tube space), this proto-type launcher design is not perfect; there are some field distributions near the cut edges. This will cause diffraction losses. Nevertheless calculations show that by using such dimpled-wall launcher, radiation patterns from the launcher aperture present an almost identically focused shape for all 9 considered modes between 105 GHz and 143 GHz. Further investigations to optimise this launcher will carry out soon.

The beam-forming mirror system consists of a large quasi-elliptical mirror and two phase-correcting mirrors. The detailed information about the design of phase-correcting mirrors for a frequency step-tunable high power gyrotron is given by [5]. Further calculations show that efficiencies of 94%-98% have been achieved for converting the rotating high-order cylindrical cavity modes into the usable fundamental Gaussian mode.

4. Cold measurement results

A low power test facility has been built to check the performance of the quasi-optical mode converter system. A new broadband QO mode generator has been designed and fabricated for the purpose of cold measurement [6]. First measurements of the output field pattern of the mode generator showed a very good performance at most of the gyrotron output frequencies. Since all operating modes of a step-tunable gyrotron have a similar structure, with their caustic radius being approximately half the cavity radius, only one set of resonator and lenses are required. During the process of the cold measurement, only a minor readjustment of the QO components is needed for generation of different modes. Two different manufacturers have manufactured two identical quasi-optical mode converter systems. The measurement results show that both mirror systems are in good agreement; identical beam patterns are formed on the output window [7]. Fig.3 shows one example of calculated (left) and measured (right) power density distribution at the gyrotron window flange for the $TE_{22,8}$ mode at 140 GHz. It is obvious that theoretical predictions agree with low power measurements. Probably due to minor mechanical tolerances of the QO mode converter, the correlation efficiency between calculation and cold measurement is only about 90%. This proves that the quasi-optical system with non-quadratic phase-correcting mirrors requires accurate alignment.

5. Conclusions

Output beams at the launcher aperture and at different positions outside of gyrotron windows show an almost identical beam pattern for all the considered frequencies. Both theoretical predictions and cold measurements prove that this proto-type QO mode converter can be used for the broadband operation of a multi-frequency gyrotron with nine operating modes from $TE_{17,6}$ at 105 GHz up to $TE_{23,8}$ at 143 GHz. Due to the availability of a large diameter (140 mm) CVD-diamond disk at FZK, hence a new structure of the Brewster window, this QO mode converter needs to be optimized. Further optimizations will be carried out soon on the dimpled-wall launcher and phase correcting mirrors.

References

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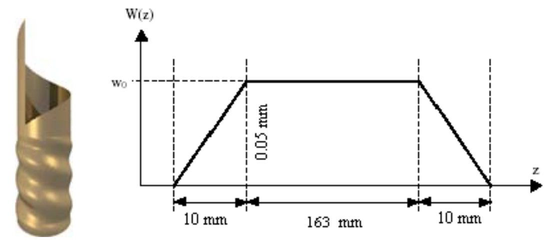

Fig. 1 Schematic drawing of the dimpled-wall launcher and its wall deformation amplitude (same for $\Delta m_1 = 1$ and $\Delta m_2 = 3$).

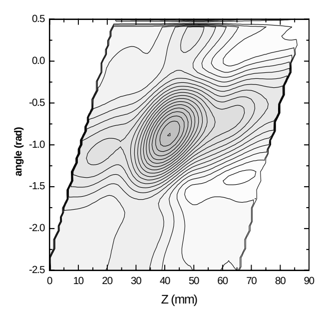

Fig. 2 The field distribution on the aperture of the launcher for the mode of $TE_{22,8}$ at 140GHz (contour lines are linear in steps of 0.05).

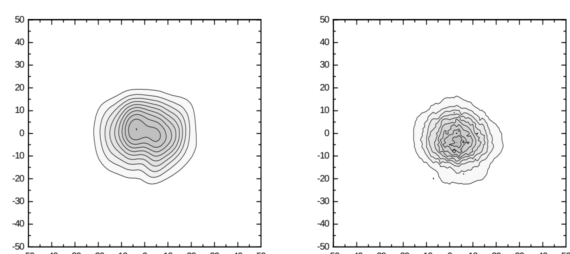

Fig. 3 Calculation (left) and cold measurement (right) of power density distribution on the gyrotron window flange for the $TE_{22,8}$ mode at 140 GHz (contour lines are linear in steps of 0.1).