THE RIBBON LASERTRON

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Abstract

The ribbon lasertron is a new r.f. amplifier tube designed for linac collider applications. Three design features permit extension of the lasertron concept to very high frequencies. First, a ribbon beam geometry mitigates space charge depression and facilitates efficient output coupling. Second, a traveling wave output coupler is used to obtain optimum coupling to a wide beam. Third, a gated field-emitter array is employed for the cathode. A prototype device is currently being developed.

Introduction

The ribbon lasertron is a design for a compact, efficient microwave power amplifier tube. It employs the lasertron concept,[1] in which a bunched electron beam is extracted from a modulated cathode and accelerated through a DC diode structure as shown in Figure 1. The resulting beam is fully modulated at high energy without the requirements of a modulator and drift region that characterize all conventional amplifier tubes. RF energy is then extracted from the beam in an output coupler. Because there is no DC component to the beam current, very high efficiency can in principle be obtained.

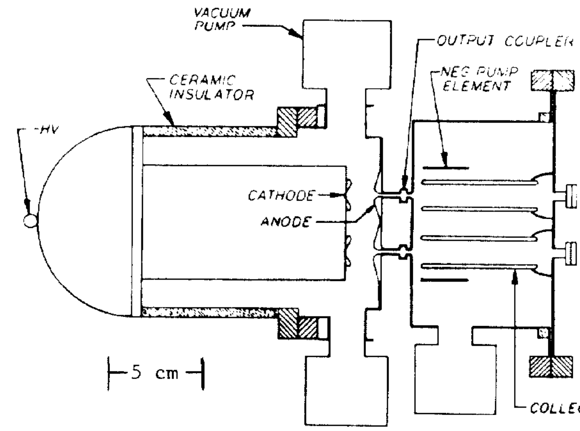
A major motivation to develop the ribbon lasertron arises in current efforts to design a multi-TeV e^+e^- linac collider for elementary particle physics.[2] Performance of a linac collider improves substantially as the frequency of the linac structure is increased. Several current design concepts[3,4] would operate at frequencies from 10 to 30 GHz. One key challenge for future linac colliders is to develop a compact, efficient source for ~100 MW peak power, 20 GHz. Technologies that are being explored in this connection include the gyroklystron,[5] the free-electron laser,[6] and the lasertron.

The ribbon lasertron has been designed to extend the advantages of previous lasertron designs to very high frequency and high peak power. Three developments make this possible. First, a ribbon beam geometry is adopted instead of the conventional round beam. Second, a traveling wave output coupler[7] is used to obtain optimum coupling across a wide beam. Third, a gated field emitter array[8] is employed for the cathode; this appears to offer a simpler and more reliable modulated cathode than the laser-modulated photocathode of previous designs.

A preliminary design has been prepared for a prototype ribbon lasertron. It is designed to produce 10 MW peak power at 20 GHz with an efficiency of ≥ 60%. Major specifications are summarized in Table 1. The following text describes several novel features of the ribbon lasertron and presents the results of beam transport and rf field calculations for the prototype design.

Ribbon Beam Geometry.

The ribbon beam geometry is used to eliminate several limitations of round-beam devices for high power operation at high frequency. High output power requires large beam current. Large beam current in a round beam entails substantial space charge depression and consequently a transit time spread in the diode region. The resulting phase spread limits high frequency performance. Large beam current also requires a transverse beam size that is comparable to wavelength at high frequency, so that output coupling becomes inefficient.



1. Cross-sectional view of the ribbon lasertron.

These problems are mitigated by adopting a ribbon beam geometry. Space charge depression for a given beam current is reduced by a factor equal to the transverse aspect ratio (width/height). High beam currents are readily achieved. The narrow (height) dimension can be kept small to facilitate efficient output coupling. Extension to higher power can be achieved simply by making the entire device wider. The wide dimension of the beam raises special problems for output coupling, which have been solved by the invention of the traveling wave coupler structure described in the following section.

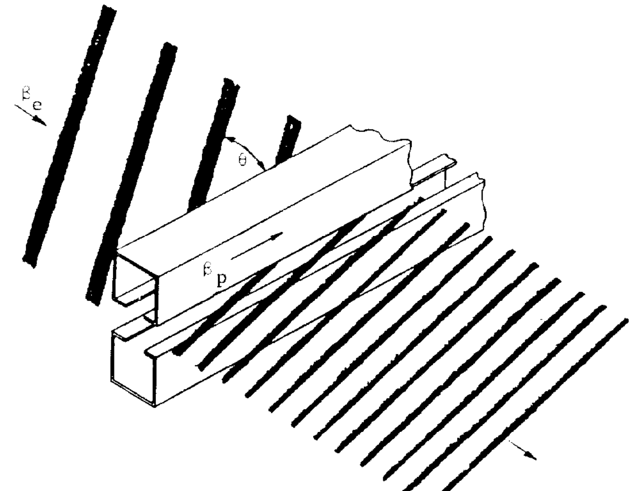
The ribbon beam geometry is produced from a standard Pierce rectilinear diode.[9] The diode voltage is 200 kVDC; the diode spacing is 1.8 cm; and the emission current density is 65 A/cm². The cathode is a (.4 x 14)cm² ribbon.

