RECIRCULATING ELECTRON BEAM LINAC

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One method to achieve a high gradient, linear induction accelerator is to recirculate the electron beam in phase with a repeating accelerating voltage. A two-cavity recirculating accelerator has been designed and operated in a single-pass mode. The prototype accelerator uses a 2.0-MV, 10-kA, 25-ns duration injector and an accelerating cavity that will produce a total accelerating voltage of 5.3 MV for four passes. The design of this machine involved key areas of development in pulsed power, specifically, low-jitter spark gaps and vacuum-liquid interfaces for bipolar electric fields. The recirculation technique under investigation employs an ion focus regime (IFR) electrostatic channel created by a magnetically guided, 300-V, 800-mA electron beam in low pressure (0.10 mTorr) Argon gas. This paper will discuss the recirculation concept, machine design parameters and scaling relationships, and summarize the pulsed power issues.

Introduction

Iron free, high current, linear induction accelerators have been described by Pavlovski[1,2] and Miller.[3] The Pavlovski accelerator achieved an average gradient of 2 MV/m. RADLAC I, described by Miller, achieved an average gradient of 3 MV/m.

RADLAC I program considerations also included the design of compact, high efficiency, accelerating cavities using deionized water or ethylene glycol as insulating dielectrics. One of the compact cavities that was evaluated, referred to as ET-2,[4,5] is shown in schematic form in Fig. 1. The center conductor in

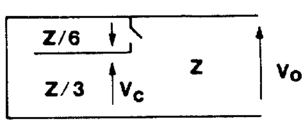

Figure 1. Transmission line circuit diagram for an ET-2 cavity. The relative impedance of each transmission line is indicated. The electrical length of each line is equal to one-half the pulse duration.

the cavity is charged to a voltage, V_c. When the switch closes, electromagnetic waves are launched into the three transmission lines producing, at the output terminals of the cavity, the bipolar waveforms shown in Fig. 2. In the matched load case, the cavity

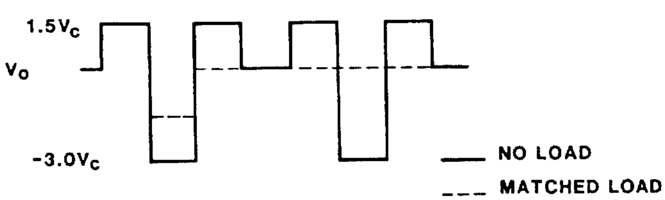

Figure 2. Waveforms produced by the ET-2 cavity for a matched load and a no load condition.

transfers 100% of stored energy to the load. However, by operating the cavity mismatched, a higher accelerating voltage can be produced by accepting reduced energy efficiency for a single pass of the electron beam. When the cavity is operated open circuit or with a large mismatch, the waveform repeats with a period equal to four times the accelerating pulse duration. Since higher gradient particle accelerators can be realized by recirculating the beam several passes through the accelerator, the ET-2 cavity is ideally suited for this concept.

Recirculation Technique

A schematic diagram of the recirculating linac is shown in Fig. 3 The injector/cavity timing is such that the electron beam arrives at the cavities at the

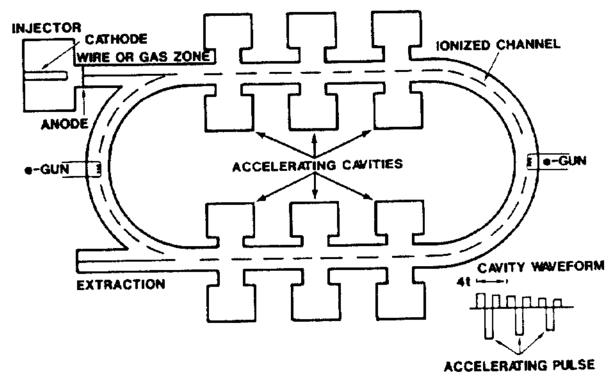

Figure 3. Schematic diagram of the recirculating linac. The waveform shown indicates a 25:1 mismatch. The waveform damping is due to energy extraction from the cavity.

beginning of the first accelerating pulse. The transit time around the racetrack is equal to four times the pulse length insuring that the beam arrives back at the cavities at the correct time. The recirculating concept requires an injection voltage sufficient to insure initial electron velocities near the speed of light. The IFR guiding technique[6,7,8,9] shown in Fig. 3 is generated on the racetrack with a low energy (300-V, 800-mA) electron beam guided by a 170-G magnetic field.

