THE MM-WAVE SHEET BEAM KLYSTRON: PERFORMANCE AT DIFFERENT VOLTAGES

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Abstract

The aim of our work is the design of a simple and light, small and cheap mm-wave source with moderate power. Our choice has been a 25kV PPM-focused sheet beam klystron (SBK). However, the efficiency predicted for such a device is very poor: A low beam voltage means small coupling coefficients and a sheet beam profile means a gun with one-dimensional compression only resulting in a low current density. Thus, the performance can be improved by either splitting the wide beam into several round beams with higher current density, or by raising the beam voltage. In this paper the performance of a 25, 50 and 100kV mm-wave SBK is investigated. Simulation results for the electron guns and the cavity resonantors are presented and an overview on the predicted electrical parameters is given.

1 INTRODUCTION

The concept of a low voltage sheet beam implies several advantages which led to our choice of a 25kV PPM focused SBK: A low voltage drastically reduces the requirements of x-ray shielding and power supply while a flat beam is well adapted for modern microfabricational techniques where a planar geometry is necessary. The moderate level of current density permits focusing using a light periodic permanent magnet structure.

Unfortunately, opposed to the advantages inherent in a low voltage sheet beam concept is the drawback of a low efficiency resulting from a low current density and a small shunt impedance value. A low beam velocity degrades the shunt impedance for two reasons: the transit angle as well as the transverse dependence of the impedance is increased. The best possible efficiency within reach for a 25kV PPM focused SBK was predicted to be approximately 10% (without making use of a depressed collector). A way to improve this situation is going to higher voltages. Within the present study simulations have been performed to examine what gain in klystron performance may be achieved by raising the beam voltage. Due to the high aspect ratio of the beam (25:1), a twodimensional treatment yields good approximation results and is used throughout this paper.

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2 ELECTRON GUN SIMULATIONS

Basis for the electron guns considered here is a design of a 25kV electron gun providing a sheet beam of 400 μm thickness and current of 1.9 A/cm at a cathode loading of less than 5 $\mathrm{A/cm}^2$, [1]. The implemented modulation anode allows nearly powerless beam switching for pulsed operation while keeping the costs for the power supply at a moderate level. Together with the anode it forms an electrostatic lense thus heavily increasing the compression up to a ratio of 10:1. Keeping the number of electrodes included small and their shapes as simple as possible is expected to reduce the manufacturing costs.

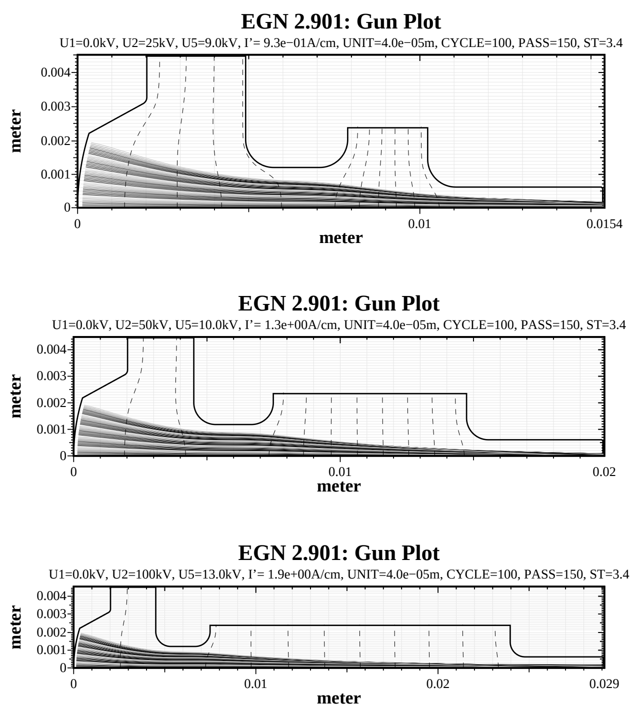

Figure 1: Vertical cut of 25kV, 50kV and 100kV electron gun

Starting with an anode voltage V_0 of 25kV its value was increased in two steps to 50kV and 100kV. One way would have been simply scaling all the voltages leading to a modanode voltage of 36kV in case of 100kV applied to the anode. Since we prefer a low modanode voltage switching the beam we did not further follow this idea. The minimum electrode spacing d_{min} between modulation anode and anode necessary to avoid electrical breakdown was determined using Kilpatrick's criterion [2] and a relationship given by Staprans [3] as a guideline which reads in the worst case (D.C. operation and beam switched off) $d_{min} = \left(V_0/3 \cdot 10^6\right)^{1.25}$ with d_{min} and V_0 taken in MKS units leading to 2.5mm, 6.0mm and 14.2 mm spacing for 25kV, 50kV and 100kV anode voltage, respectively.

