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Two-Dimensional Design of a Low Voltage mm-Wave Sheet Beam Klystron

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The paper reports the latest results on the following design parts: electron gun (EGUN and MAFIA-PIC simulations), input and output cavities (GdfidL simulations) and focusing (analytic calculations). Finally, an overview of the current sheet beam klystron (SBK) parameters is given.

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Abstract

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1 INTRODUCTION

In the last years the idea came up to develop electron accelerators in the millimeter-wave range around 100GHz. In this range the available tubes have either too low output power or they are gyrotron oscillators which are not well suited for accelerator needs. Also, they are operated at very high voltages and are large and expensive. Other possible candidates are the ubitron [1] and the FEL. But again, both require high voltages and consequentely they will be large. The question is: Why developing new small accelerators, when the power sources are large and the total is not smaller or cheaper than the extremely well established existing technique? We rather believe that it is more appropriate to have a large number of small, simple and cheap tubes with moderate output power and a small distribution network, than a small number of very high power tubes with a large distribution network. But for accelerator applications moderate output power still means something between 20 and 200kW. Our present goal is therefore to study the feasibility of a tube with a power rating at the lower end, between 10 and 30kW, but with the potential to go up to 100 or even 200kW. This tube, together with the power supply, should be small, simple and hopefully cheap. The choice is a low voltage sheet beam klystron with a modulation anode and PPM focusing.

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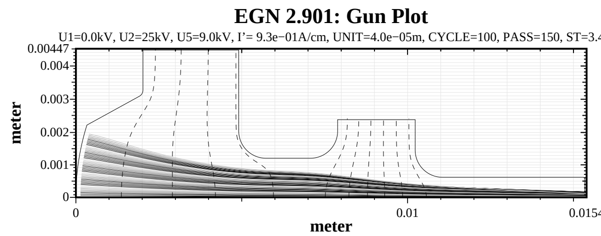

Figure 1: Plot from EGUN simulation

2 GUN DESIGN

The electron gun was designed to provide a 1-3 A/cm, 0.3 mm thick 25 kV sheet beam at a cathode loading of less than 5 A/cm^2. A modulation anode had to be used since switching the anode for pulsed operation would raise the costs for the power supply. Another design issue was to include as few electrodes as possible and to keep the electrode shapes simple which is expected to contribute towards a reduction of manufacturing costs.

Starting out with a slightly modified version of a sheet beam gun proposed by True [2] two years ago, the geometry has been further modified step by step in order to achieve the beam parameters mentioned above and to simplify the electrode shapes. All simulations have been performed with the electron optics code EGUN. Figure 1 shows the output from a final run which predicts the following values: $I' = 1.9$A/cm, $J_{cathode} = 4.8$A/cm^2, a beam thickness of 0.4mm and a compression ratio of 10 : 1.

Since the compression could not be further increased by simple variations of geometry parameters, the required beam thickness can only be achieved by reducing the cathode height. Obviously, if the same current is desired this would result in a higher cathode loading. The idea of applying an additional electrostatic lense was immediately dropped since this would not only increase the number of electrodes but also the field strength in between.

Although originally included for switching purposes only, the modulating anode is essential for high density sheet beam guns since the lense formed together with the anode heavily increases the electrostatic compression ratio. One may conclude that realistic values for the compression of sheet beam electron guns are 3 : 1 for a simple diode and 10 : 1 when including a modulating anode.

Finally, the gun designed was simulated again with the particle-in-cell module of MAFIA. While the beam current was aproximately 2A/cm also, the beam shape turned out to be different from that predicted by EGUN, see figure 2.

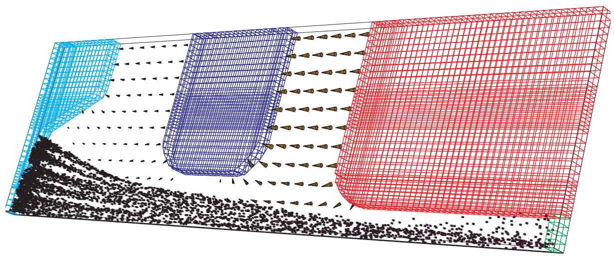

Figure 2: Plot from MAFIA simulation

3 CAVITY DESIGN

Two major objectives in the cavity design of sheet beam tubes are a flat field across the whole beam width and a large (unloaded) shunt impedance. Another objective was to reduce the transit time effect. However, the corresponding reduction coefficient has been included in the shunt impedance throughout this paper for having a comparable parameter for single cell as well as for multicell resonators.

3.1 The Flat Field Problem

Obtaining a high efficiency requires a constant shunt impedance across the width of the beam for the input and idler cavities as well as for the output cavity since the position of maximum rf current depends on the experienced voltage and the modulated beam has to be saturated over its whole width.

