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BEAM TRANSPORT ISSUES IN HIGH CURRENT LINEAR ACCELERATORS[a)]

R. B. Miller, J. W. Poukey, B. G. Epstein, S. L. Shope,[b)]
T. C. Genoni, M. Franz,[c)]
B. B. Godfrey, R. J. Adler,[d)]
and A. Mondelli[e)]

Summary

Stable beam transport may be the limiting factor in the development of a new generation of high current linear induction accelerators. In this paper we analyze several important beam stability topics, including radial oscillations induced by an accelerating gap, the diocotron, resistive wall, and cyclotron maser instabilities, and the transverse beam breakup and image displacement instabilities. At present image displacement appears to represent the most serious limitation to high current beam transport in linear accelerator structures.

Introduction

The modular low impedance pulse power technology developed as a result of nuclear weapon effects simulation and inertial confinement fusion applications can also, in principle, be used to construct high voltage linear accelerators. In comparison with the more conventional linear induction accelerators (LIA) which use ferrite-loaded accelerating modules, the pulsed transmission line approach appears to have the advantage of higher accelerating gradients (~ 3 MV/m), higher voltage per accelerating unit (~ 2 MV/stage), and the capability to accelerate very high beam currents due to the low line impedance. In particular, this approach has been described by Pavlovskii, et al. as having the capability for accelerating high beam currents (10-100 kA) to high kinetic energy (10-100 MeV).[1,2]

A schematic outline of our first device, called RADLAC I for Radial Line Accelerator, is presented in Figure 1.[3] The accelerator's essential features include a foilless diode injector, four oil-insulated radial line cavity structures, associated accelerating gaps and self-breaking cavity switches, the charging circuits, and the solenoidal field coils for beam transport. Beam parameters of 25 kA and 9.0 MV have been achieved, with an average acceleration gradient of 3 MV/m. The observed current transport efficiency was ≳90% through the four accelerator stages.

A comparison of the RADLAC I accelerator parameters with those of other linear induction accelerators is presented in Table I. Shortly after the RADLAC I results were obtained Pavlovskii, et al. reported that they had previously achieved beam parameters of 13.5 MeV and 50 kA with 14 water dielectric RPL modules.[4] Beam current losses were held to 25%, while the average gradient was 2 MV/m. A notable difference between RADLAC I and the Soviet machine, the LIU-10, is that the latter uses triggered gas switching elements with eight triggered gaps per radial line. With three radial lines per accelerating module, the LIU-10 contains in excess of 300 gas switches triggerable to nanosecond accuracy.

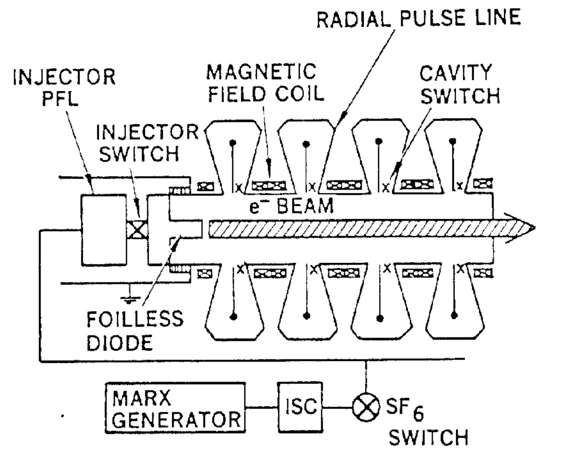

Figure 1. Schematic design of the RADLAC I device, indicating the key accelerator components.

TABLE I
Linear Induction Accelerators

	Voltage (MV)	Current (kA)	Pulse Duration (ns)
LLL - Astron	4	0.15	250
LBL - ERA Injector	4	1	20
LLL - ETA	4	8	20
SLA - RADLAC I	9	25	15
USSR - LIU-10	13.5	50	20-40

Beam Transport Issues

At the beam currents and accelerator lengths of the RADLAC I experiments, beam transport difficulties were relatively unimportant compared with the basic pulse power issues. However, in scaling to higher beam kinetic energies and currents, beam transport becomes the major concern. The three primary topics are the high current injector design, the design of the accelerating gap, and the beam stability in the accelerator. Although the foilless diode injector developed for RADLAC I was successful at the 2 MV level, a higher voltage injector (~ 4 MV) is desirable for several beam transport reasons; unfortunately, at these higher voltages the beam emittance can become excessively large unless special design precautions are taken. These questions have been addressed with RADLAC I accelerator hardware. Two of the RPL's were connected in such a fashion as to provide a 4 MV voltage pulse to a single diode. This cavity design is termed an isolated Blumlein;[5] it has the additional advantage that there is essentially no prepulse voltage applied to the diode. Using this configuration we have been able to produce 4 MV, 80 kA electron beam pulses.

