High Power X–Band Coaxial Amplifier Experiments

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Abstract

Studies are continuing on the development of X–band coaxial microwave amplifiers as a source for next generation linear colliders. Coaxial amplifiers employ an annular electron beam propagating between inner and outer drift tube conductors, a configuration which allows large increases in beam current over standard pencil beam amplifiers. Large average diameter systems may still be used without mode competition since TM mode cutoff frequencies are controlled by the separation between conductors. A number of amplifier configurations are being studied, all primed by a driven initial cavity which resonates around 9 GHz. Simple theory of coaxial systems and particle-in-cell simulations are presented, as well as initial experimental results using a 420 keV, 7–8 kA, 9 cm diameter annular beam.

I. Introduction

Next generation designs of e^+e^- linear colliders have set stringent requirements on the r.f. drive source. In order to achieve the high accelerating gradients (>100 MeV/m) necessary for ~ TeV beam energies, an r.f. driver operating above X–band and 500 MW peak power levels will be needed. Several competing technologies for this source are currently being examined, including intensive efforts in relativistic klystrons [1] and gyroklystrons [2]. A developing method is to use binary energy compression [3] to raise the peak power and reduce the pulse length of a lower power tube.

Without the need for pulse compression, an alternative to these hollow tube amplifier configurations is the development of coaxial amplifiers. This geometry uses an annular electron beam propagating between inner and outer drift tube conductors. Previous coaxial high power microwave devices have been built in oscillator configurations [4], and lower frequency (~ 1 GHz) coaxial amplifiers may be capable of ultra–high powers [5].

The coaxial geometry addresses two fundamental limitations of hollow tube devices. First, the use of a large average diameter system reduces the power density (and hence the surface fields) for a given power level, effectively by increasing the cross sectional area of the device. This reduces the possibility of r.f. pulse shortening and field emission in the microwave structures, conditions often seen in highly stressed relativistic klystrons. Second, the coaxial geometry allows for propagation of much higher current beams than conventional pencil beam amplifiers, as a result of increases in both the beam cross sectional area and the limiting current of the system. This increase in beam current, up to a factor of ten in many instances, may enable a higher peak power device at lower beam energies, hence at considerably lower cost. The coaxial configuration does allow TEM as well as higher order TE modes to propagate in the drift regions of the system. Single TM mode interactions may still be designed, since the cutoff frequencies of these modes is controlled only by the separation distance between conductors, not the average diameter. However, control of the TEM and TE modes remains the most difficult problem in design and operation of these amplifiers.

II. Design

The simplest conceptual design for a coaxial amplifier is illustrated in figure 1. An annular electron beam is propagated along the coaxial drift region and is initially modulated by a driven input cavity. The modulated beam is then passed through downstream sections, shown in the figure as a rippled wall slow wave structure (but just as easily other cavities or a mixture of both), to enhance the beam modulation and extract power.

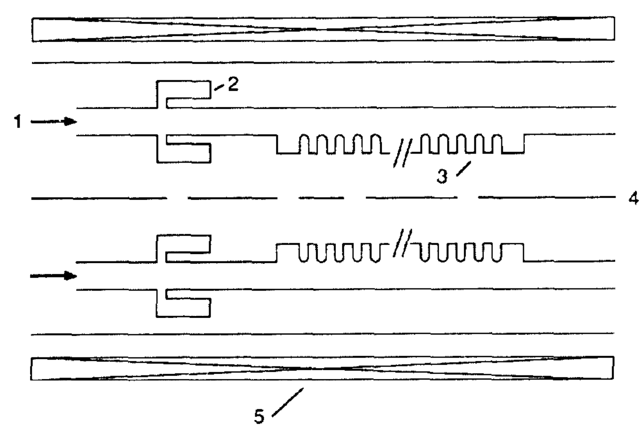

Fig 1. Simple coaxial amplifier. (1) Annular electron beam, (2) driven input cavity, (3) slow wave structure, (4) centerline, (5) field coils.

