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HIGH AVERAGE POWER LINEAR INDUCTION ACCELERATOR DEVELOPMENT

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John R. Bayless and Richard J. Adler
Pulse Sciences, Inc.
5330 Derry Ave., Suite J, Agoura Hills, CA, USA 91301

ABSTRACT

There is increasing interest in linear induction accelerators (LIAs) for applications including free electron lasers, high power microwave generators and other types of radiation sources. Lawrence Livermore National Laboratory has developed LIA technology in combination with magnetic pulse compression techniques to achieve very impressive performance levels. In this paper we will briefly discuss the LIA concept and describe our development program. Our goals are to improve the reliability and reduce the cost of LIA systems. An accelerator is presently under construction to demonstrate these improvements at an energy of 1.6 MeV in 2 kA, 65 ns beam pulses at an average beam power of approximately 30 kW. The unique features of this system are a low cost accelerator design and an SCR-switched, magnetically compressed, pulse power system.

1. INTRODUCTION

The linear induction accelerator (LIA) concept, which is illustrated in Fig. 1, was first proposed in 1958. It has been extensively developed at Lawrence Livermore Laboratory (LLNL) and Pulse Sciences, Inc. (Ref. 1, 2, 3). This accelerator operates in many respects like an electrical transformer. A pulsed voltage, which is only a small fraction of the final beam voltage, is applied to a series of ferrite cores contained within accelerator cells. The electron beam, which is equivalent to the secondary of a transformer, passes through the cells where it is accelerated in the gaps between grounded electrodes to attain a final voltage that is the sum of the cell voltages. Thus, high beam voltage is achieved without requiring comparable voltages in the system. Furthermore, the use of a pulsed drive means that the cell voltage is present only a small fraction of the time (<0.1%). Thus, voltage breakdown issues are greatly reduced in comparison to other types of accelerators. Because LIAs readily operate at peak currents in the kiloampere range, high electrical efficiency can be achieved. High average power is attained by repetitively pulsing the system. Because of these characteristics, the LIA is the only type of accelerator capable of providing the combination of high beam voltage and current, high average power, high efficiency, and low cost that is required for applications including free electron lasers, high power microwave generators and two-beam accelerators.

The major elements of a LIA system are the power supply, the pulsed power source and the LIA. Pulse lengths of less than 100 ns are necessary to achieve reasonable accelerating gradient size and cost. For high average power systems, voltage pulses with this duration are generated using thyratron or SCR switches and a series of capacitors coupled through saturable inductors. These magnetic compression (MC) stages act to compress the pulses to

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the final pulse length. A step-up transformer is employed to obtain the final charging voltage. Other devices such as spark gaps can be used as the primary switch; however, they are not appropriate for systems where life, repeatability, and reliability are critical. The combination of LIA and MC technology yields a concept which is inherently scalable to high beam energies and high average power levels with good efficiency. Furthermore, the concept is simple, and tolerances and tuning are not critical.

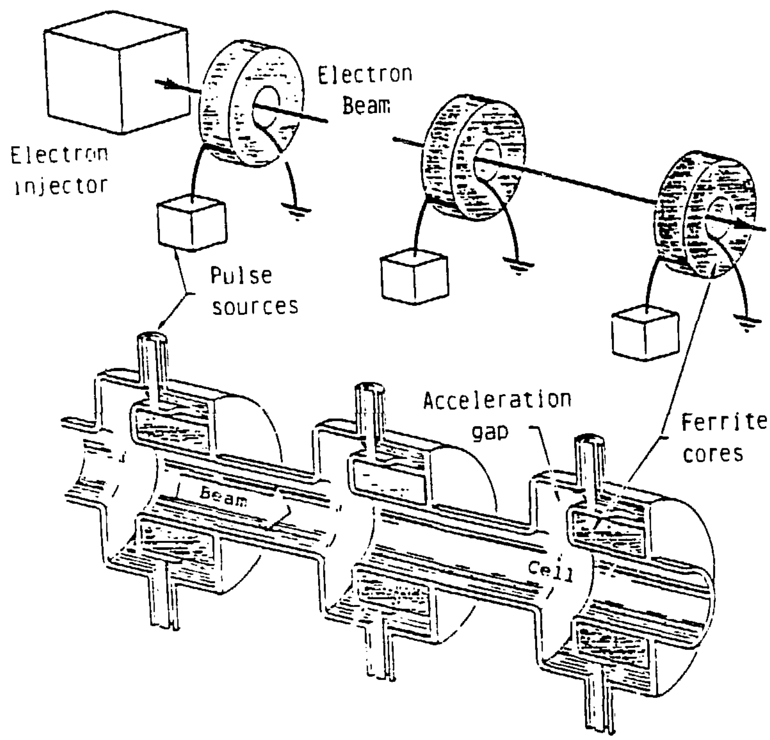

Fig. 1. The LIA concept.