A cut-away artist concept for the ET-2 cavity using coaxial transmission lines is shown in Fig. 4. A schematic diagram of a radial transmission line ET-2 cavity is shown in Fig. 5. Both of these cavities are designed to produce a four-pass accelerating voltage of 5.3 MV for a 10-kA, 25-ns electron beam. The main advantage of a coaxial design is considerable savings in accelerator weight while accepting some reduction in accelerating gradient. The coaxial cavity also has additional corners in the path of the electromagnetic waves.

The accelerating voltage per cavity, V_b, for a recirculating accelerator is given by

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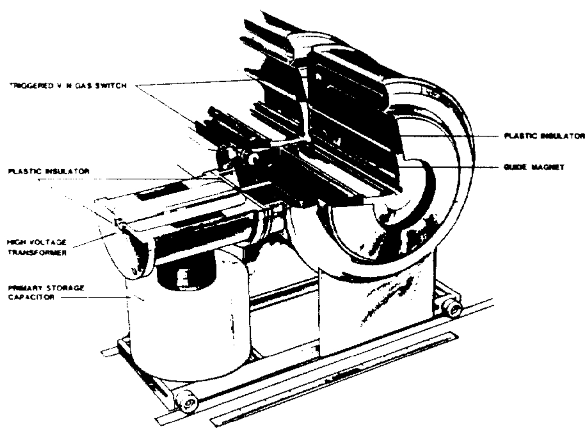

Figure 4. Artist concept of a coaxial transmission line ET-2 cavity using a high voltage transformer charging system.

$$V_b = 3\ p\ V_c\ (n+1-p)/(n+1), \qquad (1)$$

where p is the number of times the beam recirculates, and n is the initial impedance mismatch ratio (effective beam impedance divided by the cavity output impedance). The effective beam impedance is the accelerating voltage for a given pass divided by the beam current. The energy extraction efficiency is given by

$$e_f = 4\ p\ (n+1-p)/(n+1)^2. \qquad (2)$$

If p = (n+1)/2, all of the energy is extracted from the cavity. Allowing the beam to recirculate more than this maximum number of passes will extract energy from the beam to recharge the cavity.

Analysis of the cavity and electron beam equivalent circuit, combined with the above equations,

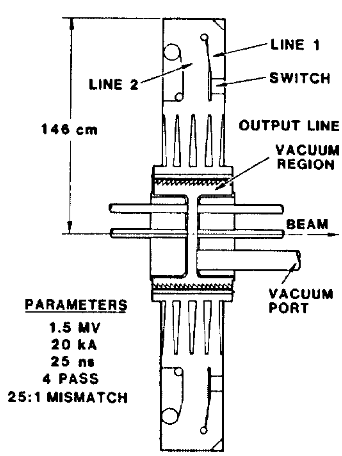

Figure 5. Schematic diagram of the radial transmission line ET-2 cavity used in the prototype accelerator.

leads to the relationship between accelerating voltage, beam current, I, and cavity output impedance, Z_o, as given in Eq. (3).

$$V_b = 3\ p\ V_c - p^2\ I\ Z_o. \qquad (3)$$

Expressing the maximum number of beam passes in terms of cavity parameters yields

$$p \leq 3\ V_c/(2\ I\ Z_o). \qquad (4)$$

These results are plotted in Fig. 6 for a 3- output impedance cavity, with number of passes as a parameter. The charge voltage for this cavity is

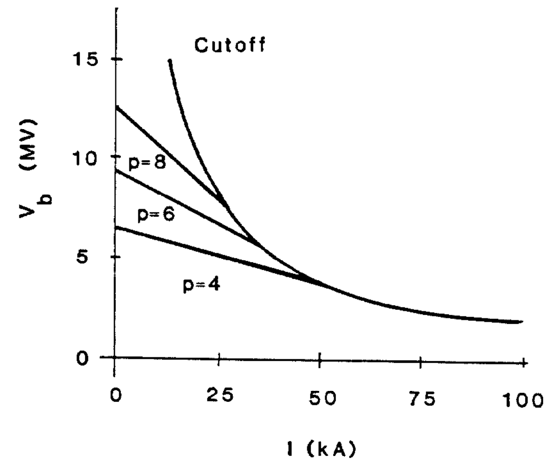

Figure 6. Accelerating voltage as a function of beam current with number of passes as a parameter.

520 kV. The graph clearly indicates the beam loading effect on the accelerating voltage. For a 4 pass device, increasing the beam current from 25 kA to 50 kA decreases the total accelerating voltage from 5 MV to 3 MV per cavity.