Traveling Wave Coupler.

The ribbon beam geometry makes it possible to couple strongly to a high current beam even at high frequency. There is however a problem in matching the phase of the rf field stored in the coupler with that of the beam current as it passes the coupler slot. A coupler extracts energy from an electron by decelerating it across a gap g (see Figure 2). The coupler must store energy to produce a decelerating field $\tilde{E}_c$ sufficient to extract a significant fraction of the electron energy T_e.

$$\tilde{E}_c g \sim T_e$$

The decelerating field is oscillating at the desired frequency, $\tilde{E}_c = E_c \cos(\omega t+\phi)$. Coupler structures are normally designed as standing wave resonators. In



2. Traveling Wave Coupler

the ribbon lasertron, however, the beam is wide ($\ell \gg \lambda$). The phase ϕ in a standing wave structure would thus vary through several full cycles across the width of the beam. Some elements of the beam would be accelerated, while others would be decelerated, so that no net energy transfer would result.

The traveling wave coupler of Figure 2 removes this difficulty. The coupler is a segment of waveguide which is slot coupled to the beam. The ribbon beam is modulated such that the incident beam front makes an angle θ with respect to the beam direction. A simple model requiring uniform acceleration across the beam yields a relation between the beam angle θ, electron velocity β_e, and the waveguide phase velocity β_p.

$$\beta_e = \beta_p \tan\theta$$

The beam will then drive this traveling wave at a constant phase across the entire beam width. The beam "surfs" with the traveling wave. Waveguide magnetic fields require further refinements to this simple model. Each beam component is bent sideways by an angle δ due to the in phase magnetic field ($B = E_c/v_p$) of the traveling wave:

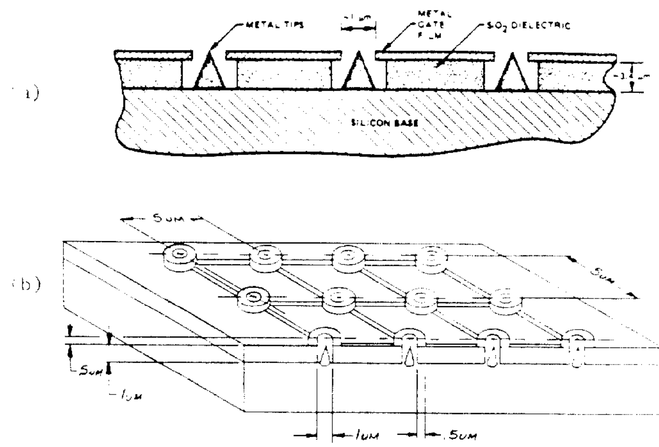
$$\delta = c\int \frac{\hat{B}\cdot d\ell}{\sqrt{meV}} \sim \frac{\hat{E}_o \cos\phi}{\beta_p \sqrt{meV}} = 0.38 \text{ rad.}$$

This effect can be compensated by a vertical dipole magnetic field across the coupler beam exit. Further analysis of this effect is being simulated numerically.

The coupler must return sufficient beam energy back into its input to generate the required decelerating field. This can be accomplished by 1) shorting the waveguide at each end and slot coupling output power at one end (only one traveling wave component will be driven by the tilted beam); 2) linking two traveling wave couplers end-to-end in a resonant loop; or 3) configuring the waveguide in a circular ring driven by a helical beam.

The Gated Field-Emitter Cathode

Present lasertron designs utilize either a photocathode[3] or a field-emitter brush[4] which is excited by a modulated laser beam. While these approaches are feasible on a laboratory scale, even



3. Gated field-emitter cathode (from Ref. 8)

(a) thin-film field-emission cathode array;
(b) modified array for lasertron application.

for high frequency applications,[10] the laser and particularly the photocathode represent significant uncertainties for reliable continuous operation. The gated field-emitter array appears to offer an attractive alternative.

