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Output Cavity Studies for a Low Voltage mm-Wave Sheet Beam Klystron

S. Solyga, H. Henke and W. Bruns

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Unfortunately, the efficiency predicted for such a device is very low, since at w-band the resonator impedances for a low voltage beam are small.

In this paper simple equations for the klystron efficiency are derived and the latest results from cavity and coupler design are presented. A final discussion deals with strategies for improving the performance of a low voltage mm-wave sheet beam klystron.

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The aim of our work is the design of a small and light, simple and cheap millimeter-wave source with medium power (10 to $50\mathrm{kW}$). Our present choice is a low voltage ($25\mathrm{kV}$) PPM focused klystron with a $1\mathrm{cm} \times 0.4\mathrm{mm}$ sheet beam carrying about $2\mathrm{A}$.

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1 INTRODUCTION

The advantages of the low voltage sheet beam concept are: A low voltage requires little x-ray shielding and a simple power supply only. A flat beam geometry keeps the current density at a moderate level which makes focusing easier and meets the requirements of microfabricational techniques, since the components will be planar.

However, this concept results in serious problems with cavity and coupler design: A low beam voltage results in large transit angles and the dissipated power is proportional to the cavity width. Thus, the shunt impedance will be small. Additionally, a sheet beam requires a flat cavity field across its width, which complicates the task of achieving a small external quality factor without destroying this flatness.

2 EFFICIENCY FORMULAS

Formulas for the conversion and circuit efficiencies have been derived by analysing the equivalent circuit shown in figure 1. The resonant circuit is driven by the rf beam current mI_0, where m is the modulation and I_0 the dc current component. R^* and R^*_{ext} are representations of the unloaded and the external shunt impedances $R = \mathrm{Re}^2\{V\}/2P|_{R^*_{ext}=0}$ and $R_{ext} = \mathrm{Re}\{V\}/2P|_{R^*=0}$, respectively. V is the voltage experienced by the beam and P the average converted power. Note, that the shunt impedances are transit time reduced.

Then, the conversion and circuit efficiencies are given by

$$\eta_{con} = \frac{m^2}{2}\frac{R_l}{R_0} \tag{1}$$

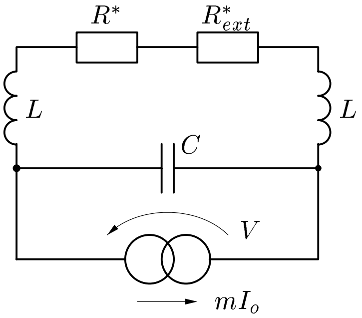

Figure 1: Equivalent circuit for a beam driven rf cavity resonator

$$\eta_{cir} = \frac{Q}{Q+Q_{ext}}, \tag{2}$$

where R_0 is the dc beam resistance, R_l the loaded shunt impedance, Q the unloaded and Q_{ext} the external quality factor of the cavity. Defining a saturation degree

$$\delta = \frac{V}{V_0} = m\frac{R_l}{R_0}, \tag{3}$$

which must be between 0 and 1, and the potential saturation degree

$$\theta = m\frac{R}{R_0} \tag{4}$$

– saturation is possible for $\theta \geq 1$ only – the overall efficiency becomes

$$\eta = \frac{m}{2}\delta\left(1-\frac{\delta}{\theta}\right), \tag{5}$$

with a relative maximum at $\delta = \theta/2$. Since

$$\delta = \frac{\theta}{1+Q/Q_{ext}} \leq 1, \tag{6}$$

the efficiency takes its absolute maximum

$$\eta_{max} = \frac{m}{2}\left\{\begin{array}{ll} \theta/4 & \text{for} \quad \theta \leq 2 \\ 1-1/\theta & \text{for} \quad \theta \geq 2 \end{array}\right. \tag{7}$$

at an external load of

$$Q_{ext} = \left\{\begin{array}{ll} Q & \text{for} \quad \theta \leq 2 \\ Q/(\theta-1) & \text{for} \quad \theta \geq 2 \end{array}\right. \tag{8}$$

These relationships are illustrated in figure 2.

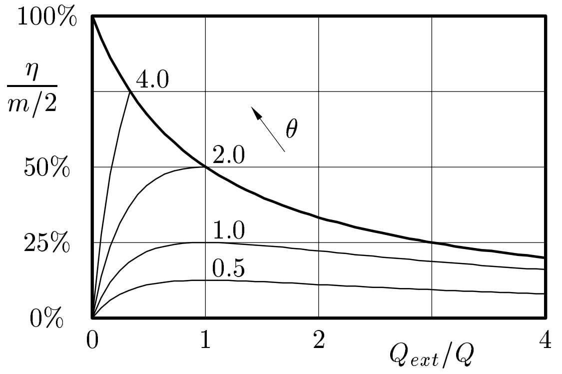

Figure 2: Klystron efficiency as a function of external to internal quality factor ratio for different potential saturation degrees. The thicker curve refers to saturation.

