EFFICIENCY AND FREQUENCY STABILITY IN A HIGH POWER MICROWAVE GAP

Y. Y. Lau and D. G. Colombant
Beam Physics Branch, Plasma Physics Division
Naval Research Laboratory, Washington, DC 20375-5000

ABSTRACT

We calculate the power transfer of an intense, modulated electron beam to an external load. The simple model fully incorporates various effects such as nonlinear beam loading, finite transit time, AC and DC space charges, and the beam's initial velocity modulation. We show that a fully modulated beam may deliver up to 57% of its power to a load without forming a virtual cathode.

I. INTRODUCTION

Relativistic klystron amplifiers (RKA) [1,2] were recently used to accelerate electrons to energies greater than 60 MeV over a distance of one meter [3,4]. In the RKA at the Naval Research Laboratory [2,3], the beam's intense space charge provides electrostatic insulation [2] against vacuum breakdown at the cavity gaps. It also significantly loads the gap [5,6], leading to (a) reduction in the operation efficiency, (b) long build-up time in the current modulation, and (c) detuning of the cavities. Here, we address some of these issues, using a simple one-dimensional parallel plate model of the gap. Some recent 1-D theories of beam-gap interactions are given in Refs. 6-9.

II. THE MODEL AND THE TOTAL CURRENT I_A

The model consists of an electron beam impinging upon a gap formed by two parallel plates, K and A, separated by a distance D [Fig. 1a]. The electrons enter plate K, carrying a velocity $v_i(t)$ and current $I_i(t)$. For the time being, we shall leave V_g, v_i, I_i unspecified. In this one-dimensional model, the total current (convection current and displacement current)

$$I_A(t) = I(x,t) - A\varepsilon_0 \partial E(x,t)/\partial t \qquad (1)$$

is independent of the position x within the gap. It is also the current which is delivered to the load [Fig. 1b].

Since Eq. (1) is independent of the position x, we may evaluate I_A in front of

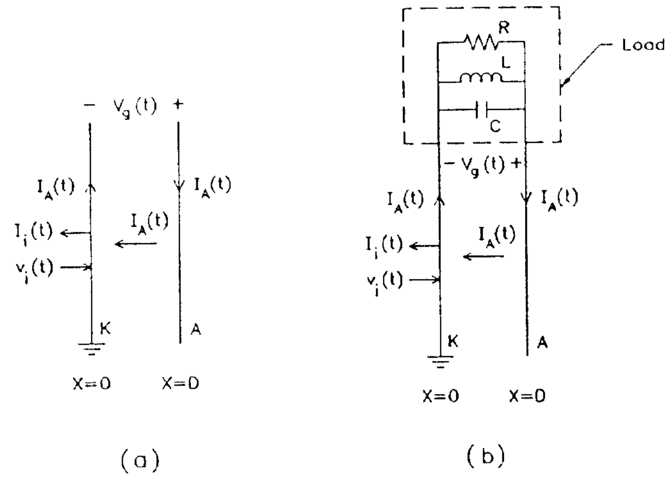

Fig. 1. The gap (a) and its connection to the load (b).

the plate K at $x = 0^+$; in which case $I(0^+,t)$ is simply the input current $I_i(t)$ entering the gap and this incident current is presumably given as an input. Thus, we treat the input current $I(0^+,t)$ as an ideal current source. The remaining quantity $-A\varepsilon_0 \partial E(0^+,t)/\partial t$ in Eq. (1) is then the current that is shunted by the (nonlinear) beam-loaded gap capacitance. The gap transit time effect, and its modification due to AC and DC space charges, are also included in this formulation, as we shall solve for E(x,t), ρ(x,t), v(x,t) self-consistently from both a fluid code and a particle code [10].

III. CONVERSION EFFICIENCY

We consider the transfer of beam power to a load. The modulated beam enters the gap with input current $I_i(t) = I_o[1 + (I_1/I_o)\sin\omega t]$ and input velocity $v_i(t) = v_o[1 + (v_1/v_o)\sin(\omega t + \theta)]$. Let ω_o and Q be the natural frequency and quality factor of the RLC circuit which represents the load [Fig. 1b]. The following parameters need to be specified: R, L, C, I_o, v_o, I_1/I_o, v_1/v_o, ω, θ. Our problem is to find suitable combinations of these parameters, so that the average rf power delivered to the load is maximized. There is one requirement, namely, no virtual cathode is formed at

0-7803-0135-8/91$01.00 ©IEEE

the gap. We consider this requirement satisfied if no reflected particle is detected at $x = 0^+$ in the particle code.

