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A MICROWAVE POWER DRIVER FOR LINAC COLLIDERS GIGATRON

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ABSTRACT

The gigatron is a new rf amplifier tube designed for linac collider applications. Three design features permit extension of the lasertron concept to very high frequencies. First, a gated field-emitter array is employed for the modulated cathode. Second, a ribbon beam geometry mitigates space charge depression and facilitates efficient output coupling. Third, a traveling wave output coupler is used to obtain optimum coupling to the ribbon beam. This paper describes recent developments in the gigatron design, and progress towards experimental tests.

I. INTRODUCTION

This paper describes recent progress in the development of gigatron as a high-power microwave driver for future e^+e^- linac colliders.[1] The gigatron design concept has been described previously.[2] We have evaluated its design for the parameters required for most TeV linac collider designs:

rf frequency	10-30 GHz
rf power	>100 MW
efficiency	>50%.

The only rf devices with comparable capability are the relativistic klystron[3] and the gyroklystron[4]. By comparison to either of these the gigatron offers a simple, compact structure and low capital cost.

In the gigatron a bunched electron beam is extracted from a field emitter array (FEA) cathode, and accelerated through a pulse-modulated high-voltage diode as shown in Figure 1. The resulting beam is fully modulated at high energy without the requirements of modulator and drift region that characterize all conventional amplifier tubes. RF energy is then extracted from the beam in an output coupler. Since the bunching process is a dominant limitation to high power-high frequency operation in conventional tubes, this approach results in high performance for the above design parameters.

Three features of the gigatron design extend its performance to very high frequency and peak power. First, a ribbon beam geometry is adopted rather than the conventional round beam. Second, a traveling wave output coupler is used to achieve optimum output coupling across a wide beam. Third, a gated field emitter array (FEA) is employed for the cathode; this appears to offer a simple, reliable modulated cathode for microwave applications.

By the beginning of the past year we had calculated the beam dynamics in gigatron and verified the impressive performance estimated earlier. During the past year we have addressed three design issues raised in reviews of the gigatron technology. First, it was suggested that the ribbon beam might be unstable, since many previous ribbon beam devices have proven unstable. Detailed calculations have demonstrated that the gigatron beam is in fact extremely stable to a variety of perturbations over the full range of parameters contemplated. The reason for this is simply that the gigatron approaches a switch tube geometry: the beam has no time in which for instabilities to grow. From cathode to collector is ~6 rf cycles.

Second, it was suggested that the traveling wave coupler might have parasitic modes that could compromise the coupling to the desired loop-resonant traveling wave. We have shown that, by distributing the beam-wave coupling along ~ half the circumference of a loop-resonant circuit, higher-order modes (corresponding to different harmonics of the loop-resonant frequency) are in fact naturally suppressed. Only transverse harmonics remain; these occur at multiples of the operating frequency and are weakly coupled to the beam. The waveguide coupler thus appears to be a particularly benign structure for this traditional tube designer's headache.

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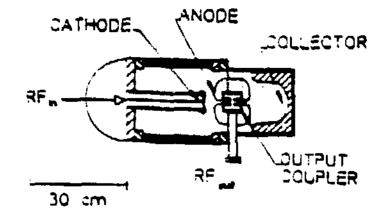

Figure 1. Cross section of gigatron.

The third problem is more substantial: microwave modulation of the FEA cathode. FEA cathodes have been built by several groups,[5,6,7] and have achieved impressive performance. Currents of >100A/cm² have been achieved. Extended life-cycle tests show no deterioration during a year of continuous operation. But these results were obtained in DC operation. The FEA gate structure presents a highly capacitive load to a modulation driver. The charging resistance R through the silicon substrate appears in series with the gate capacitance C and renders the FEA cathode configurations built by previous authors unworkable at microwave frequencies.

During the past year we have developed several specific improvements to FEA cathode design that together overcome this problem. First, a base layer metalization is incorporated so that charging currents flow in metal rather than silicon. Second, we configure the cathode as a lumped-constant resonant circuit (Q ~100), which is matched to a 50 Ω modulator input. With these improvements the system gain of gigatron is ~25-30 dB.