Thus we may conclude, that deep modulation, a large unloaded shunt impedance with respect to the beam resistance and a small external to unloaded quality factor ratio is required for highly efficient klystron operation. However, if the shunt impedance is less than the beam resistance, the external load needs only to be equal to the internal load, but the efficiency will be less than 50%.

These formulas are valid for standing wave operation. However, the field distribution in multicell resonators may depend on the terminating load. This effect has been investigated by means of three coupled resonant ciruits loaded at one end. The analysis turned out, that the load is equally distributed if the quality-bandwidth product is significantly larger than 1, which is usually the case. Thus, the single cell analysis will hold for multicell resonators also, as long as the number of cells is small.

3 CAVITY DESIGN

The major objectives in cavity design for a sheet beam klystron are a flat field across the whole beam width, a large shunt impedance and a large quality factor.

3.1 The Flat Field Problem

Figure 3 shows the general layout of a flat field cavity: The grooved waveguide of length w is operated at cut-off and terminated at both sides by $\lambda/4$-lines of length w_t. – A more detailed discussion can be found in [1]. – Since the field in the interaction region is independent of x and the terminating guides relatively short, the remaining design considerations are reduced to two dimensions.

3.2 The Shunt Impedance Problem

Figure 4 shows a simple cavity which has been investigated with the finite difference code GdfidL [2]. The aperture has been chosen to $0.6\mathrm{mm}$, since the beam thickness will be $0.4\mathrm{mm}$. The parameters of such a cavity for a $25\mathrm{kV}$ beam are shown in figure 5. Obviously, this cavity can-

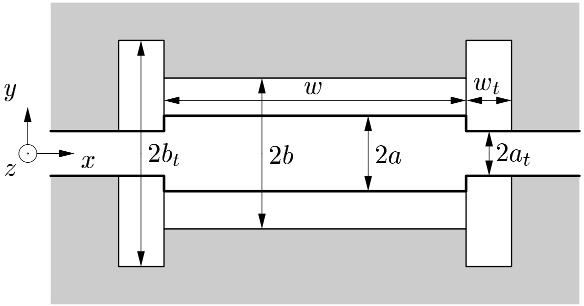

Figure 3: Cut of a general planar flat field cavity. Beam moves in z-direction.

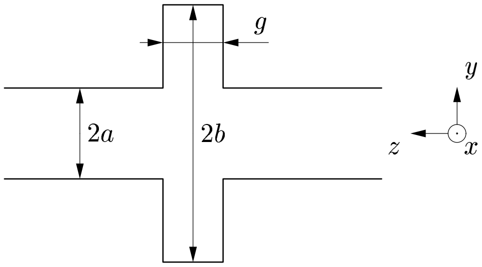

Figure 4: Two-dimensional single cell resonator for 91.39 GHz, optimized for maximum shunt impedance for a $\beta = 0.302$ beam: $a = 0.3\mathrm{mm}, b = 0.925\mathrm{mm}, g = 0.4\mathrm{mm}, Q = 1250, R' = 520\Omega\mathrm{cm}$.

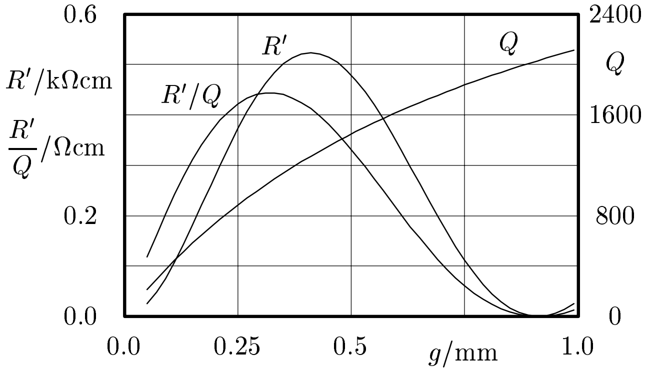

Figure 5: Parameters of the cavity from figure 4 as a function of gap width for fixed frequency.

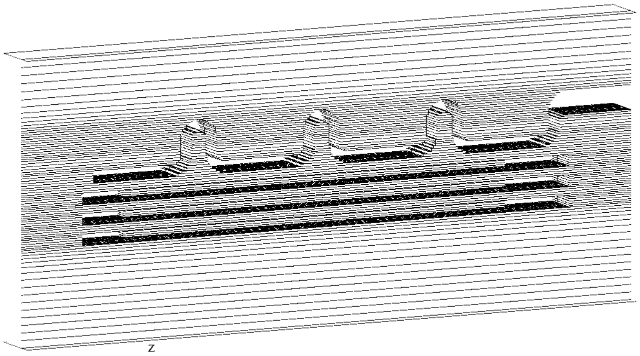

Figure 6: Lower half of a Snake-Coupler with a 3-cell flat field resonator ($Q_{ext} \approx 1000$).

not be used in a klystron but its parameters are useful for reference: Assuming a beam modulation $m = 1.6$ and a beam resistance[1] $R'_0 = 13\mathrm{k}\Omega\mathrm{cm}$, a shunt impedance $R'_{ref} = 520\Omega\mathrm{cm}$ results in a potential saturation degree $\theta_{ref} = 0.064$ and an efficiency $\eta_{ref} \approx 1\%$.

