CONDOR SIMULATION OF AN 11.4-GHZ TRAVELING WAVE OUTPUT CAVITY*

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Abstract

The CONDOR code is used to simulate the cold test and the beam-induced microwave amplification of an 11.4-GHz, six-cell, disk-loaded, traveling wave cavity. Cold test simulation results are in agreement with a modified Slater's theory. Power extraction at the output port is calculated by launching a train of Gaussian electron bunches through the structure. Results are consistent with recent relativistic klystron experiments using a similar TW output cavity. It is further shown that, depending on operating beam parameters, the power extraction efficiency can be maximized by modification of various cells in the TW structure.

INTRODUCTION

Recently there has been a resurgent interest in the traveling wave (TW) amplifier as an output power extractor for high-power klystrons. One reason is that the peak electric fields at the gaps are lower for multiple cavities, thereby mitigating the possibility of breakdown and other anomalous beam loading at the output gap of high-power devices. Recent experiments by a SLAC/LLNL/LBL collaboration[1] generated over 300 MW of microwave power using an 11.4-GHz traveling wave amplifier driven by relativistic electron bunches from an induction linac. The experimental work was aimed to investigate the relativistic klystron concept as a high power microwave source for future high gradient accelerators. A six-cell, traveling wave (TW), $2\pi/3$ disk-loaded structure[2] was used as a power extractor. With this output cavity a threefold power enhancement over a standing wave cavity used in previous experiments was observed without any pulse shortening. The TW structure was able to achieve power levels of about 300 MW with a beam of 1.3 MeV of kinetic energy and 600 A of current.

This paper reports on an effort to numerically simulate the cold test and the beam-induced high power microwave amplification of TW ouput cavities using the CONDOR program. The CONDOR code is a self-consistent, 2-1/2 dimensional electromagnetic and particle time-domain simulation code. It has the capability of utilizing external ports for driving or extracting electromagnetic radiation from an rf structure. Results of the simulations are compared with theories and experiments.

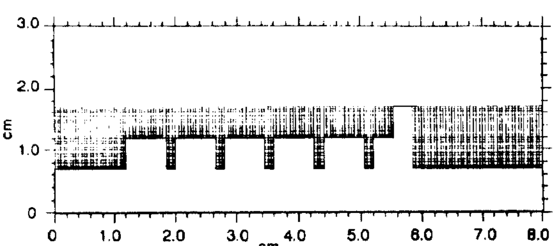

Fig. 1 Six-cell TW structure model

CONDOR SIMULATION

A six-cell TW cavity described in Figure 1 is used as the basic structure for simulation. The cavity diameter is 2.5 cm and the iris diameter is 1.5 cm. The disk thickness is 0.15 cm. The total cavity length is 4.65 cm. These dimensions are close, though not exactly the same as the cavity in references 1 and 2. They are conveniently chosen for this study so that the boundaries of the cells coincide with the mesh lines in a model of moderate size. An axisymmetric output port is opened in the last cell to extract rf power from the structure. The aperture of the output port is critically coupled to the last cell. This is done by launching an 11.4-GHz rf wave through the structure, and adjusting the output aperture dimensions until reflections into the last cell are eliminated. Using this cold test simulation technique, we study the axial electric field behavior along the cavity. Figure 2 is a 'snapshot' of the E_z field at steady state. The average wavelength is 2.91 cm, leading to an average phase velocity of 1.11c. The coupling of the cavity to the external port results in a tapering of the rf phase velocity from about 0.97c at the first cavity to about 1.24c at the output port. No attempt was made to optimize the phase velocities to synchronize with the electron velocity for maximum power extraction.

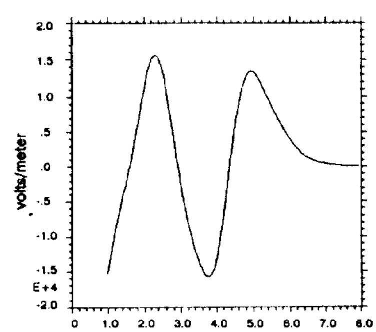

Fig. 2 Axial electric field at 6.5 nanoseconds

An important parameter which characterize any TW structure is the interaction impedance defined by $Z \equiv E_z^2/(K^2P)$, where K is the wavenumber and P is the power flow through the structure. The interaction impedance vs. axial length is plotted in Figure 3. It is seen that the impedance of the first cell is about 1/6 of the adjacent cells, implying a relatively low contribution of this cell to the overall power. The impedance of the last cell is expected to be low as the electric fields decay towards the output port (see Figure 2).

