RADLAC TECHNOLOGY REVIEW

R. B. Miller
Directed Energy Research Department
Sandia National Laboratories
Albuquerque, New Mexico 87185

Abstract

In this paper we review the technology development associated with the RADLAC program. A basic description of the pulsed transmission line approach for constructing high power electron linacs is given, and two examples, RADLAC I and RIM, are described in some detail. Important problems associated with the design of the high current beam transport line are also discussed. Finally, we describe a recirculating linac concept based on the use of closed accelerating cavities and ionization channel beam transport.

I. Introduction

In recent years a number of advanced linear induction accelerators (LIAs) and betatron concepts have been developed which have the capability for accelerating very high electron beam currents. Examples of this new technology include the advanced test accelerator (ATA),1 the RADLAC accelerators,2 and the LIU accelerators.3 In this review we will discuss the origins of the RADLAC program, various problems encountered, and progress to-date. We will conclude by describing new approaches which may substantially reduce the size and cost of these high power linacs.

II. Background

All linear induction accelerators operate by producing voltage around a circuit enclosing a time-varying magnetic flux. Mathematically, this is described by Eq. (1), where \( \mathbf{B} \) and \( \mathbf{E} \) represent the magnetic induction and the induced electric field, and \( V \) is the voltage induced around the circuit \( C \) which encloses the area \( A \).

\[
V = \frac{1}{c} \oint_{C} \mathbf{E} \cdot d\mathbf{l} = -\frac{1}{c} \oint_{C} \mathbf{B} \cdot d\mathbf{A}
\]

Time is represented by \( t \), while \( c \) is the speed of light. Note that Eq. (1) allows generation of voltage by changing either the enclosed magnetic field or the surface area normal to the field lines.

As an example consider a simple strip transmission line. The voltage between the plates can be thought of as arising from a time-changing magnetic flux as an electromagnetic wave propagates down the line. With a current \( I \) on the surfaces of the strip lines, the magnetic induction is described by

\[
\mathbf{B} = \frac{\mu I}{cW}
\]

where \( \mu \) is the magnetic permeability of the dielectric between the electrodes and \( W \) is the width of the lines. The area transverse to the magnetic field is simply \( A = \pi t \), where \( a \) is the separation of the lines and \( t \) is the linear dimension. As the wave propagates down the line, the length \( L \) increases linearly with the constant of proportionality being equal to \( \pi/\mu \),

\[
L = \frac{\pi t}{\mu}
\]

where \( \varepsilon \) is the material dielectric constant. Hence, in this case, the voltage across the gap arises from the time-changing area transverse to the magnetic field and is given by

\[
V = \frac{\varepsilon}{c} \frac{\pi a}{\mu} - \frac{\varepsilon}{c} \frac{\pi a}{\mu} t = Z_0 I
\]

where we have identified the impedance \( Z_0 \) of a strip transmission line.

As first noted by Pavlovskii,4 closed transmission lines can also be used to form the accelerating cavities of linear induction accelerators. Consider the geometry of Fig. 1.

![Figure 1. Closed accelerating cavity geometry of Pavlovskii. DAC is the closed toroidal shield and BB' is the high voltage disk. AB is the annular ring switch.](image-url)

A grounded, toroidal shield surrounds an annular disk which is pulse-charged to high negative voltage. Since the electric fields on either side of the high voltage disk are opposing, there is no net accelerating field across the gap. Now suppose that an annular ring switch internal to the cavity is closed. Although the line is shorted, no energy can escape since the cavity is (almost) completely enclosed. As a result, there will be a voltage of alternating polarity appearing across the gap of the cavity (Fig. 2). If an impedance equal to the characteristic impedance of the transmission line cavity is impressed across the gap after the time \( t \), then the output voltage will decrease by two, but all of the energy initially stored in the cavity will be delivered to the load (e.g., an electron beam). Again, note that the outside of the cavity remains at ground potential, and that only the beam sums the voltage along the length of the accelerator.

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Typical high voltage dielectric materials are transformer oil and de-mineralized water with dielectric constants of approximately 2.2 and 80, respectively. The cavity dimensions necessary to avoid high voltage insulator breakdowns for charging pulses of typically a megavolt generally imply a characteristic cavity impedance of a few ohms for water-insulated cavities and a few tens of ohms for oil-insulated cavities. As a result, efficient transfer of energy from the cavity to the beam requires that the beam current be relatively high (of the order of 100 kA). The cavity dimensions also suggest that accelerating gradients up to several MeV/meter may be achievable.

