Intense Electron Beam Modulation by Inductively Loaded Wide Gaps for Relativistic Klystron Amplifiers

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(Received 5 July 1994)

We investigate modulation of an intense relativistic electron beam by *wide* gaps which include an inductively loaded return current structure that is opaque to the unmodulated beam space charge but transparent to the RF field. This structure eliminates a number of deleterious nonlinear effects and leads to a 50% increase in the bunched electron beam peak current (>40 kA).

PACS numbers: 85.10.Jz, 41.75.Ht

During the past decade, advances in relativistic klystron amplifier (RKA) technology [1–4] have led to the generation of microwaves at frequency 1.3 GHz with peak power >10 GW for 100 ns duration. We are presently developing a new generation of RKA sources based on two major innovations: (1) An annular "triaxial" [5] structure which can handle high power over a broad frequency bandwidth with improved compactness. (2) Inductively loaded wide gaps to modulate efficiently the beam and extract microwaves at high power, while avoiding breakdown and dc space charge limits. In this Letter we report substantial improvement in RKA operation when the narrow gaps used in previous RKA's are replaced with inductively loaded wide gaps. We have increased the bunched beam peak current by over 50% to >40 kA, while avoiding nonlinear effects that degrade the RF output pulse.

In previous implementations of the RKA, as in most klystronlike devices, the electron beam has been modulated by a unidirectional RF voltage applied to a gap whose length is less than a quarter wavelength [1–4] (Fig. 1, top). The precise length of the gaps was chosen by trial and error as a compromise between competing factors: short gaps reduce the beam potential energy, while long gaps improve electrostatic insulation [6] and reduce beam loading [7]. For the high power *L*-band RKA, with wavelength 23 cm, we found the optimum length to be 1.7 to 2.0 cm. Even with optimization of these narrow gaps, problems occurred when the beam was highly modulated. The effective gap length and the electron transit time across the gap depended on the amplitude and frequency of the modulated current [3]. Also, nonlinear effects associated with beam loading changed the RF characteristics of the gap-cavity system [7,8]. These effects reduced the efficiency of the RKA, degraded the rise time of the output RF pulse, and introduced high-amplitude, low-frequency fluctuations on the envelope of the RF pulse [5]. Moreover, at high power levels the electrostatic insulation [6] proved insufficient to prevent electron emission and breakdown at the gaps.

We report here on modulation of an intense relativistic electron beam using a completely different gap geometry, which eliminates the problems associated with narrow gaps. In this geometry the gap length was about a half wavelength [9], which decreases the dc gap impedance and reduces the nonlinear beam loading. To keep the electrons in synchronism with the RF field while crossing such a long gap, we imposed a bidirectional electric field, i.e., a field which at any given time changes its sign at the midpoint of the gap. However, the potential energy of an electron beam increases when it propagates through a wide gap. This constitutes a significant drain on the kinetic energy, and can even lead to virtual cathode formation. We prevent this increase in potential energy by stacking the wide gap with thin metallic washers (Fig. 1, bottom) which are connected inductively to ground. The washer structure effectively neutralizes the beam space charge and provides a return path for the unmodulated current. However, the

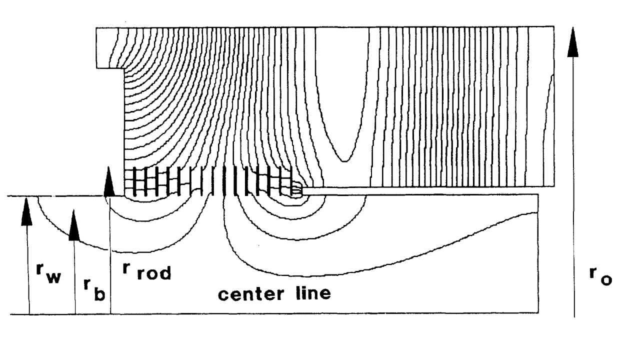

FIG. 1. SUPERFISH calculation of electric field lines distribution in a narrow (top) and a wide (bottom) gap geometries.

0031-9007/95/74(2)/322(4)$06.00

inductance of the washer-loaded structure is sufficient to prevent any substantial effects on the cavity mode.