Thinking of a wide rectangular cavity resonator as a shorted waveguide immediately yields a solution of the flat field problem: The waveguide must be operated at cut-off and the shorts have to be transformed into open circuits which can be done with $\lambda/4$-lines. Then, the terminations should be build from another waveguide that operates above cut-off. Since we have to deal with grooved waveguides – the beam requires an opening – the terminating guide can be realized by changing one of its three dimensions: height, width and aperture. These dimensions correspond to the cavity dimensions half-depth b, gap width g, half-aperture a and cavity width w, respectively. In the following, the dimensions of the termination will be subscribed with t, see figure 3.

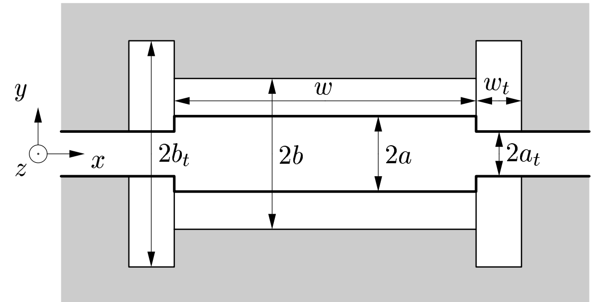

Figure 3: x-y-cut of a general planar flat field cavity

Barbell Cavity. Since the cut-off frequency of the fundamental mode depends in first order on the depth only, the easiest way is to increase the depth b_t of the terminating guides with respect to the depth b of the middle section. Such a cavity has been proposed by Yu and Wilson in 1993 [3] and is shown in figure 4. The width of the terminating cells is approximately

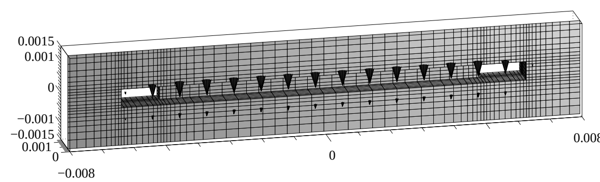

Figure 4: Barbell cavity for 91.39 GHz, view of x-z-cut (see fig. 3)

given by

$$w_t \approx \left(\frac{16f^2}{c^2} - \frac{1}{b_t^2}\right)^{-1/2}.$$

Since the field is disturbed by the aperture and the jump of the waveguide depth with respect to an usual rectangular cavity, this formula somewhat underestimates the width.

H-Block Cavity. Due to the aperture, the cut-off frequency of the fundamental mode decreases also as the gap width g increases. Although this dependency is weak, it is strong enough to have a suitable transformer. This way has been proposed in 1995 for accelerator purposes [4] and in 1996 for the sheet beam klystron [5]. Since only one depth has to be realized for such a cavity, it is well suited for fabrication by lithography. Figure 5 shows a plot from simulating a H-Block cavity with GdfidL.

Cross-Aperture Cavity. Decreasing the aperture of the terminating guide also lowers its cut-off frequency. A simulation plot is shown in figure 6.

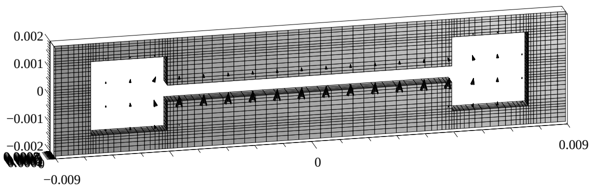

Figure 5: H-Block cavity for 91.39 GHz, view of x-z-cut (see fig. 3)

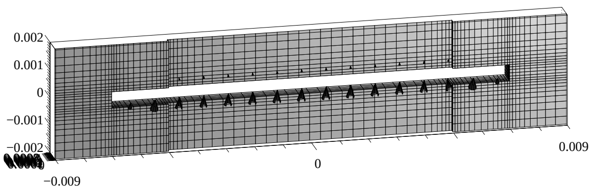

Figure 6: Cross-Aperture cavity for 91.39 GHz, view of x-z-cut (see fig. 3)

3.2 *The Shunt Impedance Problem*

For the input cavity, the shunt impedance determines the rf power needed to achieve a specific voltage modulation[1]

$$\frac{P'}{P'_0} \quad = \quad \frac{\alpha^2}{2}\frac{R'_0}{R'}.$$

Here, the dashes indicate quantities which are normalized with respect to the transverse width, the index 0 refers to the D.C. beam parameters and $\alpha = V/V_0$ is the voltage modulation coefficient. Assuming a weak modulation of $\alpha = 0.1$, for our beam with the impedance $R'_0 \approx 13\text{k}\Omega\text{cm}$ the shunt impedance has to be of the order of $R' \approx 1\text{k}\Omega\text{cm}$ for having the rf power about 7% of the D.C. beam power.