For this problem, the gap voltage $V_g(t)$ is related to $I_A(t)$ by

$$\left[\frac{d^2}{dt^2} + \frac{\omega_o}{Q}\frac{d}{dt} + \omega_o^2\right]V_g(t)$$

$$= -\frac{\omega_o R}{Q}\frac{d}{dt}\left(I_A(t) - I_o\right) \qquad (2)$$

and cannot be independently specified. Since I_o is constant, it is attached to the right hand side of Eq. (2) without loss of generality, so as to signify that it is the AC part of $I_A(t)$ which drives the load in Fig. 1b.

Tune sensitivity is shown in Fig. 2, in which we arbitrarily set $I_A = I_i(t)$ [i.e., pretending the idealized situation where all the input current $I_i(t)$ can drive the load], and set $v_i(t) = v_o = 0.866c$, $Q = 300$, $\omega D/c = 0.681$, $\bar{R} \equiv RI_s/(m_oc^2/e) = 5$, $I_o/I_s = 1.33$, $I_1/I_o = 0.56$. Here, $I_s = (A\epsilon_o/D)(m_oc^2/e)/(D/c)$ is the current scale. Figure 2a shows the normalized power $\bar{p}_L \equiv -I_AV_g/(I_s\cdot m_oc^2/e)$ that can be delivered to the load when there is a perfect tune between the drive frequency in the current modulation and the resonant frequency. Figure 2b shows $\bar{p}_L$ when one per cent of stray capacitance is added. In Fig. 2, $\bar{t} = \omega t$. Note the substantial reduction in the power $\bar{p}_L$ in Fig. 2b. Similar degree of sensitivity to tuning has also been observed in experiments [5].

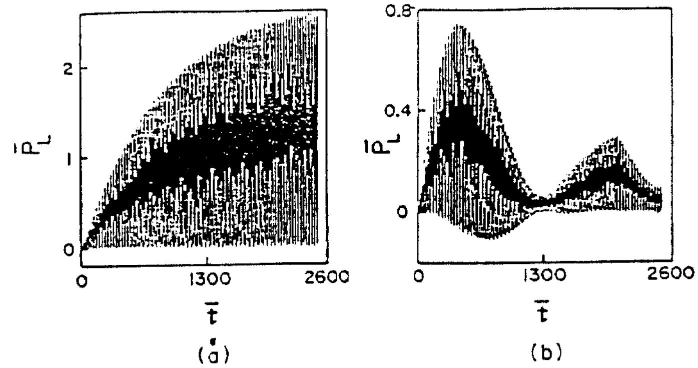

Fig. 2. The power $\bar{P}_L$ delivered to a perfectly tuned load (a) and to a load including a 1 per cent stray capacitance (b).

The effect of beam loading is shown in Fig. 3. We use the same parameters as in Fig. 2, except that we lower Q to 5 (to reduce the rise time in the numerical computation) and reduce $\bar{R}$ by a factor of 2.5. Figure 3a shows $\bar{P}_L$ in the idealized situation: All of the input current I_i is delivered to the load (i.e., $I_A = I_i$, no loading due to beam or to the vacuum gap capacitance). The circuit is perfectly tuned to the driving frequency in the current modulation. In Fig. 3b, we keep the same frequency, but include in I_A not only I_i, but also the quantity $C_o dV_g/dt$, which is the current shunted by the vacuum gap capacitance C_o. We see that the asymptotic peak value of $\bar{P}_L$ is reduced from 1.1 in Fig. 3a to 0.39 in Fig. 3b. This reduction is due to the loading of the RLC circuit by the vacuum gap through which the beam passes. In Fig. 3b, beam loading is absent. In Fig. 3c, we use the exact relation for I_A [Eq. (1)] and thus include all loading effects: the loading by the vacuum gap and beam loading. We see that the asymptotic peak power is further reduced by beam loading.

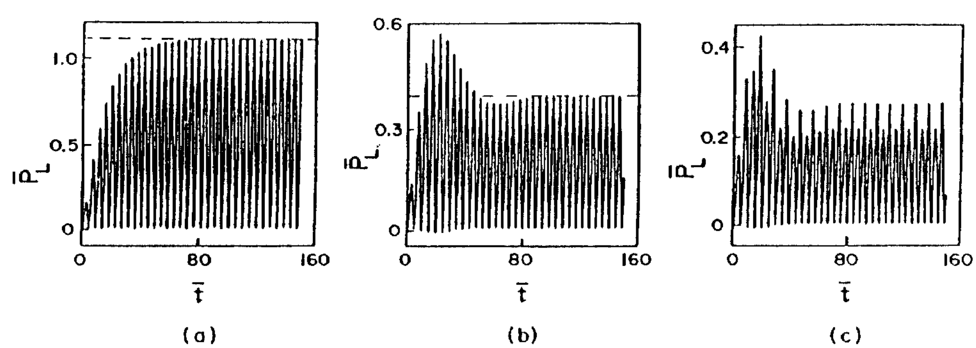

Fig. 3. The power $\bar{P}_L$ delivered to the load when (a) there is no gap loading nor beam loading; (b) there is only vacuum gap loading; and (c) both gap and beam loading are present. The dash curves show the theoretical asymptotic values.