Over ten major LIA systems have been constructed in the U.S. and others have been developed in the USSR and the PRC. Many of these machines have been designed to demonstrate the feasibility of inertial confinement fusion, charged particle beam concepts and high power free electron lasers. These machines have operated at beam energies up to 50 MeV, peak beam currents in the range of amperes to 250 kA, pulse lengths from 20 ns to more than 1 μs, and pulse repetition rates exceeding 100 Hz. Accelerating gradients have typically been on the order of 1 MV/m. The early LIA systems used spark gap switches; however, recent designs have incorporated magnetic pulse compression. The use of magnetic pulse compressors, which fac litates the use of long life switch elements, is the key factor that now makes LIA systems attractive for high average power applications (Ref. 4).

2. LIA DEVELOPMENT AT PULSE SCIENCES

Our goals in extending LIA/MC technology are, in order of priority, to achieve: (1) high reliability corresponding to more than 6000 hrs/year of operating time; (2) low installed system cost; (3) low operating and maintenance costs and (4) power line to electron beam conversion efficiencies of greater than 50%. We have focused on the energy range of

1-10 MeV as required for many applications. An accelerator system design has been developed to meet these goals. In order to demonstrate this design, we are currently building a 1.6 MeV prototype LIA/MC system which will operate at an average beam power of up to 30 kW. Major portions of this prototype system are currently operational and we expect to begin operation of the complete system in July 1987.

2.1 Accelerator System Parameters

A LIA consists of a series of acceleration cells as shown in Fig. 1. One cell design can be used for a wide range of beam energies; cells are simply connected in series to give the desired output beam energy. We have chosen to build LIAs in modules which contain a number of cells. An accelerator module of <1 MeV gives us the flexibility to address a variety of applications in a multi-module system.

The energy per cell and the pulse length are based on the unique properties of the MAG I type of magnetic compressor developed by LLNL (Ref. 4). This device takes an input of 25 kV in 5 μs pulses and delivers ~800 J in 75 ns, 150 kV pulses with greater than 80% electrical efficiency. To be conservative we chose 140 kV/cell as our operating voltage, and 6 cells per module for a total output of 840 kV/module.

The pulse current is chosen by balancing considerations of core loss, beam stability, focusing, accelerator length, cost, and relevant applications. Operation at pulse lengths less than 100 ns dictates the use of ferrite core material in order to minimize losses. Suitable material is available commercially. An assembly of cores with an overall outer diameter of 50 cm and an inner diameter of 10 cm is used to construct the accelerator cells. At a selected beam current of 2 kA the resultant accelerator efficiency (pulsed electrical power input to electron beam power output) is greater than 80%. A solenoidal magnetic guide field of about 1 kG serves to maintain a beam diameter of 2 cm. This guide field is pulsed in order to minimize the power required to generate it. A block diagram of the prototype system is shown in Fig. 2 and the partially completed system is shown in Fig. 3. Each of the major system elements is discussed below.