The input cavity geometry, designed using the SUPERFISH code, oscillates in a 5/2 wavelength mode with a maximal axial electric field at the beam location. $5/2\lambda$ is the approximate bounce length of a TEM wave traveling between inner and outer sections of the cavity. This geometry was chosen for its comparatively high Q factors and manufacturing ease relative to other designs.

Coaxial slow wave structure designs are straightforward extensions of their hollow tube counterparts. Either

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periodic or Cerenkov structures can be used to create the $v_\phi < c$ condition needed for direct beam interaction. Doubly lined coaxial Cerenkov systems have been studied analytically [6]. Note, however, that a dielectric liner on only the inner or outer conductor may also force a $v_\phi < c$ condition. As an example, the dispersion relation for azimuthally symmetric modes in a coaxial system with a dielectric liner on the inner conductor only is

$$\frac{J_0(k_2 r_{id})Y_0(k_2 r_o) - J_0(k_2 r_o)Y_0(k_2 r_{id})}{J_0(k_1 r_{id})Y_0(k_1 r_i) - J_0(k_1 r_i)Y_0(k_1 r_{id})} = \frac{k_1}{k_2 \epsilon} \frac{J_0'(k_2 r_{id})Y_0(k_2 r_o) - J_0(k_2 r_o)Y_0'(k_2 r_{id})}{J_0'(k_1 r_{id})Y_0(k_1 r_i) - J_0(k_1 r_i)Y_0'(k_1 r_{id})} \quad (1)$$

where $k_1^2 = \omega^2 \epsilon / c^2 - \beta^2$ and $k_2^2 = \omega^2/c^2 - \beta^2$ are complex, β is the wavenumber, ϵ is the relative dielectric constant of the liner, and r_i, r_o, and r_{id} are the inner conductor, outer conductor, and dielectric radius respectively. Figure 2 compares dispersion relations for a coaxial system

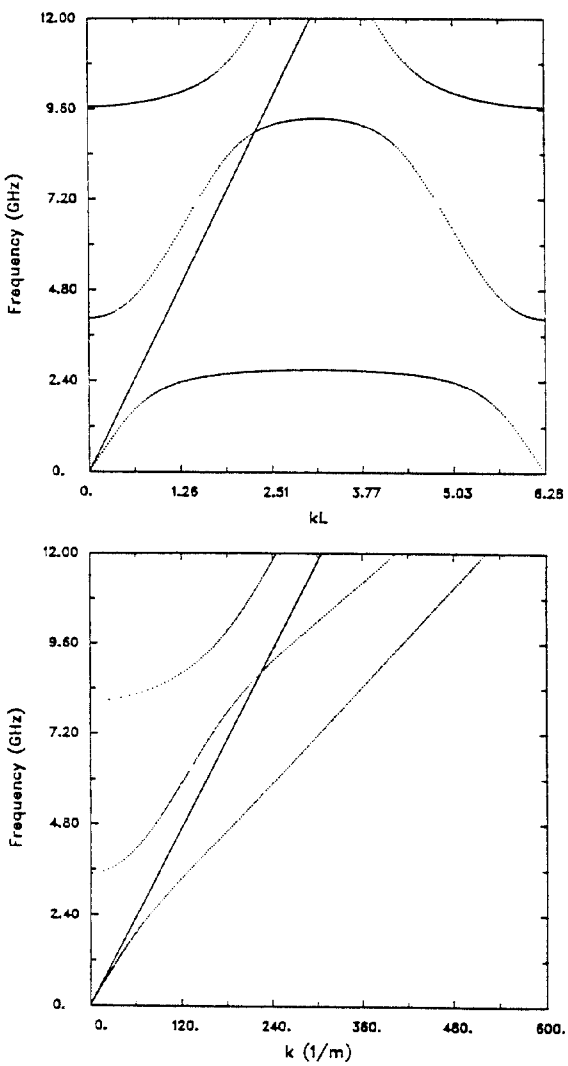

Fig 2. Comparison of dispersion relations for a coaxial system with a periodic inner conductor (above) and a dielectric lined inner conductor (below). Solid lines are beam parameters.

with a periodic inner conductor and with a dielectric lined inner conductor. Both are designed to have forward wave interactions near 9 GHz. Both also exhibit a TEM-like mode down to zero frequency. But due to broad tunability and ease of modeling, design, and manufacturing, dielectric liners will initially be used in the experiments.