In addition to the high-current capability and the relatively high accelerating gradients, development of an LIA technology based on pulsed transmission lines is attractive because it builds on the experience gained in developing modular, high-current accelerators for inertial fusion experiments. These devices consist of multiple, high-voltage (2-3 MV), oil- or water-insulated, low-impedance pulse forming lines (PFLs) arranged in parallel to supply very high particle beam currents for imploding pellets. Satisfactory machine performance requires multichannel, liquid dielectric, spark gap switching with low jitter (1-3 ns). The information gained in developing the ICF accelerators has been used to form the basis of the Radial Line Accelerator (RADLAC) approach.

A schematic outline of our first device, RADLAC I, is presented in Fig. 3. A Marx generator-intermediate storage capacitor combination was used to pulse-charge an injector PFL and four radial transmission line/accelerating cavities through a self-breaking SF6 gas switch. The lines were switched by multiple, self-closing, point-plane, oil-dielectric spark gap switches. The beam was formed using a foilless diode configuration and guided through the accelerating cavities using a solenoidal magnetic field transport system. Our initial experimental goals were to obtain a 10 MeV, 50 kA electron beam in a 2 cm beam radius with an average accelerating gradient of 3 MV/m. At the end of our experimentation, RADLAC I was operating consistently at the 9 MeV, 25 kA level.

However, two important problems were observed. When we attempted to accelerate following the first polarity reversal of the Pavlovskii cavity waveform, we found that the useful gap voltage was limited to \( \sim 1.1 \) MV because of insulator flashover due to the voltage reversal. This breakdown level was a factor of two below our design estimate based on unipolar, dielectric breakdown studies. In addition, when we injected beam currents in excess of about 30 kA, the beam current transport efficiency decreased markedly. This drop was traced to the excitation of radial oscillations of the beam envelope due to a lack of radial force balance in the accelerating gap regions. Hence, while the RADLAC-I experiments were not totally successful, they did provide much valuable data; this information has subsequently been used to design much higher current, higher energy, linear accelerators.

III. RIIM Accelerator Development

In order to circumvent the insulator flashover problem until the physics of this process could be better understood, we examined several alternate accelerating cavity configurations which could produce high voltage, unipolar output pulses. One important design was the isolated Blumlein due to Prestwich. After relatively simple hardware modifications to the RADLAC-I structure, the operation of this cavity configuration was examined in some detail: this approach later became the basis for the very successful IBEX accelerator. A unique feature of this device is a two-pulse capability.

A second, unipolar pulse approach was suggested by Martin. Beginning with the tri-plate, water stripline technology developed for the PBFA-I accelerator, a voltage pulse is applied to the split-diamond convolute structure of Fig. 4. One of the convolute legs contains a polarity inverter also developed for PBFA I. Consequently, the voltage applied to a diode accelerating region can be approximately twice that of the strip transmission line. This concept has formed the basis for development of the RADLAC II Module or RIIM. This unit consists of a Marx generator, containing 40, 1.3 uF, 100 kV capacitors, which charges a 50 uF coaxial, intermediate storage capacitor (ISC) in approximately 1 microsecond. Eight, water,
tri-plate pulse forming lines (PFLs) are subsequently energized by the laser-triggered closure of two, SF₆, spark gap switches in approximately 250 nsec. This fast-rising voltage pulse permits the use of self-closing water switches which, in turn, deliver a 50 nsec pulse to the split-diamond convolutes. To assure symmetry of the accelerating pulse, each of four diodes are fed at the top and bottom by water stripline outputs from the convolute sections. A beam injector is formed by connecting two of the diodes in series across a foilless diode structure; the remaining two diodes contain beam acceleration gaps.

Although we have experienced some difficulties in the RIIM development phase associated with proper operation of the laser triggering system, insulator arcing in the PFL section, and convolute output efficiency, RIIM is now capable of reliable operation at output levels of 9 MeV and 40 kA. The beam is annular with a nominal outer radius of one centimeter. Representative voltage and current waveforms are shown in Fig. 5.

In order to achieve these highest beam current levels with RIIM, it was necessary to carefully consider several factors in the design of the beam transport system. In particular, we developed criteria for foilless diode designs and accelerating gap designs, as well as the beam break-up and image displacement multiple-gap instabilities.

From elementary space charge considerations, the highest beam currents can be transported if the beam is annular and located near the drift tube wall. This requirement suggests use of a foilless diode injector design in which the beam is formed and guided from the injector region by a strong solenoidal magnetic field. A nominal one centimeter radius cathode tip (r_c) was chosen to allow flexibility in generating bremsstrahlung radiation patterns by simply compressing or expanding the beam radius (r_B) according to the simple approximate formula

\[ \frac{r_B}{r_c} = \left( \frac{B_c}{B} \right)^{1/2} \] (3)

where B_c and B are the magnetic field strengths at the cathode and target position, respectively.