II. GIGATRON DESIGN CONCEPT

The gigatron is a design for a compact, efficient microwave power amplifier tube. It employs the lasertron concept,[8,9] in which a bunched electron beam is extracted from a modulated cathode and accelerated through a high-voltage diode structure. Several significant innovations have been introduced to achieve high efficiency, high frequency, and high power. The principle of operation is illustrated in Figure 2. A fully modulated ribbon electron beam is produced from a strip cathode of gated field-emitter array (FEA). The ribbon beam is accelerated through a high-voltage diode structure, and enters a drift slot leading to the output coupler. The output coupler consists of a slotted waveguide connected to form a resonant loop. The waveguide slot is configured to permit passage of the ribbon beam through the waveguide, parallel to the electric field of a traveling wave. The electron beam is decelerated by the wave, and thereby drives the wave amplitude. Optimum phase match to the electron beam is maintained over an arbitrary beam width by phasing the electron beam emission from the cathode to tilt the ribbons with respect to the direction of acceleration. By a

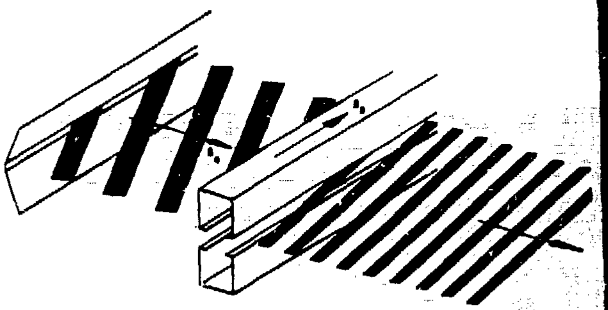

Figure 2. Ribbon beam geometry and traveling wave coupler.

suitable matching condition, the transverse position of the electron packet traversing the coupler slot can be made to move sideways at the same rate as the phase velocity of the traveling wave. The beam "surfs" with the wave, and optimum coupling can be preserved over an arbitrary beam width.

The advantages of the gigatron include a) low-loss coupling of input power to the FEA structure; b) e-beam fully modulated before acceleration; c) elimination of space-charge limits to high power/high frequency by using ribbon beam geometry; d) close coupling to the ribbon beam in the output coupler reduces phase dispersion at high frequency; e) provision of optimum output coupling over a wide beam front, using the traveling wave coupler; e) elimination of the requirement for static guide fields that characterize nearly all high frequency power tubes; f) simple, compact structure. Table I summarizes the important parameters of a particular design which has been evaluated recently.[2] The following text describes each aspect of the gigatron design. Numerical calculations are specific to the parameters of Table I.

1. Gated field-emitter cathode. The gated field-emitter (FEA) cathode appears to offer an attractive new technology for achieving a high current, fully modulated electron beam directly from a cathode structure. C.S. Spindt et al.[5] and H. Gray et al.[6] have developed microfabrication techniques by which they can prepare planar arrays of field-emitting points. Gray uses directional etching techniques to produce atomically sharp needle and knife-edge arrays directly on silicon. A silicon-insulator-metal gate structure is then deposited on the cathode substrate, and plasma-etched to form a planar array of micro triodes. Application of a modest (25 V rms) gate-cathode voltage results in full modulation of emission current. Currents of >100 A/cm² have been routinely achieved. There is no evidence of in-service deterioration during extended life tests.[5]

We have improved upon the fabrication procedure of Gray in two respects that are critical to achieve high-frequency modulation.

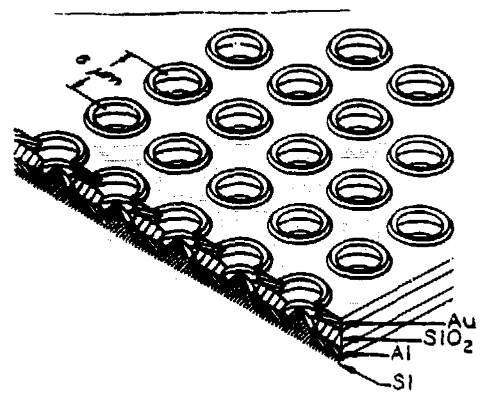

Figure 3. Gated field emitter array cathode.

