DESIGN OF A 170 GHz, 4 MW COAXIAL SUPER GYROTRON WITH DUAL-BEAM OUTPUT

M. Thumm[1,2], J. Jin[1], M. V. Kartikeyan[3], B. Piosczyk[1], T. Rzesnicki[1]

[1]Forschungszentrum Karlsruhe, Association EURATOM- FZK
Institut fuer Hochleistungsimpuls- und Mikrowellentechnik (IHM)
Postfach 3640, 76021 Karlsruhe, Germany
[2]Universitaet Karlsruhe, Institut fuer Hoechstfrequenztechnik und Elektronik
Kaiserstr. 12, 76128 Karlsruhe, Germany
[3]Dept. of Electronics & Computer Engineering, Indian Institute of Technology Roorkee (IITR), Roorkee 247 667; India

e-mail: manfred.thumm@ihm.fzk.de

The feasibility of a 170 GHz, coaxial cavity super gyrotron, operating in a ultra high order volume mode and capable of delivering powers more than 4 MW in continuous wave operation (CW) is investigated. Proper care has been taken in the mode selection that a dimpled-wall quasi-optical launcher with a dual-beam output is ideally feasible.

Introduction

Gyrotrons are high power microwave sources widely employed for electron cyclotron resonance heating (ECRH) of plasmas, and in other industrial and scientific applications. Recent experiments at FZK and IAP Nizhny Novgorod [1,2] suggest that conventional and coaxial cavity gyrotrons delivering in excess of 2 MW power at frequencies ranging from 140-170 GHz operating with very high order volume modes can successfully be realized. In this work, the feasibility of a super power coaxial cavity gyrotron at 170 GHz capable of giving power around 4 MW, CW, operating in the $TE_{44,26}$/$TE_{50,30}$/$TE_{54,32}$ modes is presented as a small step towards a big leap from 2 to 4 MW power levels. These modes are capable of giving a perfect dual-beam output through two synthetic diamond windows with a suitable dimpled-wall quasi-optical (q.o.) launcher and smooth surface phase correcting mirrors. This will reduce the technical complexities connected with high diffraction losses (stray radiation) inside the tube. The realization of such an ultra high power gyrotron will drastically reduce the number of gyrotrons and the super conducting magnets operating in tandem in DEMO reactor installations. The basic impetus and motivation to consider such a high volume mode is provided by the recent works at FZK and IAP [1-3].

Features of Quasi-Optical Mode Converter

Coaxial cavity gyrotrons operate in very high order modes like $TE_{28,16}$ at 140 GHz, $TE_{31,17}$ at 165 GHz or $TE_{34,19}$ at 170 GHz [1-3]. Unfortunately, due to the ratio of caustic to cavity radius of approximately 0.3 for these modes, their transformation into a nearly Gaussian distribution in the dimpled-wall launcher cannot be done as good as for the $TE_{28,8}$ mode of the EU 140 GHz gyrotron with a ratio of caustic to cavity radius of approximately 0.5. One gets for the azimuthal focussing the selection rule $\Delta m_2 = 2.5$ (Figure 1) instead of $\Delta m_2 = 3$ which means that $\Delta m_2 = 2$ and 3 perturbations have to be employed simultaneously and the microwave power radiated from the cut must be shaped by two non-quadratic phase correcting mirrors. In this case simple smooth toroidal mirrors are not sufficient.

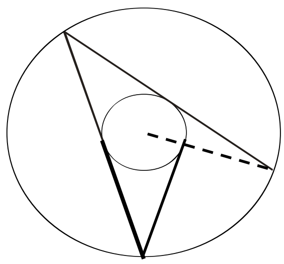

Figure 1. Geometrical optical description of ray propagation of a coaxial cavity gyrotron mode in a cylindrical waveguide (top view): $360°/\Delta\varphi = 2.5$.

However, in the present approach, this feature of coaxial cavity gyrotron modes is used to generate two output beams by a q.o. mode converter system employing a novel launcher together with simple, smooth toroidal mirrors.

In the mode selection procedure for the cavity mode, such modes have been chosen, which will give an ideal dual-beam focussing at the q.o. launcher (that is with helical $\Delta m_1 = 1$ and $\Delta m_2 = 5$ wall perturbations for which $m_2/2 = 360^{o}/\Delta\varphi = 2.5$. In this selection procedure only three well-qualified modes, namely, $TE_{44,26}$, $TE_{50,30}$ and $TE_{54,32}$ have been picked out (Figure 2).