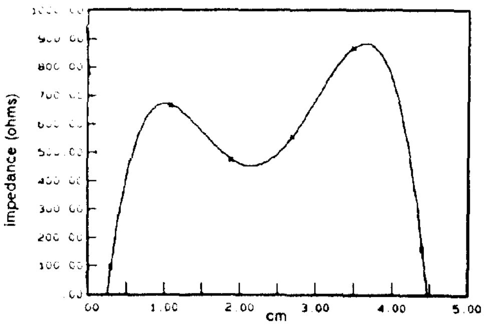

Fig. 3 Interaction impedance for 6-cell TW cavity

Introduction of beam loading into the rf structure is done by launching a fully bunched Gaussian beam with temporal width of 0.125T, where T is the rf period. The beam assumes a Maxwellian energy distribution of one percent around 1.2 MeV of kinetic energy. Figure 4 describes the electromagnetic spectrum of the output power for the case of 300 A of rf current. A second harmonic signal of 8 dB below fundamental (and a third harmonic) is observed. These harmonics reflect the spectral contents of the Gaussian bunches used in the simulation. The

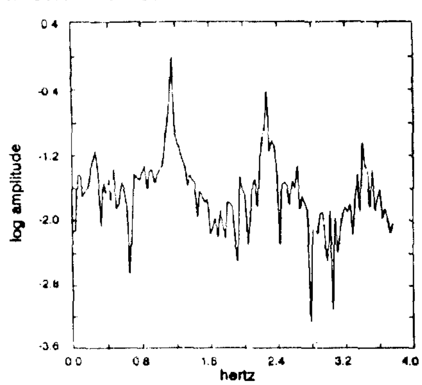

Fig. 4 Fourier components of output power

instantaneous power flow through the output port for a 1.2-MeV, 300-A driving beam is shown in Figure 5. After four nanoseconds of power overshooting, a steady state is

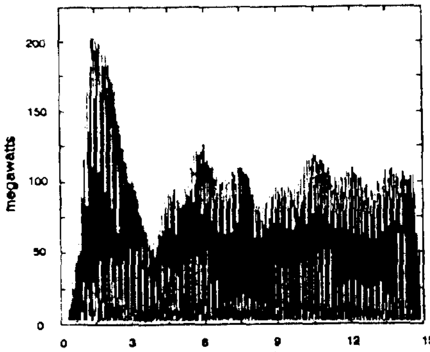

Fig. 5 Output power for a 6-cell cavity

established with an average power of 52.8 MW. Low frequency modulation of the rf power is observed throughout the entire pulse. Filtering or suppressing this modulation is required for stable phase operation. Figure 6 shows the output power vs. beam current. At low currents, the power increases quadratically. At higher currents, it varies linearly before tapering toward saturation. A peak power of 296 MW is achieved for an rf current of 700 A, with a saturated efficiency of 33%. The maximum electric field on the cavity surfaces under this operating condition does not exceed 1.2 MV/cm. Thus even without optimizing the TW structure, the CONDOR simulation is consistent with the experimental results of ref. 1.

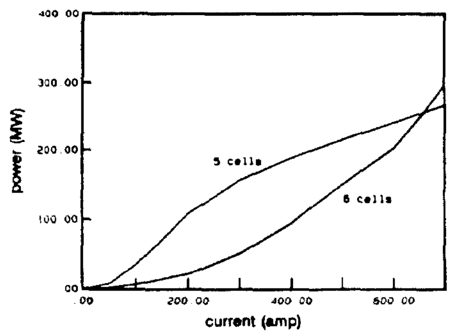

Fig. 6 Comparison of 5- and 6-cell cavity output power

By modifying various cells in the TW structure, the overall efficiency can be optimized for a given electron beam. For a 300-A, 1.2-MeV beam we have found that by applying high rf absorption to the first two cavities the efficiency increased from 14.8% to 16%. A substantial increase in efficiency is found in this case by reducing the cavity length from 4.65 cm to 4.0 cm while eliminating the first cell, leaving the structure with five cells. A peak rf power of 172 MW is obtained for a 1.2-MeV, 300-A beam with this configuration. The power further increases somewhat with a small increase in the volume of the first cell. Finally we maximize the rf efficiency to about 43%, or 156 MW of power, for the geometry given in Figure 7. As shown in Figure 6, the efficiency is beam dependent and slowly decreases from 43% at 300 A to 32% at 700 A.