First, the silicon surface is metalized after formation of the field-emitting tips, as shown in Fig. 3. This provides a metal base surface for low-impedance charging of the FEA tips. In the devices fabricated by Gray[4] and Spindt[5], charging current must flow through the bulk of the silicon substrate. Even with heavy doping, the silicon substrate presents an unacceptable charging resistance (ρ >.01 Ω cm) at high frequency.

Second, a fabrication process has been devised whereby an optimum field geometry can be produced for quiesent electron optics. The optics of the electron beam emission from the FEA cathode determines the initial emittance of the beam in the gigatron. We have calculated the beam dynamics during field emission using the computer code MASK[6]. Beam is assumed to be emitted from the tip into a cone of half-angle $\pi/4$. Figure 4 shows the transport at several time intervals after emission. The tip/gate geometry of the cathode forms an approximate point-to-parallel optical lens. As a result the emitted beam will have a much smaller emittance than the previous estimates based simply on assuming a transverse temperature $T_\perp \sim eV_m$. The beam divergence produces negligible transverse growth at the anode aperture, and hence does not pose a limitation to gigatron performance. If in fact the effective emittance is very small, the improved FEA cathode may be an excellent candidate for electron sources for linacs, FEL's etc.

2. Resonant input coupler. The field-emitter array presents a highly reactive load to a modulation driver. Matching can be optimized by configuring the cathode within a sequence of coupled lumped-constant resonant circuits, as shown in Figure 5. The gate/base junction of the FEA constitutes a capacitance C_1. A metalized quartz fiber is mounted adjacent to the FEA, and the metal-insulator-metal layers (without tips) are continued laterally to form a tuning capacitance C_2. The gate layer metalization and quartz fiber metalization are interrupted along the region where the fiber contacts the insulating layer, so that rf currents to/from the gate layer must flow around

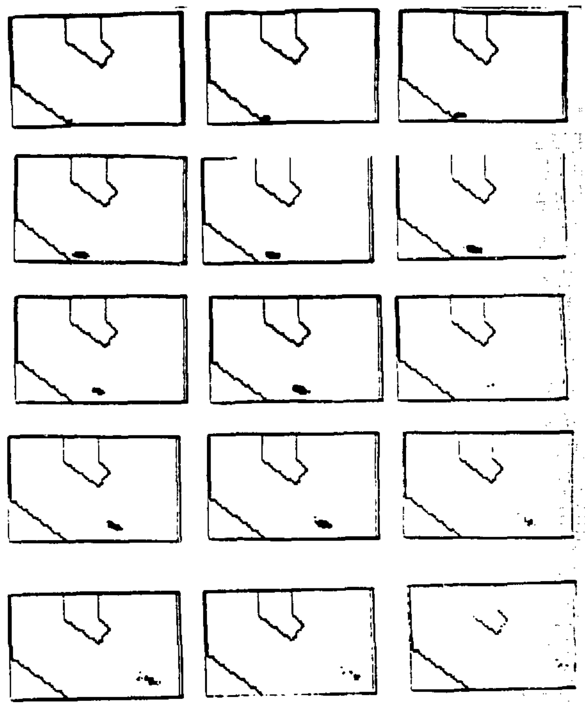

Figure 4. Acceleration of an electron bunch from an FEA cathode.

the fiber - it is an inductor L. The system C_1 - L - C_2 then forms a resonant circuit whose frequency can be controlled by choice of the radius r of the inductive fiber:

$$L = \mu_o \pi r^2 / x \qquad (1)$$

The cathode and resonant coupler are divided lengthwise into segments of equal length x = 5 mm. The metalized inductor is fabricated separately and bonded to the gate layers of C_1 and C_2 by conventional ultrasonic bonding.