For the output cavity, the shunt impedance determines the conversion efficiency

$$\eta \quad = \quad \frac{\beta}{2} - \frac{R'_0}{2R'}.$$

This formula refers to saturation drive, $\beta = I'/I'_0$ is the current modulation coefficient and has a theoretical limit of 2. Assuming a modulation of $\beta = 1.5$, for 50% efficiency the shunt impedance has to be $R' = 2R'_0 \approx 25\text{k}\Omega\text{cm}$.

Unfortunately, the values that have been achieved with a single cell cavity as shown in figure 7 are in the order of $R' \approx 60\Omega\text{cm}$ only. Obviously, since the shunt impedance was $40\text{k}\Omega\text{cm}$ for zero transit time, this problem arises from the low beam voltage. However, due to the field leaking into the aperture the transit time cannot be reduced by having a smaller gap.

[1] The definitions are: (maximum) experienced voltage $V = |\int_{-\infty}^{\infty} E_z(z)\exp(\mathrm{j}\omega z/v_0)\mathrm{d}z|$, shunt impedance $R = V^2/2P$.

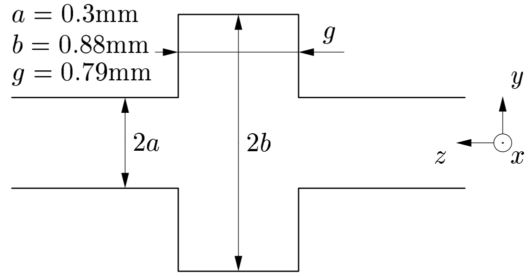

Figure 7: Two-dimensional single cell cavity for 91.39 GHz, gap width optimized for field flatness over beam thickness

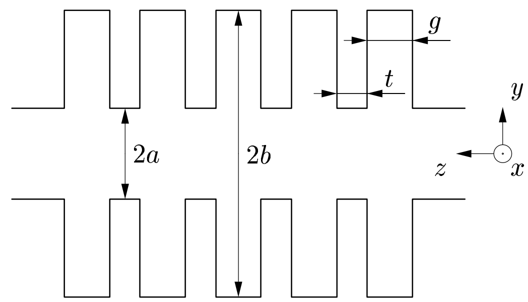

Figure 8: Two-dimensional multi cell π-mode cavity for 91.39 GHz

One way to cure the transit time problem is coupling to a travelling wave in a so called extended interaction region, which can be realized by a multicell resonator as shown in figure 8. Obviously, the resonant circuit theory still holds, since the quality factor of the loaded cavity needed for saturation[2] has to be $Q_l \approx 650$ for the values mentioned above and $Q \approx 2000$.

Now the question is what phase advance per cell should be chosen: At 91.39GHz, a 25kV beam moves only 0.991mm per rf cycle. Considering 2 cells per mm to be an electrical and mechanical limit (iris $t \geq 0.2\text{mm}$, gap width $g \geq 0.3\text{mm}$), a phase advance per cell of at least π is needed for synchronous operation. Limiting the order of the synchronous space harmonic to 2, the phase advance per cell has to be between 2π and π. Thus, we studied 2π-, $3\pi/2$- and π-mode standing wave structures with respect to their normalized shunt impedance $R^* = R'/(NL) = Rw/(NL)$, where

[2] The general relation for saturation drive reads

$$Q_l \quad = \quad Q\frac{R'_0}{\beta R'},$$

and follows immediately from the saturation condition $V = V_0$.

L is the period length, N the number of cells and w the cavity width.

mode	2π	$3\pi/2$	π
L/mm	0.991	0.743	0.495
g/mm	0.4	0.46	0.29
t/mm	0.591	0.283	0.205
b/mm	0.907	0.904	0.963
R^*/kΩ	5.7	5.1	9.2
R^*_{max}/kΩ	17.96	15.85	29.59

Table 1: Parameters of standing wave structures

The simulations have been performed with the finite difference code GdfidL [6]. The gap width g has been optimized for maximum shunt impedance in the plane of symmetry and the frequency has been adjusted to 91.392GHz by varying the cell depth b. For all structures, the half-aperture $a = 0.3$mm is the same and a beam velocity of $v_0/c = 0.302$ has been assumed. The results are shown in table 1. As already mentioned above, the field in general does not take its maximum in the plane of symmetry $y = 0$ where R^* has been calculated, but right at the gaps $y = \pm a$ where R^*_{max} has been calculated. Since the plasma wavelength of our beam is about 8cm, a structure length of $l = NL = 1$cm should be realistic. Thus, a maximum shunt impedance of $R' \approx 25$kΩcm can be achieved with a 20-cell-π-mode structure yielding a conversion efficiency of about 50%.