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b) Sandia National Laboratories, Albuquerque, NM 87185.
c) Air Force Weapons Laboratory, Kirtland AFB, NM 87117.
d) Mission Research Coporation, 1400 San Mateo SE, Albuquerque, NM 87108.
e) Science Applications, Inc., McLean, VA.

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The high beam currents pose special constraints for the physical design of the accelerating gaps. If the injected current is near the drift tube limiting current, a virtual cathode could form in the gap region if the gap width is too large and/or the gap voltage is too low. In the opposite limit, electron emission from the accelerating electrodes could excessively load the cavity. A cylindrically symmetric, quasi-static particle simulation representing the self-consistent beam equilibrium is shown in Figure 2. The numerical results indicate that gap emission is suppressed by the strong beam space charge distortion of the normally-symmetric equipotential contours of the gap. Although the beam loses energy as it enters the gap (~ 100 kV), a virtual cathode does not form.

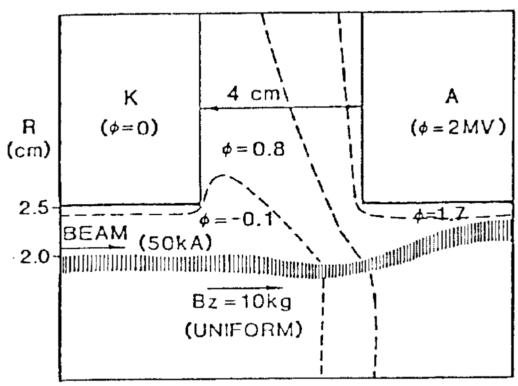

Figure 2. Particle simulation of a 2 MeV, 50 kA electron beam accelerated by a 2 MV, 4 cm gap in a uniform 10 kG axial magnetic field.

The most obvious feature of the simulation is the excitation of radial osacillations of the beam envelope due to a lack of radial force balance in the gap region. This behavior has been observed experimentally using radiochromic witness foils.[5] For high current beams such oscillations result in emittance growth (phase mixing), and can lead to a serious loss of beam current. A straightforward solution for this problem is to maintain radial force balance by appropriately varying the magnetic field strength in the gap region.[6]

In order to test this method the theoretically correct contoured magnetic field[7] was substituted into the numerical simulation code using the beam and gap parameters appropriate for Figure 2. The result (Figure 3) exhibits a beam with no appreciable radial oscillation. The results of further sensitivity tests indicated that radial oscillations were still suppressed for slightly different ($\simeq 10\%$) beam current, beam energy and gap voltage, provided that B_z (z) agreed with the theoretical model to within roughly 5%. This method of suppressing radial oscillations is presently being experimentally tested using RADLAC I hardware.

Several beam stability issues have been examined as the result of an ongoing theoretical effort. The foilless diode injector generates a hollow beam; while this beam configuration is attractive from space charge limiting current considerations, very thin beams are always diocotron unstable.[8] Since the growth rate scales as $(\gamma^2 B_z)^{-1}$, however, the instability should be controlled by using a high voltage injector (4 MV), and a strong longitudinal magnetic field (20 kG). To test this possibility the diocotron instability was investigated using

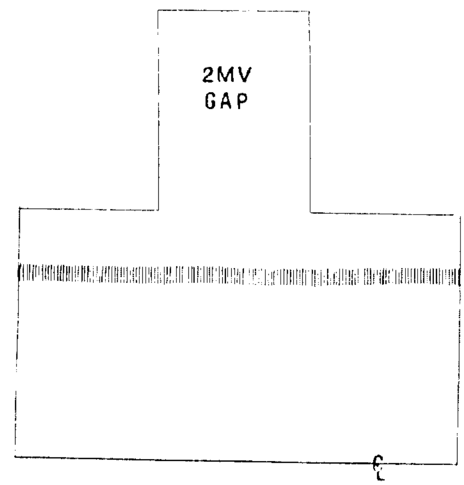

Figure 3. Particle simulation of a 2 MeV, 50 kA electron beam accelerated by a 2 MV gap with the contoured magnetic field of 10 kG average strength.

GRADR,[9] a linear theory E-M code which self-consistently derives cylindrically symmetric, radially inhomogeneous, relativistic laminar beam equilibria in the cold fluid approximation. For diode voltages of 2-4 MV use of a power law least squares fit for the peak diocotron growth rate in the beam frame yields the scaling law

$$\Gamma_D \approx I\ B_z^{-1.05}\ V_d^{-0.84}\ \delta^{-1.14}\ f\ (\varepsilon) \qquad (1)$$

where I is the beam current in kiloamperes, B_z is the axial field strength in kilogauss, V_d is the diode voltage in megavolts, δ and ε are the beam thickness and separtion from the drift tube wall in centimeters, and $f(\varepsilon) = 1$, $\varepsilon \geq 4$ mm; $f(\varepsilon) = \varepsilon^{0.42}$, $\varepsilon < 4$ mm. In the lab frame $\Gamma_{D,lab} = \Gamma_D\, \gamma^{-1}$, where γ is the usual relativistic factor.