The principle of the dual-beam q.o. mode converter is shown for the $TE_{28,16}$ mode since a low power mode generator is available at FZK for this mode at 140 GHz [4].

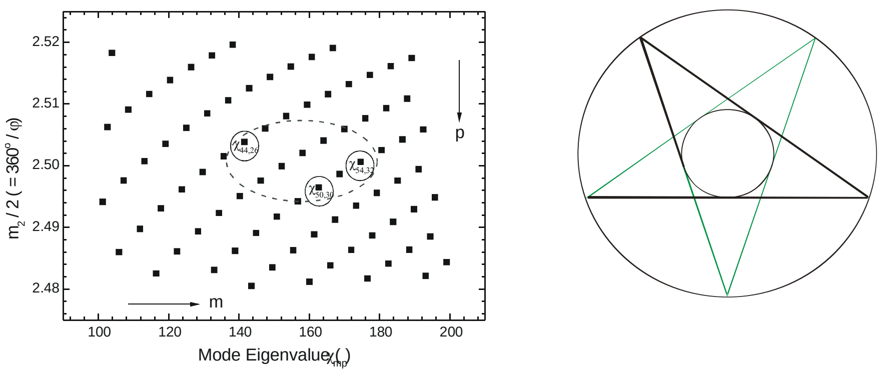

Figure 2. Mode eigenvalues and ray propagation for a dimpled-wall launcher with azimuthal $\Delta m_2 = 5$ perturbation.

The wall perturbation of the dimpled-type dual beam launcher is given by

$$R\,(z,\varphi) = R_L + a\cos(h_1 z - \varphi) + a_2 \cos(h_2 z - 5\,\varphi)$$

with

R_1 = 32.5 mm,	a_1 = 0.030 mm,	a_2 = 0.027 mm,
	h_1 = 0.093 mm,	h_2 = 0.005 mm

Here the linear input taper of the deformation depths is not included. Figure 3 demonstrates the $\Delta m_1 = 1$ longitudinal and $\Delta m_2 = 5$ azimuthal (two beam) focussing, respectively.

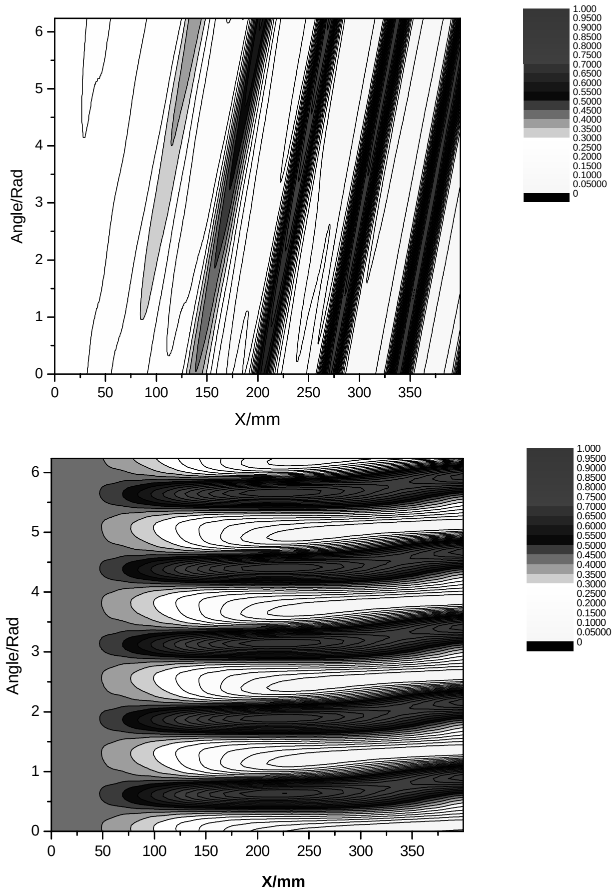

Figure 3. Longitudinal $\Delta m_1 = 1$ (upper) and azimuthal $\Delta m_2 = 5$(lower) focussing in a dual-beam $TE_{28,16}$ quasi-optical mode converter (140 GHz, I.D. = 65 mm).

Figure 4 shows the calculated contour map of the well focussed power on the unrolled waveguide wall of the launcher. The two cuts for the two output beams are indicated by the lines.