III. Simulations

Various components of these amplifiers have been simulated using the 2 1/2D particle-in-cell code MAGIC. The geometry of the simulation space and beam parameters exactly follow the real experimental quantities. Cavity and structure frequencies are determined by cold tests without particles. The simulation geometry is closed using absorbing boundaries to eliminate any wave reflections at the end of the drift space.

Multiple cavity klystron geometries have been tested and compared to hollow tube relativistic klystron simulations. Unlike the pencil beam case and coaxial klystron simulations reported elsewhere [5], this coaxial system fails to exhibit gain even though substantial modulation can be imposed on the beam. This discrepancy could be due to two factors. First, due to the nature of the time advance algorithm, simulation cavities tend to have low Q factors (<50) and hence maintain very little stored energy relative to actual cavities. Second, and more important, the use of a slightly overmoded cavity (as in the $5/2\lambda$ design) increases the harmonic content of the beam modulation and degrades the efficiency of the output coupling. A better method for system gain is the use of a single mode traveling wave structure.

The dielectric interaction shown previously has recently been simulated using new capabilities in MAGIC. The propagation characteristics of the structure wave match those predicted by the analytic theory. A driven cavity, identical in frequency to the predicted interaction, has been used to impose initial modulation on the beam prior to the dielectric structure. As shown in figure 3, the bunching process started by the cavity is enhanced due to the unstable interaction in the dielectric region.

IV. Experiments

The electron beam in the experiments is generated using a modified ETA module with a 2:1 output ferrite core transformer. The output voltage of this system is 400–500 kV at nominally 40 ohms. A one Tesla solenoidal magnetic field guides the beam down a drift tube of 7.5 cm inner diameter and 9.8 cm outer diameter. Within this drift space no TM mode will propagate.

A number of field emission foilless diode geometries were tested to maximize beam current and optimize beam propagation. Currently, a conical cathode with a graphite knife edge is used to create a uniform beam of 9 cm diameter and 2 mm thickness. The geometry of the diode and equipotential contours is shown in figure 4. This arrangement consistently produces currents of 7–8 kA at

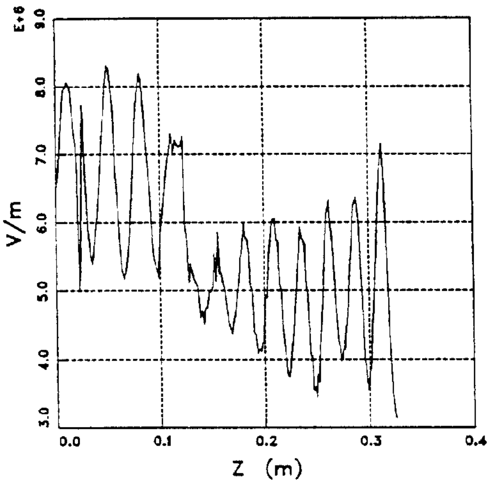

Fig 3. A simulation plot of E_r vs. distance, showing bunching enhancement past the discontinuity where a dielectric liner begins.

420 kV pulse voltages. The conical shape inhibits shank emission, reducing the beam thickness and temperature. Beam propagation and uniformity has been measured using thermal damage paper and is found to be consistent over the meter propagation distance.

