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RADLAC-II ACCELERATOR BEAM EXPERIMENTS\*

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### Abstract

A pulsed transmission line linear accelerator, RADLAC II, composed of an injector plus six postaccelerating gaps was built and successfully operated. A 3-4 MV foilless diode injector was used and an annular 30-40 kA, relativistic electron beam was produced and further accelerated through the postaccelerating gaps. The final beam energy was close to the sum of injector and gap voltages and equal to ~16 MeV.

The pulsed power drivers, the accelerator, and the beam transport system are described. Experimental results are presented and discussed.

## Introduction

In the last decade, considerable work has been devoted to the production and acceleration of intense high energy electron beams. An entirely new family of linear accelerators of the induction type were developed and commissioned into operation. Because of the extremely high currents involved, 10-100 kA, and the relatively large number of modules required, these accelerating structures incorporate a number of innovative design approaches to circumvent instabilities

inherent to high current devices. RADLAC I, 1 MABE, 2

RIIM,<sup>3</sup> and most recently RADLAC II are representative of our effort towards the development of high current high energy electron linear accelerators. In this paper we describe the RADLAC-II accelerator and its performance.

# Accelerator Description

The RADLAC-II accelerator design is based on the experience gained by the successful operation of

RADLAC I and the pulse-forming technology of PBFA I.<sup>4</sup> The RADLAC-II pulse-forming network and transmission system is designed to provide unrestricted access to the beam line. This was accomplished by replacing the completely enclosed oil-dielectric radial transmission lines utilized in RADLAC I with the open construction water dielectric strip lines of the PBFA I type.

The RADIAC-II accelerator's main pulse power source is two 4-MV Marx generators. Each Marx generator, consisting of 40, 1.3 µf, 100 kV capacitors, charges a coaxial/water-dielectric intermediate store capacitor (ISC) through a coaxial oil transmission line and oil/water interface. The capacitance of each of the two intermediate store capacitors is approximately equal to that of the Marx generator. The ISCs reach peak voltage in about 1 µs. The pulse forming (PFL) and transmission lines are tri-plate water lines which are charged when four laser-triggered SF<sub>6</sub> gas

switches close, transferring the energy from the ISCs to the PFLs (Fig. 1). A one-joule KrF laser was chosen to trigger the switches. The primary laser beam is split into four -250 mJ secondary beams via a system of partially reflecting mirrors. Each beam travels through paths of different lengths before being focused between the electrodes of the respective switch. The path lengths are chosen to give switching in phase with the beam transport down the



Figure 1. Top view of RADLAC-II. In this configuration, RADLAC-II can be considered as consisting of two RIIM accelerators connected in series. A. Intermediate Store Capacitor; B. Laser Triggered Gas Switch; C. Pulse Forming Line; D. Transmission Line; E. Convolutes; F. Accelerating Cavity.

accelerator. The observed 1- $\sigma$  time jitter of the switches was less than 5 ns.

The rapid charging of the PFL (-250 ns) permits the use of self-closing, water-dielectric switches which deliver a 50 ns pulse to split diamond-shaped convolutes. One of the convolute legs inverts the pulse polarity, via crossover hars, so that the voltage applied on the accelerating cavity would be ideally twice the transmission line voltage. The actual convolute voltage gain is of the order of 1.8. Each accelerating cavity is powered by two PFLs and transmission lines located one on the top of the other. The lines make a 90° turn and feed the accelerating cavity from two diametrically opposite sides to assure transverse symmetry of the magnetic field relatively to the beam axis, and avoid beam steering.

### Beam Generation Transport and Acceleration

The injector is powered by four PFLs providing twice the post-accelerating gap voltage to a foilless diode electron source (Fig. 2). The injector voltage is about 4 MV for an 85 kV Marx charging voltage. The foilless diode has an annular cathode tip producing a hollow electron beam. This reduces the space charge effects and avoids the formation of a virtual cathode



Figure 2. RADLAC-II foilless diode design parameters.

at the beginning of the beam pipe. A schematic diagram of the diode is shown in Fig. 2 together with the relevant dimensions. The design goals were 40-60 kA at a 4 MV diode voltage. This was also verified by the numerical simulation of the produced beam (Fig. 3). The anode cathode gap can be varied continuously from the outside without breaking the accelerator beam line vacuum. The foilless diode is immersed in the axial magnetic field that guides the beam through the entire length of the accelerator (~10 m). The field is provided by an array of solenoidal coils connected to five capacitor banks.

An improved accelerating gap design<sup>5</sup> maintains radial force balance and completely eliminates the previously observed (RADIAC I) beam radial oscillations. Furthermore the accelerating cavities (diodes), similar to those studied in Ref. 6, have a very low Q and small transverse shunt impedance, thus suppressing beam break-up instabilities.