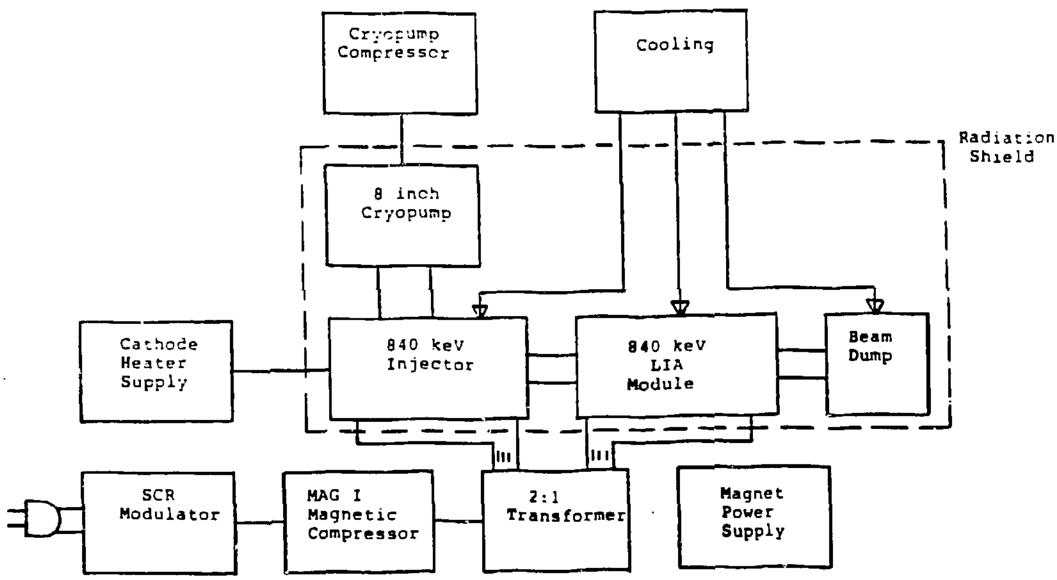

Fig. 2. Block diagram of the prototype LIA system

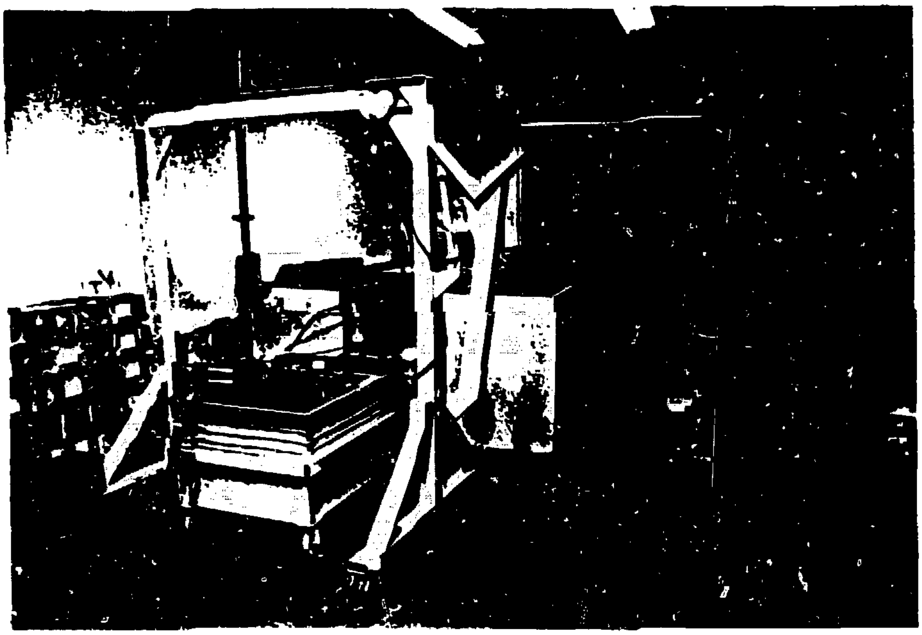

Fig. 3. Picture of the partially completed prototype LIA system showing the modulator and radiation shield.

2.2 Electron Beam Injector

The injector, which is shown in Fig. 4, is designed as a modified accelerator section and operates at 840 kV. This total voltage is applied across the central gap between the Pierce corrected electron source and the drift tube anode. An M-type dispenser cathode is used since this type of cathode is capable of supplying >25 A/cm^2 with long life. A conservative pulsed vacuum field stress level of $E < 100$ kV/cm is maintained at all points in the diode region. Independently controlled pulsed magnetic field coils are provided to facilitate optimum beam focusing. As will be discussed more in the next section, the entire injector, including cores, is placed in two oil-filled tanks with vacuum pumping in the connecting tube. This assembly is 57 inches long. The beam is compressed by the converging magnetic field in the injector, and exits with a diameter of approximately 3 cm.

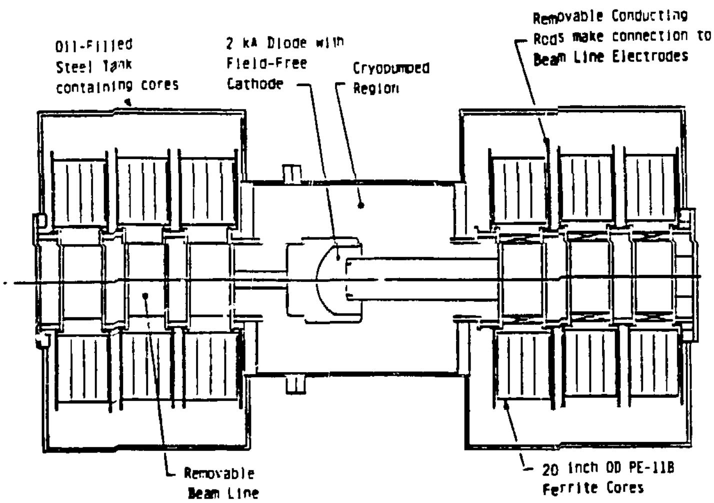

Fig. 4. Injector configuration.

