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Sheet-Beam Klystron RF Cavities*

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Abstract

A high-frequency sheet-beam klystron operating at a low perveance per square can produce high peak power at high efficiency[1]. In order to provide beam stability and to maximize power extraction efficiency for a flat beam with a finite width, we have designed rf cavities in which the electric field is nearly constant across the width of the beam (on the order of several wavelengths). However, in such cavities, the electric field in the fundamental mode can couple to the TE propagating mode in the drift section if any cavity or beam asymmetry is present. The dipole field can couple between adjacent cavities even in the absence of these asymmetries as long as the frequency is above cutoff of the drift tube. The effects of coupling between rf cavities are calculated using an equivalent circuit model. Threshold parameters for onset of rf oscillation in the fundamental mode as a result of cavity coupling are obtained. We have designed choke cavities which effectively prevent such possible oscillations.

Introduction

The sheet-beam klystron (SBK), Fig. 1, can alleviate many limitations on the efficiency of conventional round-beam X-band klystrons. Some of these include space charge effects at high current densities, electrical breakdown across small gaps at high voltages, and potential metal melting due to beam interception at high power densities. By flattening out the beam spatially, the SBK significantly extenuates the space charge effects. It can achieve high power by sustaining a high total current, while keeping a low current density and a moderate voltage. It can also avoid the serious potential problem of metal melting by keeping a low power density. As a function of frequency, the power output of a sheet-beam klystron falls only linearly with wavelength, making it more suitable for high frequency applications.

In an earlier design study[1], we found that a sheet-beam klystron operating at 11.4 GHz and a low perveance per square (about 0.1 micro-perv.) is capable of producing over 200 MW of power at 65% efficiency. Typical operating parameters of a sheet-beam klystron are: a cross sectional area of 0.4 cm x 16 cm, a moderate voltage of about 400 keV, a strip gun compression ratio of 10:1, a cathode loading of 12 A/cm^2 and a longitudinal focusing field of 3 kG. These results were obtained with CONDOR simulations, in which cavities were treated as ports with proper voltages and phases. The cavity geometry must be established in a detailed design.

We consider in this paper several design issues unique to the sheet-beam klystron cavities. In rectangular cavities, the electric field is not uniform across the transverse direction perpendicular to the sheet beam. Electrons arriving at different points along the gap at the same time would experience different axial forces which could destroy the beam coherence downstream. Another potential problem is rf feedback for the fundamental TM mode between adjacent cavities. If this mode is coupled to an above-cutoff TE mode which is excited in the drift region, power can leak back upstream. This can occur, for instance, if there is asymmetry in the cavity or beam current as a result of manufacturing imperfections. Similar considerations apply to higher order modes, some of which can couple even in the absence of any such asymmetries. Fortunately, this problem can be cured, if necessary, by the use of one or more quarter-wave chokes. The conditions under which the choke joints are necessary will be established.

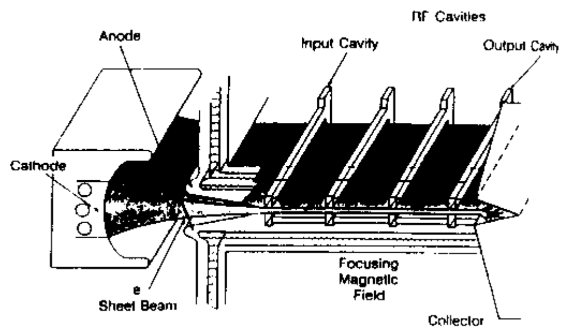

Figure 1 Schematic of Sheet Beam Klystron

SBK Cavity Design

The electric field of the lowest TM mode of a simple metallic rectangular cavity has a half sine distribution which peaks at the middle and vanishes at the boundaries. In order to accommodate a sheet beam several wavelengths wide, the rectangular cavity must be modified so that the axial electric field, at least in the region where the beam passes through, is approximately constant. One design strategy is to operate the center portion of the cavity near cutoff, with a widened portion about a quarter of a wavelength long at each end[2]. We have used the MAFIA code to design these cavities and found that good field uniformity can be achieved in this way. Fig. 2 shows the axial electric field of the fundamental mode at the midplane (perpendicular to the beam line) of such a "barbell" rectan-

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gular cavity, 12.6 cm wide and 6.885 mm high at the mid-section, and 1.3 cm high at the ends. The cavity is connected to a beam pipe 5 mm high. The cavity parameters calculated with MAFIA are f=11.42 GHz, Q_0= 6438 and R/Q_0= 17.3 ohms. The axial electric field of the fundamental mode as a function of the transverse distance along the centerline of the cavity is shown in Fig. 3.