In order to keep the already achieved beam shape and compression ratio nearly unchanged while varying the anode voltage, the voltage and position of the modulation anode was carefully adapted. This was accomplished performing simulations using the electron optics code EGUN. Figure 1 shows a vertical cut of the three guns under investigation together with the according electron trajectories and equipotentials. The obtained results apparently exhibit that the beam thickness of 0.4mm can be maintained while the beam current increases to 2.6 A/cm in case of the 50kV beam and to 3.8 A/cm for the 100kV beam. The corresponding modanode voltages required are 10kV and 13kV only and the cathode loading amounts to 7 A/cm^2 and 10.2 A/cm^2 respectively.

3 CAVITY RESONATORS

The resonator cavities are considered to consist of a certain number of identical simple muffin tin cells, see fig. 2. For each beam voltage, the gap width g has been optimized for maximum shunt impedance at $y = 0$ by means of the code GdfidL [4] with the frequency fixed to 91.392GHz.

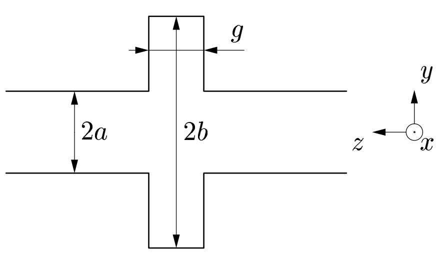

Figure 2: Two-dimensional single cell resonantor

At 25kV, the optimum gap width is $g = 0.4\text{mm}$ and the shunt impedance is $520\Omega\text{cm}$. For synchronous operation, a cell distance of 1mm, 0.75mm and 0.5mm is required for 2π-, $3\pi/2$- and π-mode, respectively. Correspondingly, within $\lambda_q/16 \approx 5\text{mm}$ 5, 7 and 9 cells can be placed, yielding a total shunt impedance of $2.6\text{k}\Omega\text{cm}$, $3.6\text{k}\Omega\text{cm}$ and $4.7\text{k}\Omega\text{cm}$, respectively.

At 50kV, the optimum gap width is $g = 0.55\text{mm}$ with $2.3\text{k}\Omega\text{cm}$ shunt impedance. The cell distances are 1.35mm, 1.02mm and 0.68mm for 2π-, $3\pi/2$- and π-mode, respectively. Again, assuming a maximum structure length of $\lambda_q/16 \approx 7.5\text{mm}$, 5, 7 and 11 cells should be realistic, yielding a shunt impedance of 13, 18 and $25\text{k}\Omega\text{cm}$, respectively.

Finally at 100kV, the gap should be 0.75mm wide and the shunt impedance predicted for a single cell is $6.5\text{k}\Omega\text{cm}$. For 2π-, $3\pi/2$- and π-mode, the cell spacing must be 1.8, 1.35 and 0.9mm, respectively. Within $\lambda_q/16 \approx 12\text{mm}$,