Empirical scaling laws and numerical particle-in-cell calculations predicted generation of 40 kA-60 kA beam currents for injector voltage in the range of 4 MV in agreement with the experimental observations.

During the course of multi-gap experiments with RADLAC I, it became apparent that the accelerating gap geometry, if not carefully chosen, could seriously disrupt the beam equilibrium. Consider the schematic accelerating gap geometry illustrated in Fig. 6. The zero-order gap dimensions are constrained by electron emission, virtual cathode formation, and radial oscillations of the beam envelope.

Although the beam space charge distorts the equipotential contours away from the cathode side of the gap, this distortion typically extends radially into the gap a distance of only a gap width L. Hence, a general rule is that the gap spacing must be chosen such that L > r_B/r_c.
where \( E_0 \) represents the applied potential and \( E_c \)

is the critical electric field for explosive emission. Conversely, for a given beam current and applied potential, the gap spacing must be sufficiently small to avoid virtual cathode formation at the entrance to the gap region. Relatively simple estimates of the space charge limiting current for these geometries can be obtained.

\[
\text{Acceleration voltage divided by the beam current is substantially greater than the characteristic transmission line impedance of the cavity, thus the output voltage will have a slowly decaying, alternating polarity waveform. Hence, if a suitable beam transport method could be found, then such cavities could be employed in a recirculating linac. This concept is being investigated using the CARP device, which consists of a 2.5 MV isolated Blumlein injector and a 1.5 MV accelerating gap energized with an ET-2 driver.}
\]

In summary, we have developed a linear induction accelerator module that consists of four accelerating diodes, pulse charged with water striplines. The unit has successfully produced a 9 MeV, 40 kA beam. This combination of the high current RADLAC beam transport technology with the module water stripline technology also forms the basis of the MARE multiple beam accelerator approach for gamma-ray simulation.\( \ddagger \)

IV. New Concepts

In the pulsed transmission line approach to constructing high current electron linacs, accelerating gradients of approximately 3 MV/m have been demonstrated; however, it is unlikely that substantially higher gradients can be achieved without a different technology approach. One promising concept for achieving very much higher effective gradients is to use the accelerating cavities more than once, i.e., the beam is recirculated through the linac structure several times.\( \ddagger \) Consider, for example, the closed accelerating cavity (ET-2) of Fig. 7.\( \ddagger \) If the load impedance associated with the accelerating voltage divided by the beam current is substantially greater than the characteristic transmission line impedance of the cavity, then the output voltage will have a slowly decaying, alternating polarity waveform. Hence, if a suitable beam transport method could be found, then such cavities could be employed in a recirculating linac. This concept is being investigated using the CARP device,\( \ddagger \) which consists of a 2.5 MV isolated Blumlein injector and a 1.5 MV accelerating gap energized with an ET-2 driver.

The four-pass beam recirculation requirements for CARP could be met with a conventional solenoidal beam transport system with corrections to circumvent grad-B drifts. The required magnetic field energy for this approach would be quite high, however, and alternate techniques are being explored. One promising approach would use the new technique of laser ionization of a low pressure background gas.\( \ddagger \) Dipole magnetic field-turning sections would be used to connect four straight laser-guided sections for recirculation as shown in Fig. 8.\( \ddagger \)

To investigate this technique a 1 MeV, 2 kA, 50 ns electron beam was generated in a laser-based foilless diode\( \ddagger \) and transported in a laser-ionized guide channel to a dipole turning magnet. The beam was then deflected to a second laser-ionized channel which made a 45° intersection angle with the first channel. The results are displayed in Fig. 9 which compares the transported current waveform with the injected waveform. The central portion of the injected beam pulse, for which the dipole field strength was properly tuned, was totally transmitted, although the beam radius was observed to increase by a factor of 1.5 in accord with single-particle simulation code predictions.

While this demonstrated level of performance should be adequate for simple applications, such as beam switch-yard steering, or directing multiple
Figure 8. Recirculating linac with laser guiding sections connected by dipole turning elements.

Figure 9. Injected and deflected beam current waveforms following a 45° deflection.

Figure 10. Schematic diagram of the 90° low-voltage, e⁻ gm bending experiment.

V. Summary

The RADLAC program has made significant contributions to the development of high current induction linac technology. In addition to the four accelerators that have been successfully constructed and tested (RADLAC I, IBEX, RIIM, and MABE), substantial progress has been made in the understanding of high current beam transport techniques. Finally, the new concept of ionization channel guiding, as applied to a recirculating linac concept, could represent a breakthrough in high power, high gradient accelerator technology.

References