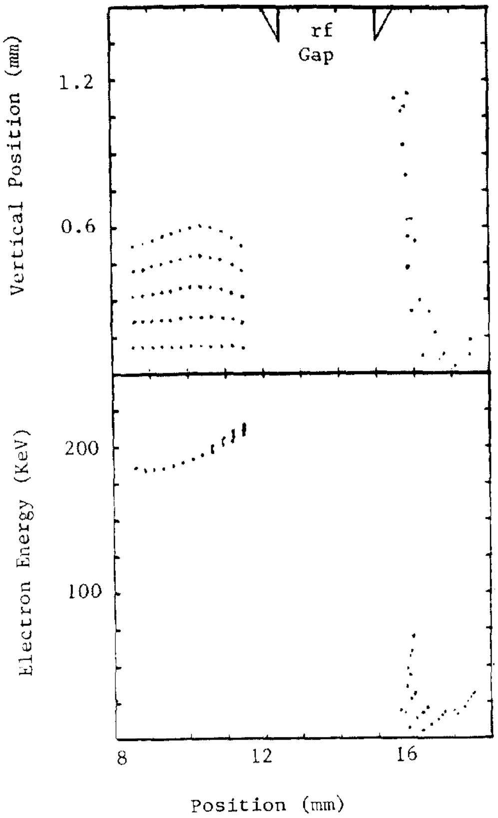
C.A. Spindt et al.[8] have developed microfabrication techniques by which they can prepare planar arrays of gated field-emitting points as shown in Figure 3. Electrons are field-emitted from an array of metal point cathodes. Each point is situated within a metal gate structure. Application of a modest (~30 V) gate-cathode voltage results in full modulation of emission current. Currents of >100A/cm² have been routinely achieved. There is no evidence of in-service deterioration during extended life tests.

Several modifications will be required for the lasertron application. First, the gate layer, which currently is deposited as a uniform sheet with holes for each tip, must be fabricated as a pattern of ring electrodes surrounding each tip, connected by lines. In this way the gate capacitence can be reduced from 1500 pF/cm² to $\lesssim$ 100 pF/cm². While the cathode would still represent a very capacitive load ($X_c \sim 1\ \Omega$ mm), it can be adequately modulated using GaAs MMIC amplifier chips bonded along the edge of the cathode.

Second, the gate layer must be configured as a suitable point-to-parallel optical lens. The electrons leave each cathode tip in a wide-angle cone. By suitable gate design, this cone can be transformed into a nearly uniform, parallel beam before acceleration in the diode. Figure 3b shows the modified configuration of the SRI cathode design.

Performance calculations for the Prototype Design

We have calculated beam transport through the lasertron geometry shown in Figure 2. Calculations were performed using the MASK computer code.[11] Figure 4 shows the trajectories of two successive ribbons through the coupler structure. Magnetic effects have not yet been included. Trajectories are shown on 5 points across each ribbon. Both transverse position and energy are for each trajectory. Slot width g and height h, coupler peak field E_c, r.f. phase ϕ and beam phase width $\Delta\phi$ were



4. Electron energy and bunch motion through the waveguide coupler.

varied to optimize rf efficiency while transporting residual beam to the collector. For the chosen parameters:

$$g = 2.4 \text{ mm} \qquad h = 3 \text{ mm}$$

$$E_c = 1.25 \times 10^8 \text{ V/m}$$

$$\phi = 230° \qquad \Delta\phi = 60°$$

rf conversion efficiency of 70% is obtained either as a linear device using flat ribbon beams, or as a round device using a thin helical beam.

Conclusion

In conclusion, a preliminary design for a ribbon lasertron has been studied. It appears to offer a number of attractive features for high frequency, high power amplifier applications. Further work will focus on the development and evaluation of the individual systems - the gated cathode, the traveling wave coupler, and the ribbon diode.

It should be noted that the ribbon lasertron could be configured either as a circular device, using a thin cylindrical beam instead of two flat ribbons. The choice of geometry would be determined by the application for the device. For a stand-alone amplifier, a cylindrical geometry might be simpler to build. For a linac collider, where rf power must be distributed along kilometers of linac length, the ribbon geometry offers the intriguing possibility of integrating the entire rf drive structure into the same envelope with the linac structure itself to make a single, essentially continuous structure. The power capability (~100 MW/m) of the prototype device is appropriate for such a configuration.

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Table 1

Parameters of Prototype Ribbon Lasertron

$\omega/2\pi$	rf frequency	18 GHz
P_o	rf peak power	10 MW
	efficiency	>60%
V	beam voltage	200 kVDC
I	peak beam current	360 A
ϕ	rf phase	230°
$\Delta\phi$	beam phase width	60°
ℓ w	cathode size	14 x .4 cm²
a b	waveguide coupler (WR42)	1.1 x .4 cm²
g	waveguide accel. gap	2.4 mm
h	waveguide slot height	3 mm
β_e	electron velocity/c	.70
β_p	phase velocity/c	1.51
θ	ribbon tilt angle	24°
E_a	peak accelerating field	15 MV/m
E_c	peak rf field	100 MV/m
X	cathode/anode spacing	1.8 cm