On the basis of these results the diocotron instability does not appear to be particularly troublesome; however, other sources of azimuthal asymmetries which require further examination are: (1) a cathode misaligned with respect to the drift tube axis, (2) a tilted cathode, (3) a drift tube offset at a flange, or (4) a misaligned external magnetic field.

GRADR has also been used to investigate growth of the resistive wall instability. In effect, resistive energy loss in the metallic drift tube causes the negative energy slow cyclotron and space charge waves to grow.[10] Estimating the instability growth rate as the ratio of wave energy loss at the wall (radial Poynting flux) to total wave energy leads to an expression for the peak temporal growth rate. For the cyclotron wave the approximate expression is

$$\Gamma_R = e^{i\pi/6}\, \sigma^{-1/3} \left[\frac{2\omega_p^{\,2}\delta c}{\Omega_c R r_b} \cdot \left(\frac{1 + m^2/k^2R^2}{1 + m^2/k^2 r_b^2} \right) \varepsilon^{-1} \right]^{2/3} \qquad (2)$$

wtih $kv = \Omega_c/\gamma$. In Eq. (4) σ is the conductivity of the drift tube wall in $(\text{sec})^{-1}$, ω_p is the beam plasma frequency, and $\Omega_c = eB_z/mc$. Waves of helicity matching that of the particles grow most rapidly. For such waves in the long wavelength ($kR \ll 1$) limit, the geometrical factor reduces to

$$f \approx \begin{cases} (R/r_b - \frac{r_b}{2R})^2 & , m = 0 \\ 9/64 & , m = 1 \\ [\frac{1}{2}(R/r_b)^{m-1} - (m+1)^{-1}(r_b/R)^{m-1}]^2 (m-1)^{-2}, & m > 1 \end{cases} \quad (3)$$

Such analytic estimates appear to scale properly with the GRADR results, although specific growth rates can be in error by as much as a factor of two. On the basis of these calculations the resistive wall instability does not appear to be serious, provided that beam misalignments are kept small (< 1 mm).

The cyclotron maser instability[11] has been responsible for generating very high microwave powers with intense electron beams; however, its severity depends on a large amount of transverse energy in the beam. On the basis of numerical simulations of foilless diode behavior the amount of transverse energy should be relatively small and we do not expect this instability to be disruptive; we may be able to use the microwave emission as a transverse beam energy diagnostic.

Because of its periodic structure the radial pulse line accelerator can be susceptible to a microwave instability termed transverse beam break-up (BBU).[12] Physically, the instability arises from the coupling between a beam oscillating off-axis, and accelerating cavity modes with a transverse magnetic field on axis (TM_{1M0} mode, for example). If the frequency of the beam oscillation occurs at a natural resonance of the cavity, then cavity mode energy will increase and be in temporal phase with the oscillations, thereby causing the oscillations to increase in amplitude during the pulse duration. Moreover, if every cavity is identical, the peak amplitude of the oscillations will also grow from cavity to cavity.

If the initial perturbation amplitude is fixed or decreasing in time, the instability will grow to its maximum in one cavity energy storage time $\tau \gtrsim Q/2\omega$, where ω is the frequency of the oscillation and Q is the usual cavity quality factor. The gain G of the instability is bounded by

$$(1 + G_f^2)^{1/2} < G < 1 + G_f$$
$$G_f = \frac{Z_\perp I \ \omega M^2}{510 \ \Omega_c} \quad (4)$$

where $Z_\perp$ is the transverse impedance in ohms, I is the beam current in kiloamperes, and M is the modulation coefficient.

In the RADLAC cavities the mode structure is essentially determined by the geometry of the accelerating gap--dielectric insulator region. The results of experimental measurements of the cavity Q (reported elsewhere in these proceedings) indicate that the insulator structure lowers the Q, depending on the relative thickness of dielectric and metal rings. Further, a suitable choice of dielectric medium (water or ethylene glycol) greatly reduces the growth of the instability because of the loss tangent at the frequencies of interest ($\gtrsim$ 1 GHz).

At present the most serious instability facing the future development of high current linear accelerators appears to be the so-called image-displacement instability.[13] This effect occurs when an off-axis beam of charged particles traverses an accelerating gap which interrupts an otherwise continuous cylindrical drift tube. Asymmetric displacement of the image charges and currents in the gap region results in a net transverse force on the beam that tends to move the beam even further off-axis. Model transport calculations, treating the accelerating gap as a defocusing thin lens, indicate that this effect is potentially serious for high current linear accelerators. While varying the intergap spacing as a function of beam kinetic energy may help to control the phase angle of the oscillation, a more straightforward approach is to avoid separation of the image charges and currents by careful design of the accelerating gap structure.

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