We report first on experimental investigations. The apparatus was immersed in a quasi-dc axial magnetic field of 8 kG and was evacuated to a base pressure $<10^{-5}$ Torr. A diode generated an annular intense relativistic electron beam of radius $r_b = 6.3$ cm, thickness 0.3 cm, and current 18 kA. The maximum voltage pulse applied to the diode was 500 kV, with a pulse duration of 130 ns at maximum voltage, voltage rise time 30 ns, and fall time 50 ns. The beam propagated in a smooth metallic drift tube of radius $r_w = 6.7$ cm. Two wide gaps, each about 10 cm long, were inserted in the drift tube. Each gap was stacked with 23 washers of thickness 0.075 cm, inner radius $r_{w1} = 6.7$ cm (the same as the drift tube), and outer radius $r_{w2} = 9.2$ cm. The washers were supported by longitudinal metallic rods of radius $a_{\text{rod}} = 0.2$ cm (four rods in the first gap and eight rods in the second gap), mounted at radius $r_{\text{rod}} = 8.9$ cm and connected across the gap. The gaps were connected to coaxial cavities tuned to 1.281 GHz. The first cavity had a $Q \approx 200$ and the second had $Q \approx 450$. Only the first cavity was energized by an external RF source. The electron beam RF current I_{RF} was measured by small magnetic loops. The signals, dI_{RF}/dt, were displayed on a Tektronix oscilloscope model SCD 5000 and were integrated numerically. The amplitude of I_{RF} at the fundamental frequency 1.281 GHz, $I_{\text{RF}}^{(1)}$, was obtained by filtering the signals. A control experiment was also performed which was similar in all respects, except that two cavities with narrow gaps and $Q \geq 1000$ were used.

The principle results of the experiments were the following.

(1) With an RF pulse of power $P_{\text{in}} = 4$ MW externally injected into the first cavity, $I_{\text{RF}}^{(1)}$ reached a maximum of 4 kA at a distance $l_{\max} = 20$ cm downstream of the middle of the first gap [Figs. 2(a) and 2(b)]. Detuning the frequency f of the injected RF pulse by ± 5 MHz reduced $I_{\text{RF}}^{(1)}$ by only 20%. In the control experiment, the maximum $I_{\text{RF}}^{(1)}$ was 5 kA, and detuning f by <1 MHz reduced $I_{\text{RF}}^{(1)}$ by 50%. Evidently, one effect of the inductively loaded gap geometry is to reduce Q. In both cases, linear response was observed as $I_{\text{RF}}^{(1)} \propto P_{\text{in}}^{1/2}$ and the duration of the modulated current was the full beam duration (including the rise time and fall time).

(2) When a second wide-gap cavity was added at the position $l_{\max}$, then $I_{\text{RF}}^{(1)}$ reached 20 kA [Fig. 2(c)] 25 cm from the middle of the second gap. (Note that the