Figure 6 shows an equivalent circuit of the cathode system, including dc bias network, resonant network, and impedance matching network. Each resonant circuit is capacitively coupled (C_c) to an impedance matching network which matches rf power from a waveguide into the sequence of input couplers. Resonance occurs at an angular frequency

$$\omega = \frac{1}{\sqrt{LC_o}} \qquad (2)$$

where C_o is the equivalent capacitance of C_1, C_2, C_c. The resistance R in the equivalent circuit is the effective series resistance to current flow in the resonant circuit:

$$R = (\tfrac{4}{\pi} w + 2\pi r)\, R_s / x \qquad (3)$$

where R_s = .04 Ω is the surface resistance of the metalizations.

The Q of the resonant circuit is

$$Q = \frac{1}{\omega C_o R} = \frac{2}{\omega C_1 R} \qquad (4)$$

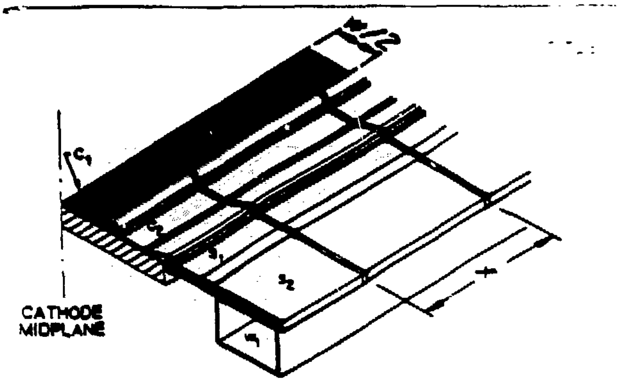

Figure 5. FEA cathode and resonant coupler.

The resulting load impedance Z_L for critical coupling is

$$Z_L = \left(\frac{1}{1+1}\right) Q^2R/4 \qquad (5)$$

Using parameters of Table I, each resonant network has

$$\begin{aligned} C_1 &= C_2 = 72\ \text{pF} \\ C_c &= 5\ \text{pF} \\ L &= 2.2\ \text{pH} \\ r &= 50\ \mu\text{m} \\ R &= 9 \times 10^{-3}\ \Omega \\ Q &= 28 \\ Z_L &= 2\ \Omega \end{aligned} \qquad (6)$$

The emission current corresponding to the above modulation characteristic is $I_m = 390$ A peak, $I_o = 8$ A from a (14 cm x 1 mm) cathode. The power supplied from the input modulator that is required to supply this emission is

$$P_e = I_m V_m \frac{\sin(\Delta\phi/2)}{\pi} = 2.2\ \text{kW} \qquad (7)$$

The input power P_m required to drive each resonant network is

$$P_m = R(\omega C_1 V_m)^2/2 = 350\ \text{W} \qquad (8)$$

In the overall cathode there are $N = 2\ell/x = 56$ networks. The total input rf power requirement is

$$P_{in} = P_e + NP_m = 22\ \text{kW} \qquad (9)$$

The rf gain of gigatron is therefore

$$G = \log (P_{out}/P_{in}) = 27\ \text{dB}. \qquad (10)$$

3. Traveling Wave Coupler. The traveling wave coupler naturally suppresses all parasitic modes. The resonant loop of waveguide has a total length chosen to be an integral number M of phase wavelengths:

$$2\ell = 2\pi M \frac{\beta_p c}{\omega} \qquad (11)$$

For the parameters of Table I, an appropriate choice would be $M = 14$. In principle, parasitic modes could be excited at frequencies corresponding to neighboring integral harmonics $M' \neq M$. The coupling to each mode M' must, however, be averaged over the length ℓ of the ribbon beam. The ribbon beam tilt is adjusted

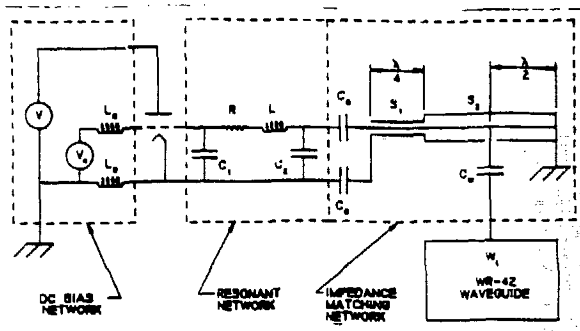

Figure 6. Equivalent circuit of FEA cathode and resonant coupler.