Since the beam already fills 60% of the tunnel, decreasing the aperture for shunt impedance improvement is unrealistic. Having the cell the usual reentrant geometry has been considered, but this neither results in a larger shunt impedance nor in a larger quality factor.

The final way is to stack a certain number of single cells. For synchronous operation, a period length of 1mm, 0.75mm and 0.5mm is needed for 2π-, $3\pi/2$- and π-mode, respectively. Simulations of a 3-cell resonator have shown, that independent of the operating mode, the maximum shunt impedance of an N-cell structure is exactly NR'_{ref} and is taken at the same gap width as for a single cell. Since the plasma wavelength is about $8\mathrm{cm}$, 5, 7 and 9 cells for 2π-, $3\pi/2$- and π-mode could be realistic. The corresponding quality factors are 1250, 1200 and 1000, respectively.

4 COUPLER DESIGN

As seen in figure 2, for a potential saturation degree less than 1 the external quality factor should be made equal to the internal, but the efficiency does not change significantly if it is somewhat greater. Thus, we need $Q_{ext} \approx Q/N$ for a single cell.

Since the transverse group velocity in a flat field cavity is small, the external quality factor cannot be made very low by coupling from the sides. This way we achieved $Q_{ext} \approx 1000$ for a single cell which is too large for a multicell resonator.

An alternative is coupling from the back with a parallel waveguide operated above cut-off, see figure 6. The interaction between the beam and the waveguide field should not disturb a proper operation significantly for three reasons: 1. if the phase is chosen properly the waveguide even increases the structure's shunt impedance, 2. the waveguide field will be relatively small and 3. the beam will be debunched when crossing the guide.

The operation of such a coupler may be explained as follows: If one attaches a simple grooved waveguide, almost no coupling is achieved, since the cavity width is several times the wavelength in the guide: half the coupler produces positive and the other half negative coupling. If we bend half of the guide length away from the cavity, the field near the cavity has everywhere the same direction and couples good to the uniform cavity field.

The external quality factor that has been achieved with this coupler is in the order of $Q_{ext} \approx 300$ for a single cell. Thus, with 5, 7 and 9 cells, the corresponding external quality factors were 1500, 2100 and 2700 and the efficiencies 6.3%, 8.3% and 9.1% for 2π-, $3\pi/2$- and π-mode, respectively.

5 DISCUSSION

Since the small potential saturation degree is responsible for the low efficiency predicted for the sheet beam klystron, there are essentially two ways for its improvement:

Decreasing the beam resistance. This can only be done by increasing the beam current per width, since decreasing the voltage meant even enlarging the transit time effect. The electric field in the gun is currently about $2.5\mathrm{MV/m}$, doubling the current would mean a field strength of $3.5\mathrm{MV/m}$. If the compression can be kept, this could be a way for doubling the efficiency.

Increasing the shunt impedance. If no better resonator geometries can be found, the only way is going to higher voltages. This would increase the impedance for two reasons: On the one hand the transit angle would reduce, and on the other hand the transverse dependence of the impedance would decrease, see [3]. Doubling the beam voltage would increase the shunt impedance by approximately 2.3. With the same electron gun, the beam resistance would decrease by 0.7, finally resulting in an efficiency increase by about 3.2.

6 REFERENCES

[1] S. Solyga and H. Henke, Two-Dimensional Design of a Low Voltage mm-Wave Sheet Beam Klystron, Proceedings of the 8th ITG-Conference on Displays and Vacuum Electronics, April 29-30, 1998, Garmisch-Partenkirchen, Germany, pp. 275-279

[2] W. Bruns, GdfidL: A Finite Difference Program for Arbitrarily Small Perturbations in Rectangular Geometries IEEE Transactions on Magnetics, vol. 32, no. 3, 1453-1456, May 1996

[3] S. Solyga, On the Transverse Dependence of the Shunt Impedance in 2-Dimensional Muffin-Tin Structures, TET-NOTE 98/05, TU-Berlin, April 1998 (internal paper, see http://www-tet.ee.tu-berlin.de/solyga/research/)

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[1] EGUN simulations of a 25kV electron gun have shown, that a current of $I'_0 \approx 2\mathrm{A/cm}$ at 0.4mm beam thickness and $\approx 5\mathrm{A/cm}^2$ cathode loading should be realistic, see [1].