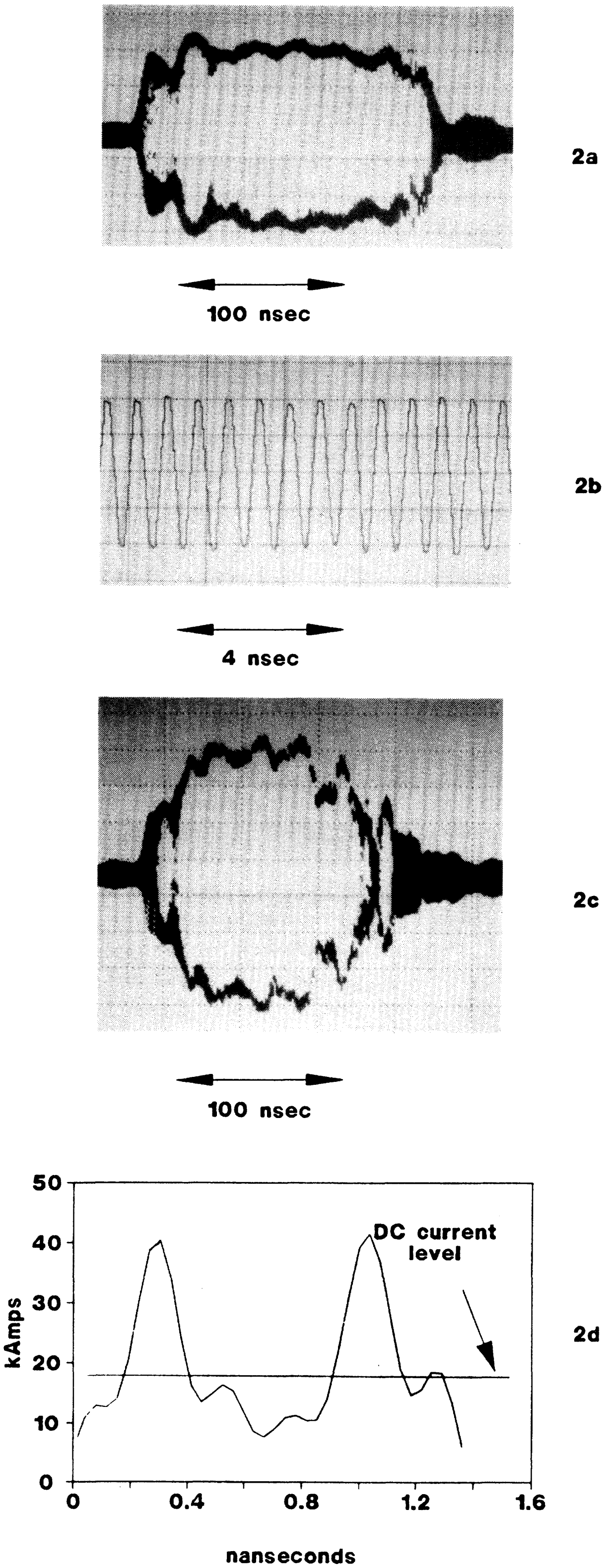

FIG. 2. From top to bottom: (a) The envelope of dI_{RF}/dt measured 20 cm from the first wide gap ($I_{\text{RF}} = 4$ kA). (b) Expanded time window of (a). (c) The envelope of dI_{RF}/dt measured after the second gap ($I_{\text{RF}} \approx 20$ kA). (d) The computed current profile of individual electron bunches. [Note (a)–(c) display the RF current at frequencies between 1 and 2 GHz.]

current prob signal was corrected as was outlined in a previous publication [10].) The duration of the RF current envelope equaled the duration of the electron beam at maximum dc voltage (excluding rise time and fall time). The experiment operated in the nonlinear regime, since reducing P_{in} by a factor of 2.5 reduced the $I_{\mathrm{RF}}^{(1)}$ by only 10%. The operational bandwidth was about 3 MHz. In the narrow-gap control experiment, the maximum I_{RF} was only 14 kA, and I_{RF} fell off by 50% late in the pulse due to beam loading effects.

(3) We calculated the shape of single electron bunches [Fig. 2(d)] from dI_{RF}/dt signals, assuming that the magnetic probe sensitivity did not change at frequencies above 1.3 GHz and taking into account cable attenuation, oscilloscope response, and the correction to the current as outlined in Ref. [10]. Figure 2(d) shows compression of the electron bunches to a peak current >40 kA, and the presence of large amplitude higher harmonics.

We conclude that the use of inductively loaded wide gaps yielded higher current modulation and broader bandwidth than was achieved with the standard narrow gaps under similar conditions. Moreover, the problems associated with beam loading of narrow gaps, which plagued our earlier experiments, were eliminated.

We now consider the interpretation of these experimental results. We first consider the interaction of the *unmodulated* beam current with the gap. The characteristic inductive response time of the washer-rod structure is 1–2 ns. Thus we assume here that the washers are always at ground potential. We then solve Poisson's equation numerically in the presence of N discrete grounded washers within the gap. With even as few as $N = 4$ washers, we find that all of the electric field lines emanating from the beam space charge terminate at the inner edge of the washers. Thus the potential energy of an electron is slightly larger than $(e/2\pi\varepsilon_0)(I_b/v_0)\ln(r_{w1}/r_b)$ where v_0 is the electron velocity. In the absence of the washers, r_{w1} would be replaced by the cavity outer radius, and the potential energy would be much larger. When N is increased, the maximum current that can propagate converges rapidly to the limiting current in a smooth-walled drift tube of radius r_{w1}. With 23 washers, effects due to the discreteness of the washers are nearly imperceptible.

As a second line of analysis, we have used the 2D(r-z) code SUPERFISH [11] to calculate the RF properties of the cavities with either standard narrow gaps or washer-loaded wide gaps (Fig. 1). Since SUPERFISH is axisymmetric, it cannot calculate the RF current flow along the discrete rods. However, our washer-rod structures are designed with rod inductance sufficient to minimize RF current along the rods. Thus, in this part of the calculation we simply neglect the rods and represent the washers as electrically floating. The calculations indicate that the presence of the washers neutralizes the radial RF electric field E_r in the annular region between the inner and outer radius of the washers, but otherwise has little influence on the RF properties of the cavities or the gaps.