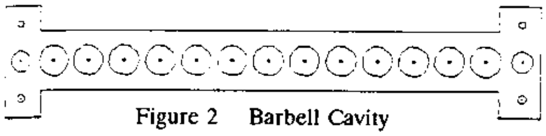

Figure 2 Barbell Cavity

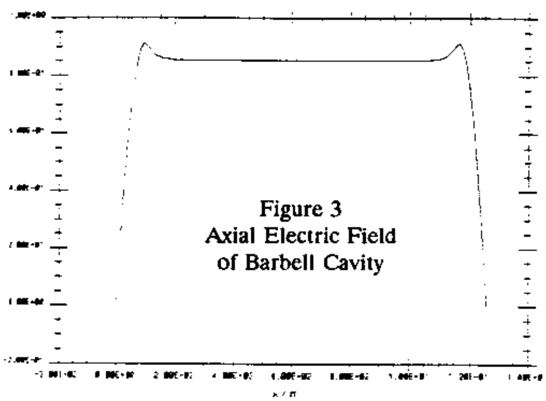

Figure 3
Axial Electric Field
of Barbell Cavity

Coupling between RF Cavities

The electric field of the fundamental mode of two rectangular cavities separated by a distance (2.32 cm) is shown in Figs. 4 and 5. In Fig. 4, each cavity is assumed to be perfectly symmetric about the center plane. The perfect symmetry in this case precludes any coupling between the cavities. In Fig. 5, a large artificial asymmetry is introduced in the cavity geometry: the height of the upper cavity is greater than that of the lower cavity by 14.3%. In this case, the TM cavity mode readily couples to a TE mode in the beam pipe. The coupling of the two cavities via the beam pipe splits the uncoupled frequency into two normal modes: a symmetrical and an antisymmetrical mode. The coupling strength k between the two asymmetric cavities is directly proportional to the frequency splitting, Δf. For these cavities, we find $k=\Delta f/f_0=0.0467$.

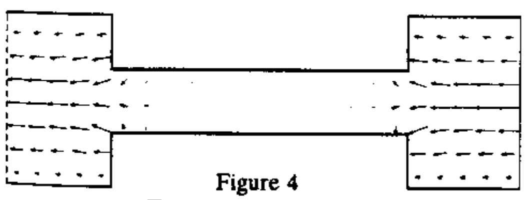

Figure 4
Fundamental Mode of
Two Coupled Symmetric Cavities

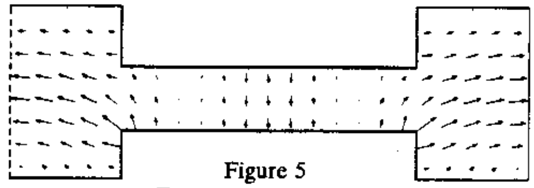

Figure 5
Fundamental Mode of
Two Coupled Asymmetric Cavities

Alternately, the external Q of an asymmetric cavity coupled to the beam pipe can be calculated using the Kroll-Yu (KY) method[3]. Making four URMEL runs with different pipe lengths, we find Q_{ext} = 246.

The electric field of the dipole mode for two coupled symmetrical cavities is shown in Fig. 6. Because the cavity field pattern for this mode reverses directions about the center plane, the asymmetry naturally allows coupling to TE in the beam pipe, resulting in strong coupling between the two cavities. The coupling constant and the external Q are calculated similarly as above. We find in this case k=0.127 and Q_{ext}=11.4. Introduction of an artificial cavity asymmetry as in Fig. 5 does not affect these results significantly.

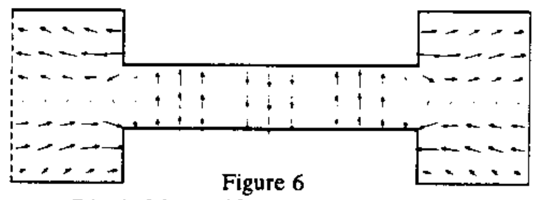

Figure 6
Dipole Mode of Two Coupled Cavities

The transient and steady-state cavity voltages of two coupled klystron cavities are calculated using an equivalent circuit model shown in Fig. 7. Each cavity is represented by a parallel RCL circuit. The circuit resistance, capacitance and inductance (R, C and L) are computed from the shunt impedance, frequency and R/Q_0 of the cavity.