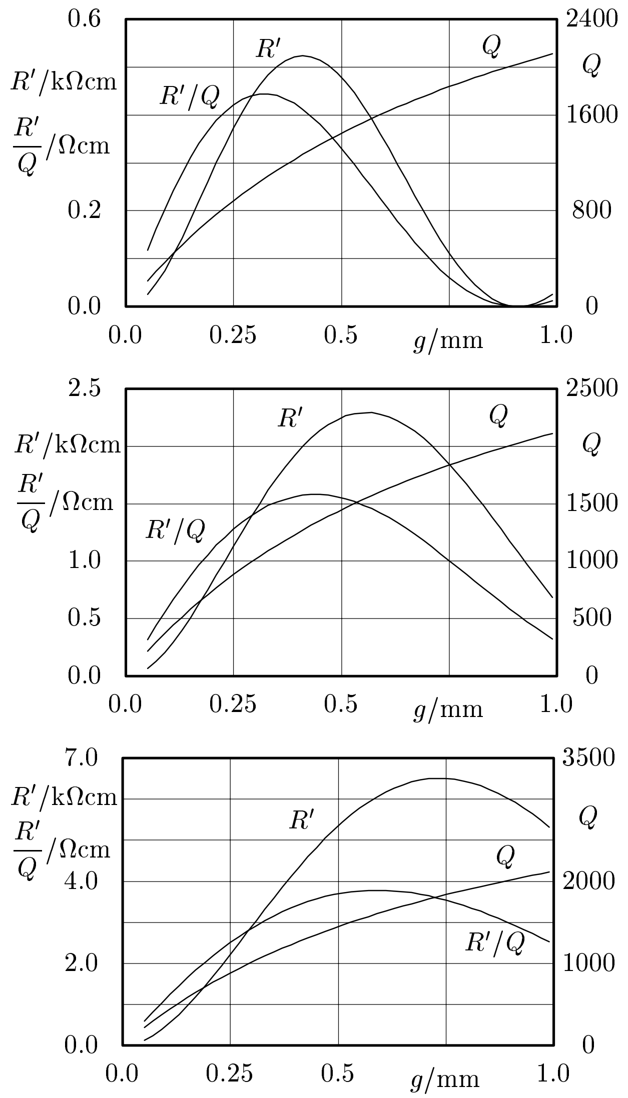

Figure 3: Parameters of the cavity from fig. 2 for 25, 50 and 100kV beam voltage

6, 9 and 12 cells may be placed, and the total impedance would be 39, 58 and $78\text{k}\Omega\text{cm}$.

4 PREDICTED EFFICIENCIES

As shown in [5], the d.c. to r.f. conversion efficiency takes its maximum

$$\eta = \begin{cases} \frac{m^2}{8}\frac{R}{R_0} & \text{for} \quad mR \leq 2R_0 \\ \frac{m}{2} - \frac{R_0}{2R} & \text{for} \quad mR \geq 2R_0 \end{cases}$$

at an external load of

$$Q_{ext} = \begin{cases} Q & \text{for} \quad mR \leq 2R_0 \\ Q/(mR/R_0 - 1) & \text{for} \quad mR \geq 2R_0 \end{cases}$$

where the lower lines refer to saturation drive. Here, m is the current modulation, R_0 the beam resistance, R the unloaded shunt impedance, Q the unloaded and Q_{ext} the external quality factor of the resonator.

For all voltages, maximum shunt impedance is achieved at π-mode, and the predicted efficiencies are 11% at $25\mathrm{kV}$, 41% at $50\mathrm{kV}$ and 63% at $100\mathrm{kV}$. - Saturation drive is possible only at the the higher beam voltages. - The external quality factors required are 1260, 1430 and 490, respectively. Here, a current modulation of 1.6 has been assumed.

5 REFERENCES

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Table 1: Parameter values according to 25kV, 50kV and 100kV beam voltage, respectively

section	parameter	symbol	25kV	50kV	100kV	unit
main	frequency	f	91.392			GHz
	D.C. input	P_0	47.5	130	380	kW
	rf output	P	5.2	53	240	kW
	efficiency ($I_{rf}/I_0 = 1.6$)	η	11	41	63	%
	duty cycle		1:100			1
	pulse width		1			ms
beam	voltage	V_0	25	50	100	kV
	current	I_0	1.9	2.6	3.8	A
	beam width	w	10			mm
	beam height	h	0.4			mm
	current density	J_0	47.5	65.0	95.0	A/cm^2
	perveance per square	$K_\square$	19	9.3	4.81	nP
	resistance	R_0	13.2	19.2	26.3	kΩ
	velocity	v_0	0.302	0.413	0.548	c
	charge density	ϱ_0	$5.2 \cdot 10^{-3}$	$5.2 \cdot 10^{-3}$	$5.8 \cdot 10^{-3}$	C/m^3
	plasma frequency	ω_p	10.2	10.2	10.7	GHz
	reduced plasma frequency	ω_q	7.6	6.6	5.8	GHz
	reduced plasma wavelength	λ_q	75	118	178	mm
gun	mod. anode voltage	V_m	9	10	13	kV
	cathode width	w_c	10			mm
	cathode height	h_c	4.0			mm
	cathode loading	J_c	5.0	7.0	10.3	A/cm^2
	beam compression		10:1			1
focusing	period length	L_f	8.0			mm
	half-aperture	a_f	0.6			mm
	magnet thickness	t_f	2.0			mm
	field amplitude	B_0	60	53	47	mT
	pole tip field	$\hat{B}$	110	94	84	mT
	magnetization	M	87	75	67	kA/m
cavities	half-aperture	a	0.30			mm
	half-depth	b	0.92	0.90	0.89	mm
	gap length	g	0.40	0.55	0.75	mm
	shunt resistance p. cell	R	0.52	2.29	6.51	kΩ
	R/Q ratio p. cell	R/Q	0.42	1.48	3.52	Ω
	unloaded quality factor	Q	1260	1545	1850	1
	external quality factor	Q_{ext}	1260	1430	490	1
	number of cells (π-mode)	N	9	11	12	1