To calculate the RF response of the cavity with the complete washer-rod structure, we have developed both an approximate analytic theory and a more complete simulation scheme [12]. To work within a 2D (axisymmetric) framework, we simplify the problem as follows: (1) The charge on the washers is represented as axisymmetric and smooth in z; i.e., the discreteness of the washers is neglected. (2) The current in the rods is represented as the sum of two components: an axisymmetric shell of current density $J_0(r,z) = I_0(z)\delta(r - r_{\mathrm{rod}})$, plus a correction J_1 consisting of the difference between current I_0 flowing in N discrete rods and the same current in the axisymmetric shell. The complete Maxwell equations with cavity boundary conditions are applied to calculate the field E_0 resulting from J_0. However, since J_1 is an array of quadruple sources, the associated field E_1 is localized near $r = r_{\mathrm{rod}}$, and an inductive model can be used to calculate E_1. With these approximations, the analytic solution of the Helmholtz equation yields the cavity eigenmodes and the response to a modulated beam. At the cavity resonance frequency, the effective inductance of the rods is found to be approximately

$$L_{\mathrm{rods}} \approx (\mu_0/2\pi N)\ln(\pi r_{\mathrm{rod}}/2Na_{\mathrm{rod}})\,. \tag{1}$$

For $N \le 8$, this inductance is sufficient to inhibit RF current in the rods, so that the presence of the washer-rod structure has only a small effect on the eigenfunctions and resonant frequencies.

The theoretical analysis indicates that there are two fundamentally different contributions to the gap longitudinal electric field. First is a nonresonant inductive field associated entirely with the presence of the washer-rod structure. We have noted that E_r is essentially completely neutralized in the annular region between r_{w1} and r_{w2}. However, the azimuthal magnetic field B_θ is given by $B_\theta \approx (\mu_0/2\pi)I_b(z,t)/r$, in the region $r < r_{\mathrm{rod}}$. In fact, this is approximately correct even out to $r = r_{w2}$, since the rod current is a small fraction of the beam current. Thus the flux in the region $r_{w1} < r < r_{w2}$ gives rise to a purely inductive axial field

$$E_z^{\mathrm{nr}} \approx -(\mu_0/2\pi)(dI_b/dt)\ln(r_{w2}/r_{w1}) \qquad (r \le r_{w1})\,. \tag{2}$$

Note that E_z^{nr} remains large even for highly relativistic beams. By way of contrast, an electron beam propagating within a smooth drift tube of radius r_w gives rise to a capacitive field $(\mu_0/2\pi)(dI_b/dt)(1/\beta_0^2\gamma_0^2)\ln(r_w/r_b)$, which goes to zero when γ_0 is large, due to cancellation between inductive and space charge terms. Here, $\beta_0 = v_0/c$ and $\gamma_0 = (1 - \beta_0^2)^{-1/2}$. The inductive field E_z^{nr} compresses each electron bunch by slowing the front and accelerating the back. In the experiment, the large I_{RF} in the second gap gibes rise to $|E_z^{\mathrm{nr}}| > 0.6 \times 10^5$ V/cm, which boosts the modulation effectiveness of the second cavity, as compared to the control experiment.

In addition, the beam is modulated by a resonant electric field associated with the cavity mode. In earlier publications [2,3] we showed that the RF current impressed on an electron beam after traversing a distance z from the gap of the first cavity is

$$I_{\mathrm{RF}} = M(V_{\mathrm{RF}}/Z)\sin(kz)\,, \tag{3}$$

where $V_{\mathrm{RF}} = E_m L$, E_m is the peak electric field, Z and k are functions of the experimental parameters, and the gap coupling coefficient [13] M is a function of the spatial distribution of the gap electric field, the electron velocity, the phase velocity, and the ratio of the gap length L to the wavelength λ of the RF wave. V_{RF} is optimized at large R_{sh}/Q, where R_{sh} is the shunt resistance to the cavity. This is equivalent to reducing gap capacitance, i.e., increasing gap length. If the gap voltage is unidirectional, increasing L reduces M. However, for a bidirectional electric field distribution at the gap, M has a maximum at $L/\lambda \approx 1/2$. Thus the overall factor MV_{RF} is optimized by using a half-wavelength gap with a bidirectional electric field distribution. The large R_{sh}/Q (i.e., the reduced value of Q) also increases the operational bandwidth, and eliminates nonlinear behavior in the second cavity. The reduced value of Q leads to a fast rise time of I_{RF}. Spreading the RF voltage over a wider gap reduces the probability of electron emission and gap breakdown.