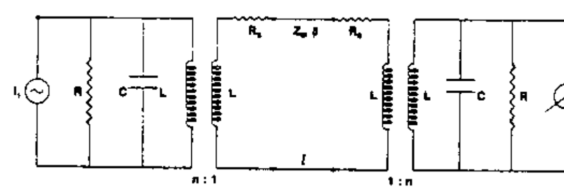

Figure 7 Equivalent Circuit

To simulate the klystron operation, the first cavity is driven by a current source at a frequency, ω, at or near the fundamental frequency of the cavity, $\omega_0=1/\sqrt{LC}$. The second cavity is driven by a current controlled by the voltage of the first cavity with a gain $g=I_2/Y_cV_1$, where I and V are the current and voltage of the respective cavity and Y_c is the cavity admittance, $Y_c=1/R+1/j\omega L+j\omega C$. The increased rf current in the second cavity results from velocity modulation of the beam due to its interaction with the first cavity and with the drift tube. The two cavity circuits are coupled by ideal transformers connected by a transmission line with a characteristic impedance Z_o and a phase delay, βl, where β and l are, respectively, the propagation constant and the length of the transmission line. The coupling constant[4] $\beta_o(=Q_o/Q_{ext})$ is also equal to the ratio of the transmission line transconductance to the cavity transconductance, divided by the square of the transformer turns ratio, or $\beta_o=(1/n^2)(R/Z_o)$. We use the PSPICE program to simulate the circuit performance. In general feedback in coupled cavities, if unabated, could lead to an exponential rise in voltages. However, with proper choice of parameters, it is possible to essentially uncouple the cavities. Fig. 8 shows a simulation in which the voltages gradually rise and reach steady state in a few rf cycles. The cavity parameters for this case are: $R=1 \times 10^5$ ohms, f=11.424 GHz, $R/Q_o=20$. The transformer is assumed to be perfect, i.e. n=1. The transmission line is characterized by $Z_o=1 \times 10^7$ ohms ($\beta_o=.01$) and $\beta l=\pi/2$. The second cavity is driven by a current gain of 10 over the first cavity.

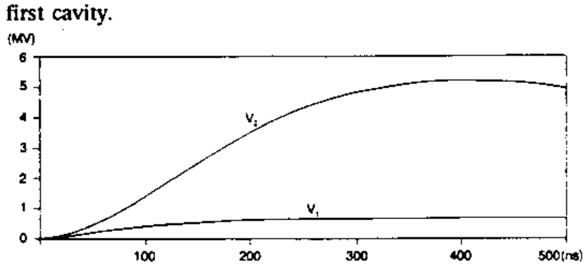

Figure 8 Transient Response from PSPICE Simulation

The allowable gain without onset of oscillation can be derived from the steady-state solution. Thus, we find

$$g=\frac{1}{\sqrt{1+x^2}}[2+jx(\frac{\beta_o}{y_c}+\frac{y_c}{\beta_o})] \quad ,$$

where $x \equiv \tan(\beta l)$, and

$$y_c=Y_c/G_c=Y_cR=1+j2Q_o\delta; \quad \delta=(\omega-\omega_o)/\omega_o \quad .$$

At critical coupling ($\beta_o=1$) the allowable gain is g=2 for any x. On the other hand, if $\beta_o \ll 1$, i.e. weak coupling or $Q_{ext} \gg Q_o$, then $|g| \approx 1/\beta_o$ except when x is close to zero. Thus to facilitate a gain of 10, for instance, the value of Q_{ext} must be greater than 6.4×10^4.

Parasitic oscillations between cavities can also be prevented using absorptive materials in the drift section, or using choke joints. The latter will be discussed in the next section. To simulate absorption, we add a series resistance, R_s, on either side of the transmission line in our circuit model. The series resistance has the effect of increasing the effective value of Z_o to $Z_o+R_s(R_s/Z_o)$. The cavity voltages can be stabilized in the presence of strong coupling by choosing a suitable value of R_s/Z_o.

Choke Joints

A very effective way to decouple adjacent resonating cavities at a given frequency is by placing a choke cavity an odd multiple of quarter wavelengths away from the end of the main cavity. The choke cavity height is about a quarter wavelength. Fig. 9 is an URMEL field plot of the fundamental mode of an asymmetric cavity with a choke joint. Compared with Fig. 5, the TE propagation in the beam pipe has been clearly halted by the choke. Using the KY method, we calculate Q_{ext} for this waveguide loaded cavity with the choke joint to be 9.9×10^4, sufficient to prevent oscillations up to a gain of 15. A choke joint for the dipole mode can be similarly designed. Fig. 10 shows an URMEL plot for this case. The calculated Q_{ext} for the dipole mode with choke is 5.9×10^3, compared to 11 with no choke.

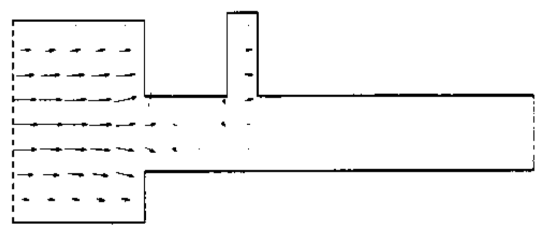

Figure 9 Choke Cavity for Fundamental Mode

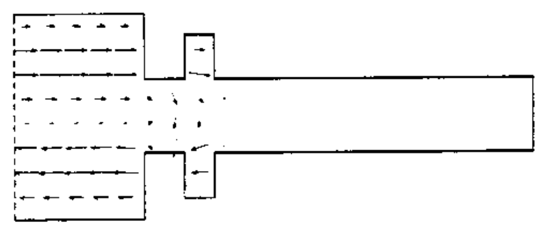

Figure 10 Choke Cavity for Dipole Mode

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