Prototype Accelerator

We have designed, constructed, and are operating a prototype recirculating linear induction accelerator. The main components of the device are an isolated Blumlein (IB)[10] injector, an ET-2 accelerating cavity using radial transmission lines, Marx generator primary energy store, and an IFR beam transport system.[7,8,9] The accelerator is shown in Fig. 7. The 2.0-MV IB injector is shown on the right

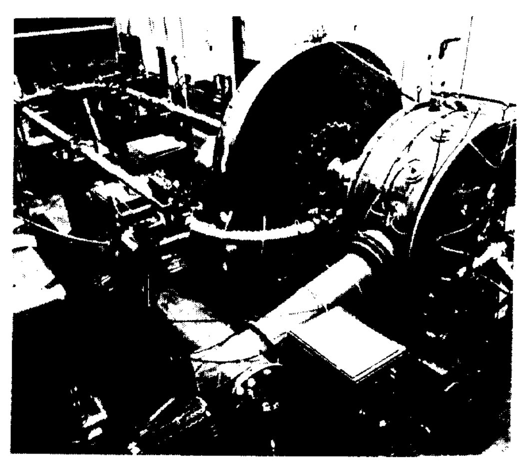

Figure 7. Prototype recirculating linac at Sandia National Laboratories. The IB injector is located on the right hand side. Beam propagation is from the right through the ET-2 cavity, around the 180 degree turn, and returning to the ET-2 cavity. An oil transmission line connects the Marx tank, shown in the extreme left foreground, to the injector and cavity.

hand side of the photograph while the ET-2 cavity (5.3 MV for 4 passes) is to the left of the injector. Because of space restrictions due to construction work in the laboratory, the accelerator is configured with one-half the required path length. This means that the second beam pass will occur during the null portion of the accelerating waveform. However, this experiment allows us to study beam generation, injection, acceleration, and propagation around the racetrack.

In the single-pass mode, a 5-kA, 2-MV electron beam has been transported through 270 degrees for a total distance of 17 m.[7] Injection hardware for wire zone transport[11] experiments has been added to the accelerator and these experiments are being conducted at the present time. Other areas of research are pulsed power cavity and component development and conceptual advanced accelerator designs.

Pulsed Power Issues

There are four key areas in pulsed power technology that affect the design of a recirculating linac: interface flashover at the vacuum/liquid-dielectric region, low inductance cavity switches, liquid dielectric breakdown, and a compact charging supply. We are studying the first three of these areas on the prototype accelerator and have published results on interface flashover[12,13] and low inductance, low jitter switching.[14] The ET-2 cavity vacuum interface has been subjected to more than 2000 shots and has operated flawlessly. The 36 triggered switches (12 in the injector and 24 in the cavity) have also been tested more than 2000 shots. Closure performance on the 12 injector switches is 92% with a 1-σ jitter of 4 ns. The cavity switches have achieved a closure performance of 90% with a 1-σ jitter of 4.5 ns. A future upgrade to the prototype accelerator will be the installation of a high-voltage transformer (520-kV charging voltage for the accelerating cavity and 1.2-MV charging voltage for the injector) and a low voltage (~60 kV) energy storage capacitor bank. These types of charging circuits have been developed over the past several years.[15]

Four Stage Accelerator Parameters

We have initiated a design for a four stage recirculating linac based upon the initial results obtained with the prototype accelerator. The accelerator beam line will pass through four ET-2 cavities each supplying 5.3 MV of accelerating voltage on four passes. Final beam voltage will be 24 MV for the 10-kA, 25-ns electron beam.

Since beam recirculation time for a full length configuration is 100 ns, there are two straight sections of beam line of 12.1 meters, with the remainder of the required 30.5 meters in the 1 m radius turns at each end (see Fig. 7.) The four stage accelerator can be expanded by installing eight additional ET-2 cavities in the forward straight section of the beam line and 12 more ET-2 cavities in the reverse direction. Including the beam line turns and the injector cavity, the gradient for this device would be 9 MV/m. The 9 MV/m gradient assumes coaxial transmission line cavities. Radial transmission line cavities would boost the gradient to 14 MV/m, but at considerable increase in accelerator volume and weight.

Conclusions

The prototype recirculating linac is operating and beam transport experiments are underway. The pulsed power design goal of multiple V/N spark gap operation has been verified in the ET-2 cavity and the IB injector. Improvements in vacuum insulator flashover with bipolar fields has led to increasing the flashover strength by 50%. A conceptual design for an four-stage accelerator has been initiated. The major parameters of this accelerator have been determined and the design appears feasible.

Acknowledgment

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