to achieve the phase-match condition.
The phase shift between the electron bunch and a traveling wave of harmonic M' varies linearly along the ribbon beam:

$$\Delta\phi(x) = 2\pi(M' - M) \left(\frac{x}{2\ell}\right) \qquad (12)$$

Averaging over the width ℓ of the ribbon gives a coupling for each parasitic mode:

$$\frac{E}{E_o} = \int_0^{\ell} \cos \Delta\phi(x)\ \frac{dx}{\ell} = \begin{cases} 0 & M' \neq M \\ 1 & M' = M \end{cases} \qquad (13)$$

All parasitic modes $M' \neq M$ thus receive no net coupling. This feature is a result of the distributed beam waveguide coupling, and is unique among electron tube designs.

III. DEVICE PERFORMANCE

We have calculated beam transport through the gigatron. Calculations were performed using the MASK computer code. Fig. 7 shows the trajectories of successive bunches through the diode region. Fig. 8 shows the trajectories of two successive ribbons through the coupler structure. Trajectories are shown on five points across each ribbon. Both transverse position and energy are shown for each trajectory. Slot width and height, coupler peak field, RF phase, and beam phase width were varied to optimize RF efficiency while transporting residual beam to the collector. For the optimized parameters, RF conversion efficiency of 74 % is obtained. No beam is intercepted before entering the collector structure.

We now have operational FEA cathodes at Texas A&M. The IV curves of these cathodes are presented below. The cathodes were made for us by C.S. Spindt, and employ the traditional fabrication approaches. We have built a vacuum assembly for testing the IV characteristics of cathodes in pulse mode, including provision for rf modulation. We have also built the complete vacuum structure for a round-beam gigatron prototype, with design parameters 12 GHz, 40 kW.

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TABLE I
Parameters of Example Gigatron

$\omega/2\pi$	rf frequency	18 GHz
P_o	rf peak power	10 MW
G^o	power gain	27 dB
	rf efficiency	74%
V	beam voltage	200 kVDC
	peak beam current	390 A
ϕ	rf phase	230°
$\Delta\phi$	beam phase width	60°
$\ell \cdot w$	cathode size	14 x .1 cm²
a · b	waveguide coupler (WR42)	1.1 x .4 cm²
g,h	slot width, height	.2 cm, .3 cm
β_ε	electron velocity/c	.70
β_p	phase velocity/c	1.37
θ	ribbon tilt angle	27°
Ψ	magnetic bend angle	22°
E_o	peak rf field	125 MV/m

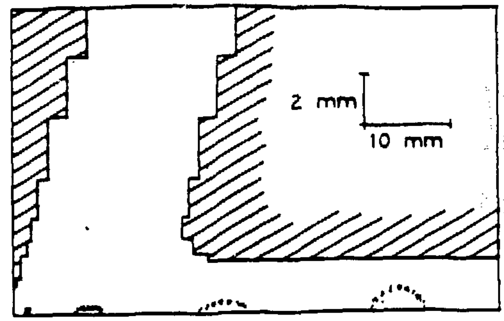

Figure 7. Calculated ribbon beam trajectories through diode region.

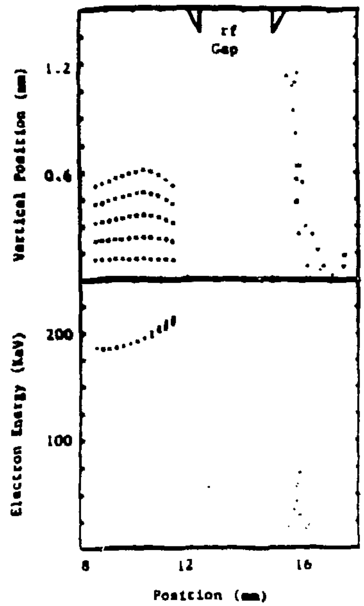

Figure 8. Electron energy and bunch motion through the traveling wave coupler.

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