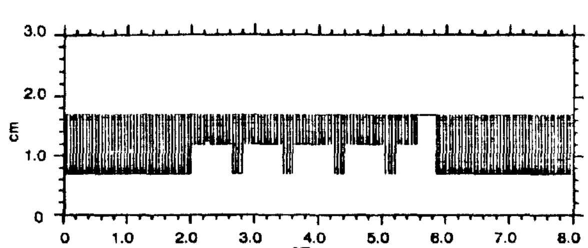

Fig. 7 Five-cell TW structure model

DISCUSSIONS

It is interesting to note that the numerical results for cold test in the last section agree well with J.C. Slater's theory, but not with J.R. Pierce's analysis of TW periodically loaded waveguide. The cold test phase velocity predicted by Pierce for an infinite periodic structure with our six-cell geometry is 0.37c, compared with 0.97c to 1.24c variation obtained by the CONDOR code. Moreover the TW interaction impedance predicted by Pierce is about 8 ohms for this geometry, compared with the variation between 100 ohm to 900 ohm seen in Figure 3. The discrepancy is likely attributed to negligence in treating field distortion around the irises in Pierce's theory. Cold test numerical results, on the other hand, match quite well with the theory of periodic structures developed by J.C. Slater. A phase velocity of 1.14c is predicted for an infinitely long TW structure with about 600 ohms of interaction impedance.

Slater's approach can also be adopted for a finite-length structure as we show below. In this approach, a single cell is viewed as a two port (or four terminal) rf structure in which the iris is treated as a lump susceptance. Using Slater's notation the transverse electric and magnetic fields are related by:

$$I_n = iV_nY_0\,[\cot(kL)-b_0] - iV_{n+1}Y_0 csc(kL)$$

$$I_{n+1} = iV_nY_0 csc(kL) - iV_{n+1}Y_0\cot(kL)$$

where k is the wavenumber and L the length of a single cell, Y_0 is the waveguide admittance, $-ib_0Y_0$ is the iris susceptance, I_n and V_n are respectively the transverse magnetic and electric field for the nth cell. Eliminating I_n from two successive cells gives the relation among V_n:

$$V_{n+2} - V_{n+1}A + V_n = 0$$

For an infinitely long periodic structure one can substitute $V=V_0\exp(igL)$ to obtain an expression for the wavenumber:

$$\cos(gL) = \cos(kL) - \frac{b_0}{2}\sin(kL)$$

with the phase velocity given by $v_p = \omega/g$. For a finite length structure, the above equation for V_n becomes a matrix equation to which we have to apply appropriate boundary conditions at the ends of the structure. As an example we outline a design procedure for a six-cell cavity. Requiring zero transverse electric field on the l.h.s. of the cavity and a given reflection coefficient ρ on the r.h.s., we obtain a 4x4 matrix whose eigenvalues are given by the solutions of the secular equation:

$$(A^2-1)+(A_f-A)A(A^2-2)=0$$

$$A_f = iZ[\sin(kL_6) + iZ\cos(kL_6)]^{-1}$$

where $Z=(1+\rho)/(1-\rho)$, and L_6 is the effective length of the last cell. We obtain immediately a particular solution for V_n, i.e. $V_1=0$, $V_2=1$, $V_3=A$, $V_4=A^2-1$, $V_5=A(A^2-2)$, and $V_6=A_fA(A^2-2)$. Starting with a closed cavity ($\rho=-1$), we can solve the secular equation analytically to give four modes which have, respectively, π/6, π/3, π/2 and 2π/3 phase shift per cell. The cell dispersion relation is given by:

$$A = 2\cos(kL) - b_0\sin(kL)$$

$$\textit{where} \qquad A = \pm\sqrt{\frac{3}{2}\pm\frac{\sqrt{5}}{2}}, \qquad k = \sqrt{\left(\frac{\omega}{c}\right)^2 - \left(\frac{2.405}{R_w}\right)^2}$$

for the propagating mode in the cell. R_w is the cavity radius. Given the operation frequency f and the beam energy the length of each cell is determined by the requirement of synchronizing the electron velocity with the phase velocity (v_p). For example, $L=v_p/3f$ for 2π/3 mode, and $L=v_p/4f$ for π/2 mode. The wall radius is determined for a given iris susceptance. The iris susceptance can be calculated using the SUPERFISH code ($b_0=0.99$ in our CONDOR runs). Next, changing the reflection coefficient ρ from -1 to 0 will allow for output power flow. For a given value of ρ, an eigenvalue k (now complex) is obtained from the secular equation for the mode of interest. To keep the cavity on resonance, the wall radius, R_w, can be obtained from the real part of k. Finally, the waveguide-loaded Q of the TW cavity is determined by the imaginary part of k. A further extension of the modified Slater method to include beam loading for a finite length structure is being considered.

SUMMARY

We have presented numerical simulation results for a TW output cavity using the CONDOR code. The results are consistent with data from recent relativistic klystron experiments. It is shown that the simulation technique can be a useful tool to complement other TW cavity design methods. A simple design procedure has been outlined to determine the dimensions of the TW cavity.

ACKNOWLEDGEMENTS

We thank S.T. Brandon and R. Ryne of LLNL, and P. D. Coleman of SSC Laboratory for helpful discussions.

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*Work supported by DOE SBIR grant DE-FG03-90ER81080
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