The actual geometry of the RKA with washer-rod structure is three dimensional, with fine structure in both r, θ (rods) and r, z (washers) which would be difficult to resolve in a simulation. However, we have developed a two-dimensional simulation model, based on the r, z particle simulation code MASK [14] which has been used with much success for previous RKA studies [2,3]. The charge and current on the structure are inserted as external sources in the code, with the charge residing in axisymmetric shells at r_{w1} and r_{w2}, and the current $I_0(z,t)$ spread into axisymmetric shell at r_{rod}. This current is essentially the J_0 described previously in connection with our analytical model, and its magnitude is determined as an inductive response, $\partial I_0/\partial t = E_z(r_{\mathrm{rod}})/L_{\mathrm{rods}}$, with L_{rods} given by Eq. (1). The simulation calculates both the RF and dc response self-consistently. Simulation results confirm [15] that the maximum beam current that can propagate through the gap is essentially equal to the limiting current in a drift tube of radius r_{w1} and that the "cold" cavity RF parameters are insensitive to the presence of the washer-rod structure. The simulation also shows beam modulation after propagation through the washer-loaded wide gap, with the location of maximum modulated current in agreement with experiment. High harmonics are observed on the beam current when the modulating voltage is high.

In conclusion, we have shown that the use of wide gap cavities improves high-frequency modulation of intense relativistic electron beams in many ways. We believe that even wider gaps can be used for beam modulation with the appropriate choice of RF mode. We believe that the inductively loaded wide gap is applicable also to microwave extraction. Experiments supporting this view have been performed and will be reported in a forthcoming publication.

This work was supported by BMDO/ARL and by ONR.

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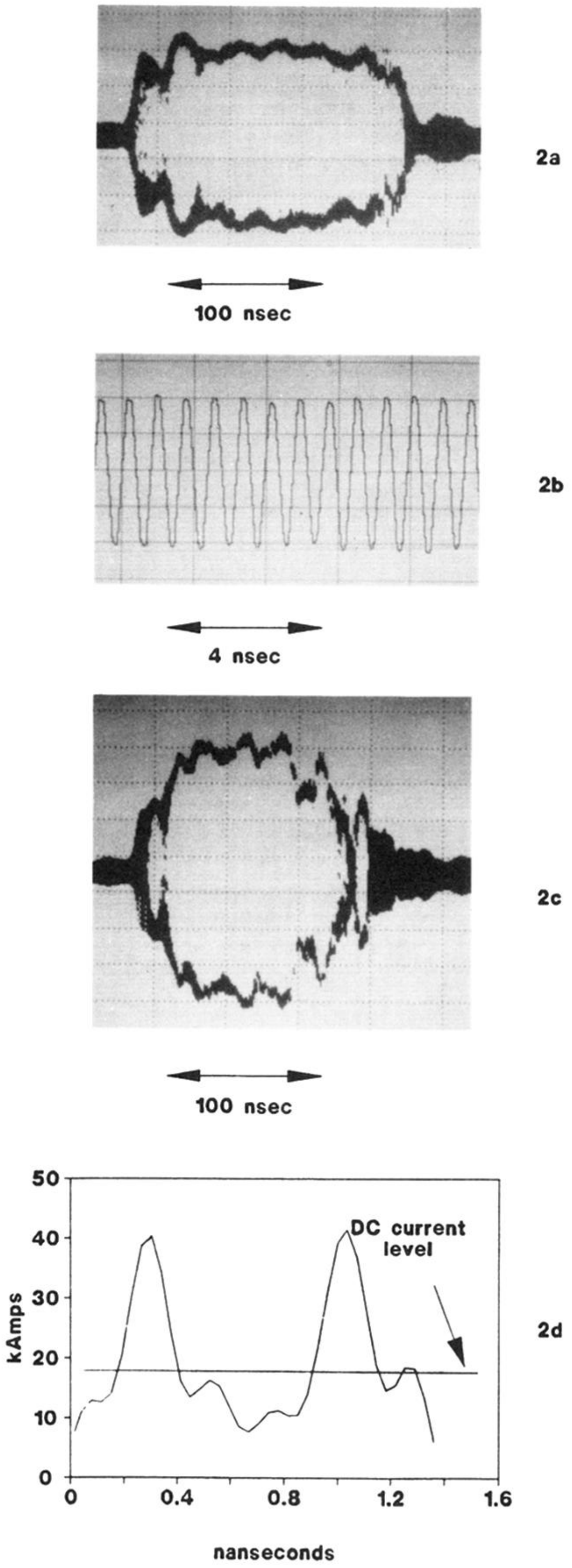

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