Experiments are continuing to characterize the $5/2\lambda$ cavity. The initial coupling arrangement to the cavity was found to excite numerous higher order azimuthal modes and has been changed to a more uniform and higher power cylindrical–coaxial transition. Wires mounted across the cavity aperture have been used to raise cavity Q and isolate resonant peaks, but are too susceptible to beam damage to be used consistently in experiments.

A network analyzer trace of the cavity resonances is shown in figure 5. The dominant resonance is broadband due to coupling of energy out of the cavity aperture. Other peaks correspond to the high order azimuthal modes. Current experiments are attempting to measure the modulation resulting from this cavity using $\dot{B}_\theta$ probes mounted on the drift tube.

V. Conclusions

The choice of a coaxial geometry enables the use of high current, large diameter annular beams, and allows for greater output powers because of reduced surface fields. Since breakdown limits are relaxed, a dielectric lined traveling wave structure is planned to provide a substantial fraction of system gain. Experiments are continuing to characterize the driven input cavity, an essential part of several amplifier configurations.

VI. Acknowledgements

This work was supported by the U. S. Department of Energy, under contract #DE-AC02-80ER10569, and in part by AFOSR and SDIO–IST managed by Harry Diamond Laboratories.

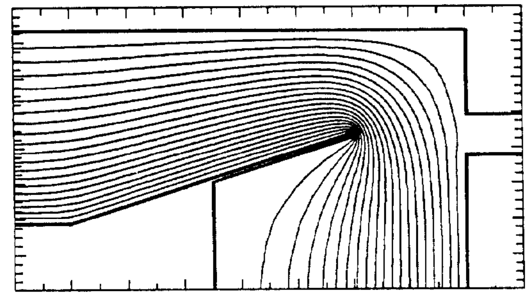

Fig 4. Equipotential contours of annular beam diode.

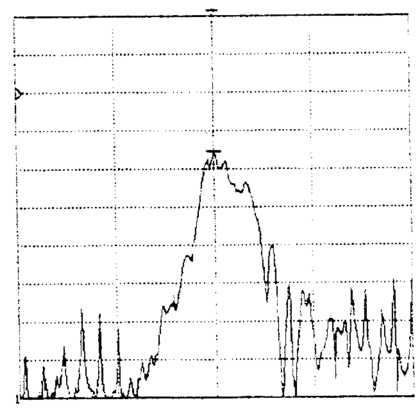

Fig 5. Network analyzer trace of resonances in $5/2\lambda$ cavity.

The MAGIC particle–in–cell code was obtained from Mission Research Corporation through the sponsorship of AFOSR.

VII. References

[1] M.A. Allen et al., "Relativistic Klystrons," in *Proceedings of the 1989 Particle Accelerator Conference*, Chicago, Ill., March 1989, pp. 1123–1127.

[2] K.R. Chu, V.L. Granatstein, P.E. Latham, W. Lawson, and C.D. Striffler, "A 30-MW Gyroklystron–Amplifier Design for High–Energy Linear Accelerators," IEEE Trans. Plasma Sci., vol. 13, pp. 424–434, December 1985.

[3] Z.D. Farkas, "Binary Peak Power Multiplier and its Application to Linear Accelerator Design," IEEE Trans. Microwave Theory Tech., vol. 34, pp. 1036–1043, October 1986.

[4] John A. Nation, "On the Coupling of an High–Current Relativistic Electron Beam to a Slow Wave Structure," Appl. Phys. Lett., vol. 17, pp. 491–494, December 1970.

[5] J. Krall, M. Friedman, Y.Y. Lau, and V. Serlin, "Simulation Studies of a Klystronlike Amplifier Operating in the 10–100 GW Regime," NRL Memorandum Report 6750, November 1990.

[6] Eusebio P. Garate, Amnon Fisher, and William G. Main, "Coaxial Configuration of the Dielectric Cherenkov Maser," IEEE Trans. Plasma Sci., vol. 18, pp. 831–836, October 1990.