2.3 Accelerator Modules

A diagram of a single 840 kV module is shown in Fig. 5. At the present time, we are fabricating the injector and one accelerating module. A 5 MeV machine, for example, would consist of 5 accelerating modules plus the injector and would be about 8 m long.

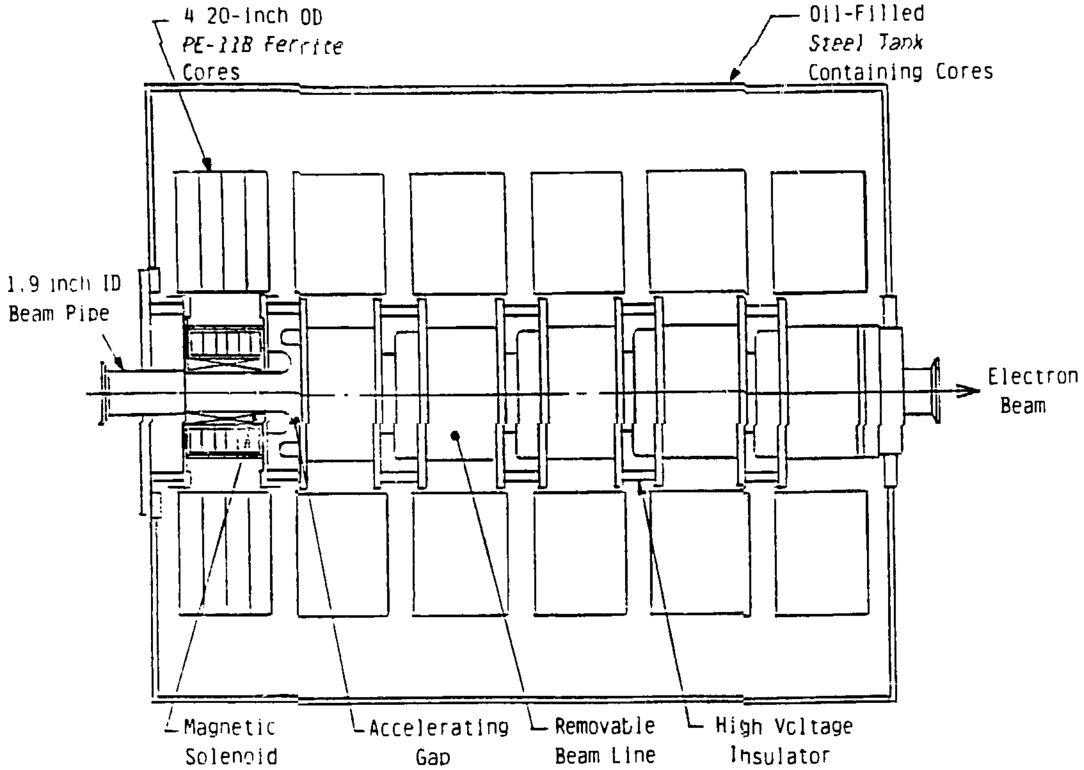

Fig. 5. 840 kV linear induction accelerator module.

The module is made from two separable pieces: the tank in which the cores for 6 cells are mounted, and the removable beam line. The tank is filled with transformer oil and voltage pulses are delivered to the module by six, 50 Ω, 200 kV DC high voltage calbes. The cables are connected to a bus bar, which runs the length of the module. Conducting rods provide the connection between the bus and the beam line electrodes. The overall length of a module is 40 inches.

The beam line itself includes all the stainless electrodes, drift tubes, magnetic field coils, vacuum insulators, etc. required to transport the beam. It is held together with insulated bolts. Circulating oil is brought in through fittings on the beam line to provide cooling. At the planned operating frequencies of ~100 Hz, the waste heat per module is estimated to be ~2000 Watts; we expect to be able to run at up to 600 Hz with this design without excessive ferrite core heating. This type of construction has considerable advantages in cost and ease of maintenance over conventional cylindrical cell designs.