3.3 The Coupling Problem

Since the (transverse) group velocity within a flat field cavity is very small, the loaded quality factor cannot be made as low as desired by coupling from the side. An alternative for the output cavity was coupling from the back with a parallel waveguide operated well above cut-off. This method is currently under investigation.

4 PPM FOCUSING DESIGN

Since the lower half of the focusing structure may be shifted with respect to the upper half, in contrast to axial symmetric PPM structures, there are two types of planar PPM structures suitable for sheet beam focusing, figures 9 and 10. The first type corresponds

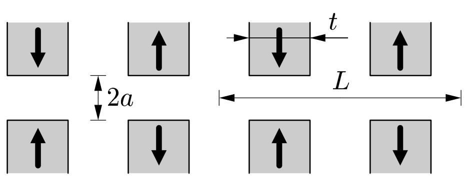

Figure 9: Odd PPM structure

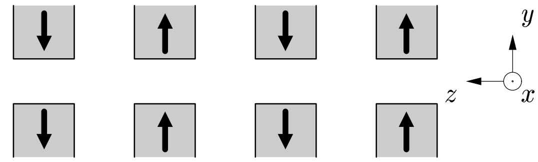

Figure 10: Even PPM structure

to the axial symmetric case and since the magnetic field is odd we called it and odd structure. Consequently, for its even magnetic field the second type is called even. Since the scalar potential must satisfy the Laplace equation, a near axis approximation of the fields is given by

$$\begin{aligned} B_y &\approx -B_0 2\pi y/L \sin(2\pi z/L) \\ B_z &\approx -B_0 \cos(2\pi z/L) \end{aligned}$$

in the odd case and by

$$\begin{aligned} B_y &\approx -B_0 \sin(2\pi z/L) \\ B_z &\approx -B_0 2\pi y/L \cos(2\pi z/L) \end{aligned}$$

in the even case. From an orthogonal expansion, the constant B_0 has been determined to be

$$B_0 = \frac{4\mu_0 M}{\pi} \sin(\pi t/L) \exp(-2\pi a/L).$$

Solving the equation of motion, for both PPM types allow for a space charge balanced flow

$$B_0 = \sqrt{2}\omega_q/\eta,$$

provided that the stability condition holds

$$\lambda_q \gg L.$$

Here, ω_q is the reduced plasma frequency of the D.C. beam, λ_q the corresponding wavelength and η the charge to mass ratio of an electron. The pole tip field of the permanent magnets is given by

$$\hat{B} = \mu_0 M = B_0 \frac{\pi}{4} \frac{\exp(2\pi a/L)}{\sin(\pi t/L)}.$$

For our beam, the stability condition reads $L \ll$ 75mm. The parameters chosen for the PPM structure are listed in table 5.

5 PARAMETER OVERVIEW

parameter	symbol	goal	actual	unit
frequency	f	91.392	91.392	GHz
D.C. input	P_0	25	47	kW
rf output	P	10	≈ 23	kW
efficiency	η	40	≈ 50	%
rf input	P_{in}	150	≈ 300	W
duty cycle		1:100	-	1
pulse width		1	-	ms

Table 2: Main Parameters

parameter	symbol	goal	actual	unit
voltage	V_0	25	25	kV
current	I_0	1	1.9	A
width	w	10	10	mm
height	h	0.3	0.4	mm
current dens.	J_0	33	47.5	A/cm^2
perv. p. sq.	$K_\square$	0.008	0.014	μP
resistance	R_0	25	13	kΩ
velocity	v_0	0.302	0.302	c
charge dens.	ρ_0	3.7×10^{-3}	5.2×10^{-3}	As/m^3
plasma freq.	ω_p	8.5	10.2	GHz
red. pl. freq.	ω_q	6.4	7.6	GHz
red. pl. wavel.	λ_q	89	75	mm

Table 3: Beam Parameters

parameter	symbol	goal	actual	unit
mod. anode voltg.	V_m	9	9	kV
cathode width	w_c	10	10	mm
cathode height	h_c	3	3	mm
cathode load.	J_c	3.3	4.8	A/cm^2
compression		10:1	11:1	1

Table 4: Gun Parameters

parameter	symbol	value	unit
period length	L	10	mm
half-aperture	a	0.9	mm
magnet thickness	t	2.5	mm
field amplitude	B_0	0.06	T
pole tip field	$\hat{B}$	0.12	T
magnetization	M	95.7	kA/m

Table 5: PPM Structure Parameters

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