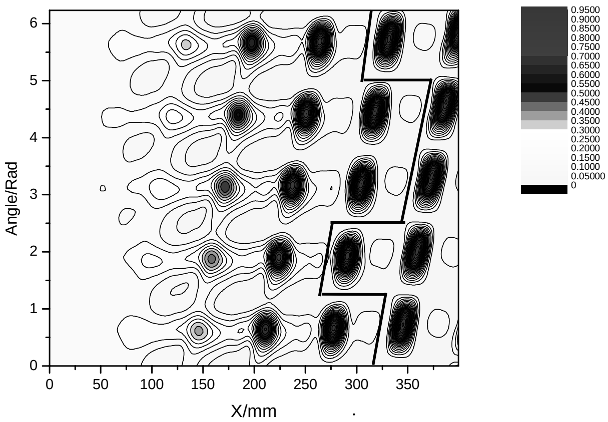

Figure 4. Contour map of the power of a dimpled-wall dual-beam $TE_{28,16}$ quasi-optical mode converter (140 GHz, I.D. = 65 mm).

Coaxial Cavity Design

The design goals of the 170 GHz, 4 MW coaxial cavity gyrotron with dual-beam output are summarized in Table 1. By choosing suitable cavity geometries,

Table 1: Design goals and parameters

Frequency	170 GHz
Output Power	≥ 4 MW (2x2 MW)
Diffractive Quality Factor Q_D	≈ 1500-3000
Beam Current I_b	100-110 A
Beam Voltage U_b	120-150 kV
Magnetic Field B (at the interaction)	7.15-7.45 T
Beam Velocity Ratio α	1.3
Total Efficiency η	≈ 30 % (without SDC)
Realistic Wall Losses	< 2 kW/cm^2
Overall Losses	< 8 %

Table 2: Cavity geometries, operational parameters and simulation results

	$TE_{44,26}/\chi$=141.5415	$TE_{50,30}/\chi$=162.6828	$TE_{54,32}/\chi$=174.5750
L_1 / L_2 / L_3 (mm)	22 / 16 / 22 (output)	22 / 20 / 22 (output)	22 / 20 / 22 (output)
θ_1/ θ_2 / θ_3 (^{o} Degrees)	3 / 0 / 2.5 (output)	3 / 0 / 2.5 (output)	3 / 0 / 2.5 (output)
R_{cav} / R_{in} / R_b (mm)	39.75 / 10.6 / 12.88	45.69 / 12.20 / 14.60	49.03 / 13.4 / 15.74
l / s (mm) / N	0.35 / 0.67 / 100	0.35 / 0.67 / 115	0.35 / 0.67 / 126
Q_D	1595	2625	2666
U_b (kV)	117	130	140
I_b (A)	100	96	108
B (T)	7.17	7.27	7.38
η (%)	34.2	34.5	33.1
P_{out} (MW)	4.0	4.3	5.0
$^*\rho_{cav}$ (kW/cm^2)	2.0	1.8	1.8
$^*\rho_{in}$ (kW/cm^2)	0.08	0.06	0.10

* - enhancement factor (temperature, roughness) of 2.0 is included

time-dependent self-consistent multi-mode computations (SELFT) have been carried out. The cavity geometries, the gyrotron parameters and the theoretical results of output powers and efficiencies are given in Table 2. R_b is the electron beam radius and N is the number of longitudinal $\lambda/4$ corrugations with slot width *l* and period s of the inner rod.

The SELFT simulation results are shown in Figures 5-7.

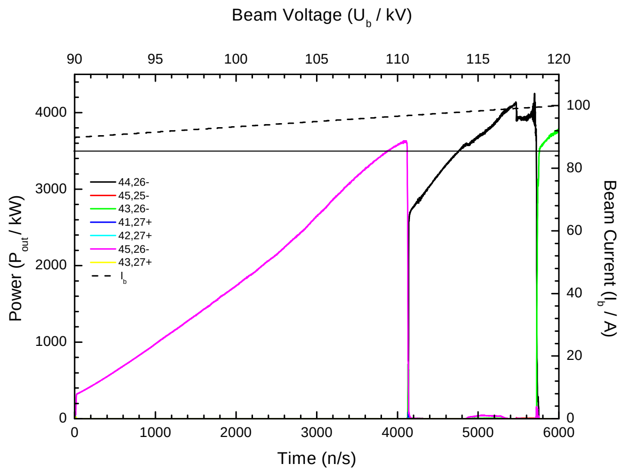

Fig. 5: SELFT simulation results for a $TE_{44,26}$ mode coaxial cavity gyrotron (magnetic field B = 7.17 T).