There are nine accelerating cavities, but for symmetry reasons, only eight are energized. In the present configuration, the cavity number five is not energized and the entire device can be considered as

being made of two RIIM accelerators 3 connected in



Figure 3. Numerical simulation of the RADIAC-II beam at the injector.

series. The first and second accelerating cavities are connected in series and form the injector. The application of the peak voltage to the diodes is synchronized to coincide with the arrival of the beam pulse in each gap. This is accomplished by adjusting the path length of each of the four secondary laser beams to fire the gas switches in the correct time sequence. Since all the PFLs and transmission lines have the same length, the time sequence of gas switch closure is the main method of synchronizing the arrival of the beam with the accelerating voltages. The beam current was measured by a number of Rogowski

coils and  $\dot{B}$  arrays positioned along the accelerator beam line. The injector and post accelerating gap voltages were measured by resistive monitors. The accelerating cavity voltages were about 2 MV, and the maximum measured beam current, all the way to the end of the accelerator, was 40. Figure 4 shows the effective accelerating voltage and beam current waveforms for 85 kV Marx charging. They track each other quite well, and the full width half maximum is 50 ns. Effective accelerating voltage is the sum of all accelerating cavity voltages as measured by the resistive monitors corrected for time coincidence with the



Figure 4. Effective accelerating voltage and beam current waveform.

passage of the beam pulse from each gap. The effective accelerating voltage is 15-16 MV and close to the sum of the individual diode voltages. This suggests a good gas switch synchronization. The final energy of the electron beam was deduced from range measurements into carbon/lucite targets. The effective accelerating voltage and the energy of the electron beam in MeV agree within 1 MV. This difference is probably due to range shortening in plastics for high current density electron beams.<sup>7</sup>

The beam envelope, at the accelerator exit and further upstream, was measured using radiochronic foils (Fig. 5). Because of the high power density of



#### BEAM ENVELOPE BEFORE EXTRACTION

Figure 5. Beam envelope on radiochromic foil inside the end of the accelerator vacuum pipe. The part of the foil enclosed by the beam annulus is carbonized.

the beam annulus, it was difficult to precisely measure the beam size on brass targets (Fig. 6). The brass targets melted and became severely damaged by

the beam. Recently, a framing x-ray camera<sup>8</sup> was used

to study the beam profile and the  $\bar{x}, \bar{y}$  of the beam centroid. A 0.127 mm thick tantalum x-ray convertor is placed over a thin extraction titanium foil on the



Figure 6. Beam pattern profile on brass target positioned at the end of the beam line ~10 m downstream from foilless dicde. The beam is annular. The small ellipticity and apparent beam displacement from the axis is probably due to the target positioning and beam misalignment. (The target was exposed to the beam before our recent precise alignment.) air side for the x-ray measurements. Figure 5 shows the beam envelope on a radiochromic foil positioned inside the vacuum pipe just before the extraction foil. It is possible to measure the beam profile and current density with the x-ray framing camera using photographs similar to that of Fig. 7. Each frame exposure is 10 ns with a variable interframe time difference; here it was 0 ns. The first frame coinciding with the arrival of the front of the beam pulse is at the bottom left. The last frame coinciding with the beam tail is at the top right while the top left and bottom right frames correspond approximately to the main body of the beam pulse. The beam appears solid and not annular as in Fig. 6. The



Figure 7. Measurements of the beam profile on the extraction foil using the x-ray framing camera. The beam appears filled in. For each frame, the shutter stays open for 10 ns. The interframe distance was 0 ns. The beam centroid is only 1 mm off axis. The apparent larger displacement is due to the paralax of the camera's six apertures. Notice that the beam does not show any B.B.U. or other type of oscillations.

reason may be due to a high gain of the microchannel image intensifiers for these early shots or to a low energy electron halo. The x-ray framing camera uses the low energy tail of the beam energy spectrum to unfold the beam spatial profile. Future experiments are planned to address this discrepancy.

After implementing a new method for a precise

beam line alignment,<sup>9</sup> the beam center was found to be less than 1 mm off axis at the exit point (extraction foil) of the accelerator. The beam was allowed to exit the accelerator beam pipe and propagate freely in the accelerator high bay. The beam propagated straight and without oscillations for at least 1 m in the air (Fig. 8). No oscillations of the beam axis are apparent. This is in good agreement with results obtained with the B array placed near the exit of the device.



Figure 8. Open-shutter photograph of the extracted beam following precise alignment of the acceleraor beam line. The trajectory scanned is equal to ~1 m.

### Conclusions

A high-current, high energy, linear induction accelerator, RADLAC II, has been developed and successfully operated. It incorporates all the pulse power improvements previously tested in the RIIM accelerating assembly. The final energy, ~16 MeV, is close to the sum of the injector and post-accelerating gap voltages expressed in MV. The optimized injector and accelerating gaps have produced a 40 kA, 16 MeV annular electron beam. The energy distribution of this beam has not been measured.

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