We next performed an extensive search of the parameter space to maximize the rf power that can be delivered to the load without the formation of a virtual cathode. To reduce the sensitivity due to tuning, we considered the simple case, where the load in Fig. 1b consists only of a single resistor. After extensive search, we found that to deliver maximum power to the load, the beam needs to be fully modulated and therefore the DC current is about half the AC limiting value [6]. The load resistance cannot be too high (to avoid virtual cathodes) or too low (to allow appreciable power dissipation at the load). The efficiency can be improved somewhat (by about 20 per cent) if the phase of velocity modulation lags that of current modulation by about 30°. When these conditions are satisfied, close to sixty per cent of the beam power can be delivered to the load. Figure 4 shows the conversion efficiency η, defined to be $(V_g^2/R)/\langle P_b\rangle$ where $\langle P_b\rangle$ is the average beam power carried by the incoming beam. The parameters used for Fig. 4 are: DC beam energy = 511 kV, DC beam current = $2.4\ I_s$, $I_1/I_o = 1$, $v_1/v_o = 0.1$, $R = 0.8\ (m_o c^2/e)/I_s$, $\omega D/c = 0.681$, $\phi = -\pi/6$. The average conversion efficiency η in this figure is 57 per cent.

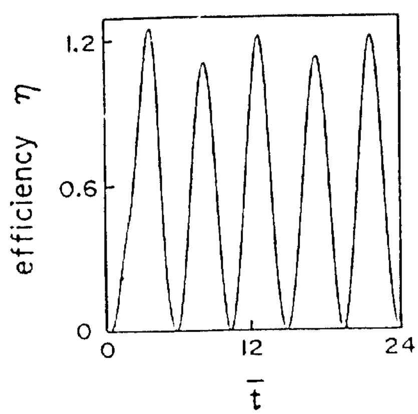

Fig. 4. Optimal efficiency in the power transfer to a resistive load, by an input beam with 100 per cent current modulation and 10 per cent velocity modulation. DC beam energy = 511 keV.

IV. CONCLUDING REMARKS

Although the idealized gap model given in this paper reveals many features observed in the NRL RKA experiments, there is one aspect that is particularly puzzling to us. It is the increase in the rise time in the current modulation that was observed in the experiments and in the earlier particle simulation of the real geometry. Our numerical results obtained thus far (using the model of Fig. 1b) failed to show a similar lengthening in the rise time. It remains to be determined whether this increase in the rise time is a result of the specific geometry used: namely, that of an annular beam interacting with coaxial cavities. We can think of two major differences between the present model and those in the CONDOR simulations [11] and experiments: the geometrical effects just mentioned, and the inductive effects that were ignored here.

ACKNOWLEDGMENT

This work was supported by the Strategic Defense Initiative Organization/Innovative Science and Technology Office, managed by the Harry Diamond Laboratory.

REFERENCES

[1] M. A. Allen, et al., SLAC Publications 4801 and 5070 (1989).

[2] M. Friedman, et al., J. Appl. Phys. 64, 3353 (1988); Rev. Sci. Instrum. 61, 171 (1990).

[3] M. Friedman, et al., Phys. Rev. Lett. 63, 2468 (1989).

[4] M. A. Allen, et al., Phys. Rev. Lett. 63, 2472 (1989).

[5] M. Friedman, et al., Proc. SPIE Meeting, Vol. 1226, p. 2 (1990); also in Vol. 1407 (1991), Ed., H. E. Brandt.

[6] D. G. Colombant and Y. Y. Lau, Phys. Rev. Lett. 64, 2320 (1990).

[7] Z. D. Farkas and P. B. Wilson, SLAC Pub. 4898 Rev. (1989).

[8] R. S. Symons and J. R. M. Vaugham, IEDM Conf. Digest, p. 885 (1990).

[9] Y. Y. Lau, D. Chernin, D. G. Colombant, P. T. Ho, Phys. Rev. Lett. 66, 1446 (1991).

[10] The fluid code solves $E(x,t)$, $\rho(x,t)$ and $v(x,t)$ from the equations: $(\partial/\partial t + v\partial/\partial x)\gamma v = -(eE/m_o)$, $\partial\rho/\partial t + \partial(\rho v)/\partial x = 0$, and $\partial E/\partial x = -\rho/\varepsilon_o$. The particle code solves these equations in Lagrangian form to account for charge overtaking and particle reflection. See Ref. [6] for code validation.

[11] J. Krall, et al., to be published.