2.4 Power System

There are two key components in the power system: the SCR modulator and the MAG I magnetic compressor. We regard the use of SCRs in this application as a major advance since thyratrons are subject to unscheduled failure, and replacement was expected to be a major cost over the accelerator life. An SCR modulator of the type we have demonstrated also eliminates the need for a separate power supply and charging inductor.

A simplified schematic of the SCR modulator is shown in Fig. 6. The power train starts at the input power line with 3 phase, 208 V power. In our prototype modulator, a 3-phase SCR bridge (SCR1) charges the capacitors C_1 to ±160 V. The pulse capacitors C_2 are resonantly charged to ~550 Volts after the SCR2 pulse. SCR2 is the primary switch. The pulse generated when it is triggered is stepped up to 26 kV by the transformer and the two magnetic compression stages shorten the pulse to approximately 4 μs. The output of this modulator is then delivered to the MAG I.

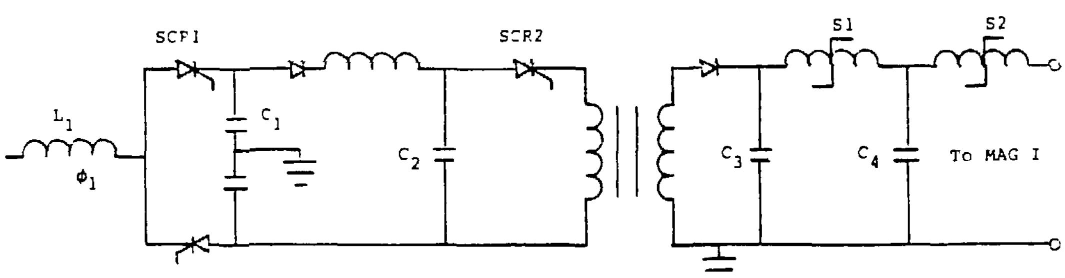

Fig. 6. SCR modulator circuit

Figure 7 illustrates the MAG I circuit. This unit has been modified slightly from the original LLNL design to deliver 70 kV, 65 ns, 200 J pulses. A 2:1 ferrite pulse transformer will be used to step the MAG I output up to the 140 kV LIA module drive voltage. No compensation is provided in the present design to offset the effects of the variation in LIA core magnetization current with time. Thus, we expect the beam current and voltage to vary about ±10% during the pulse "flat-top" period of 30-40 ns. Improved pulse voltage and/or current flatness can be achieved as required by using compensating circuit elements, tapering the output impedance of the MAG I or by controlling the injector current such as to offset the magnetization current variation.

Based on our preliminary results at 200 J/pulse, we expect the efficiency of the SCR modulator to be greater than 80% and that the overall efficiency of the power system will be greater than 70%. The overall efficiency for the prototype system is expected to be greater than 55%. At higher power levels, the wall plug to electron beam efficiency should exceed 60%.

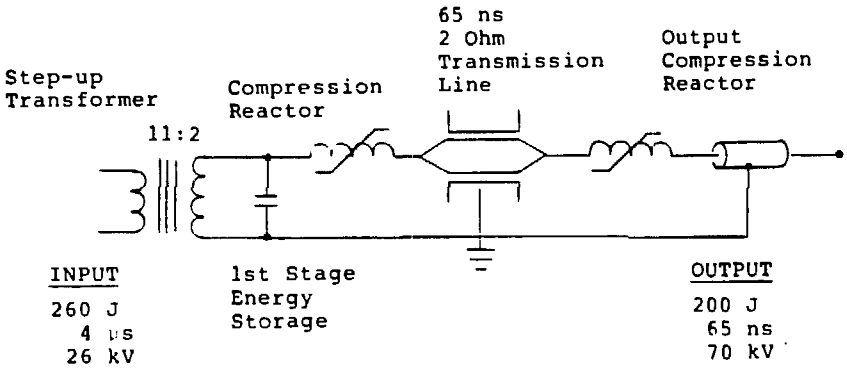

Fig. 7. The modified MAG I magnetic pulse compressor circuit.

3. CONCLUSIONS

Linear induction accelerators operating in the energy range of 1-10 MeV are attractive for a variety of scientific and commercial applications which require high beam current and/or average beam power levels in the range of 50-500 kW. LIA systems driven by all-solid state power sources are attractive for these applications since they can provide high reliability, high efficiency, low capital and operating costs, and a nigh degree of flexibility. Furthermore, such machines are simple in construction and do not have severe tuning, tolerance or high voltage insulation requirements.

ACKNOWLEDGMENTS

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