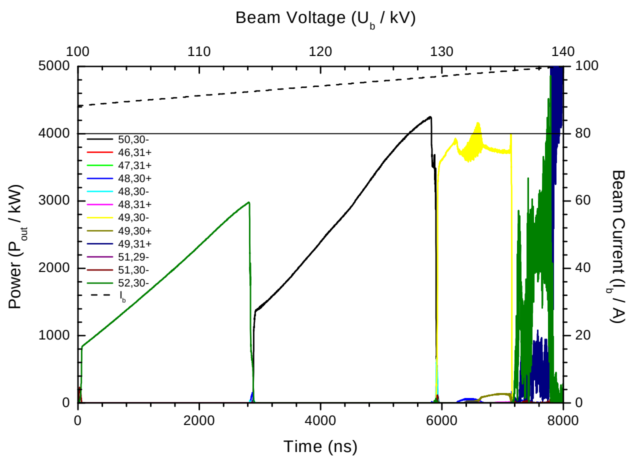

Fig. 6: SELFT simulation results for a $TE_{50,30}$ mode coaxial cavity gyrotron (magnetic field B = 7.27 T).

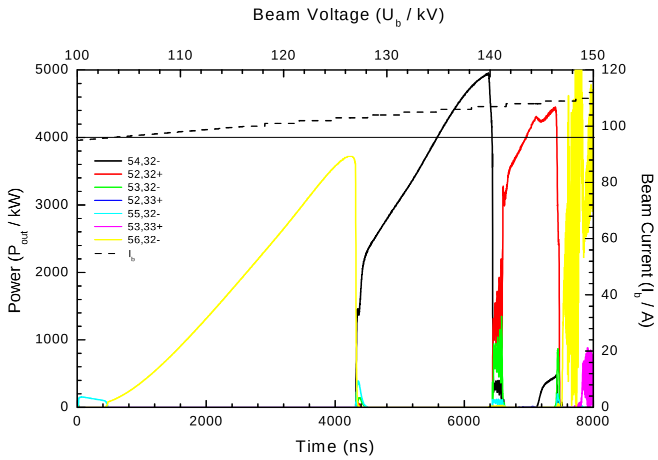

Fig. 7: SELFT simulation results for a $TE_{54,32}$ mode coaxial cavity gyrotron (magnetic field B = 7.38 T).

Conclusions

As a result of the time-dependent self-consistent multi-mode SELFT simulations it has been found that all the three modes considered are independently oscillating over a wide range of nominal parameters without problems with other competing modes. It is shown that a 170 GHz, 4 MW super power gyrotron with dual-beam output is very much feasible to operate. The $TE_{44,26}$/ $TE_{50,30}$ modes are capable of delivering powers up to 3.5-3.8 MW, CW only, if we consider a lower tolerance limit of about 20 % of the computed output power. However, the $TE_{54,32}$ mode is well capable delivering around 4 MW, CW, power at 170 GHz. Next works are the design of a 130 kV/100 A electron gun, the final design of the coaxial cavity, the further development of the quasi-optical mode converter for dual-beam output and the design of a 4 MW single-stage depressed collector with beam sweeping.

References

[1] B. Piosczyk, A. Arnold, G. Dammertz, O. Dumbrajs, M. Kuntze, M. Thumm, IEEE Trans. Plasma Science, PS-30, 828-834 (2002).

[2] V.E. Zapevalov, V.I. Khizhnyak, M.A. Moiseev, A.B. Pavelyev, N.I. Zavolsky, Conf. Digest, 27th Int. Conf. Infrared and Millimeter Waves, September 22-26, San Diego CA, USA, 335-336 (2002).

[3] Kartikeyan, M.V., E. Borie, B. Piosczyk, M. Thumm, Conf. Digest 28th Int. Conf. on Infrared and Millimeter Waves, Otsu, Japan, 2003, pp. 169-170.

[4] Braz O., Arnold A., Kunkel H.-R., Thumm M., Proc. 22nd Int. Conf. on Infrared and Millimeter Waves, Wintergreen, Virginia, USA, 1997, 21-22