PULSED HIGH-POWER BEAMS

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Abstract

The marriage of induction linac technology with nonlinear mangetic modulators has produced some unique capabilities. It is now possible to produce short-pulse electron beams with average currents measured in amperes, at gradients approaching 1-MeV/m, and with power efficiencies exceeding 50%.

A 70-MeV, 3-kA induction accelerator (ETA II) constructed at the Lawrence Livermore National Laboratory incorporates the pulse technology concepts that have evolved over the past several years. The ETA II is a linear induction accelerator and provides a test facility for demonstration of the high-average-power components and high-brightness sources used in such accelerators. The pulse drive for the accelerator is based on state-of-the-art magnetic pulse compressors with very high peak-power capability, repetition rates exceeding 1 kHz, and excellent reliability.

Introduction

The Linear Induction Accelerator (LIA) is the major research tool of the Beam Research Program at the Lawrence Livermore National Laboratory (LLNL). The LIA generates peak currents of several kiloamperes with average currents approaching 1 A. These electron pulses are of short duration (<100 ns), and high average power is achieved by increasing their repetition rate. The LIA attains a high repetition rate (>1 KHz) and high reliability because nonlinear magnetic pulse compressors are used to drive the accelerator. The role of these devices is similar to that served by the klystron in an rf accelerator. Although the LIA has been used primarily for the study of beam propagation and free-electron lasers, there has been considerable interest in applying this technology to other areas such as radiation processing.

The Linear Induction Accelerator (LIA)

The accelerator module is the heart of a multistage LIA. Each module incrementally adds kinetic energy to the beam as it traverses the acceleration gap. Therefore, by increasing the number of modules that make up the accelerator, one can increase the beam energy to any desired level. In a qualitative sense, the accelerator module has been thought of as a one-to-one pulse transformer with the beam as the secondary current. More appropriately, however, the module is a decoupling element that allows the acceleration voltage to appear across the gap while inducing a voltage around the magnetic core to ground (Fig. 1).

This arrangement allows stacking of these modules to any energy level with no external voltage appearing anywhere. The acceleration cycle, more specifically, is as follows: Before the beam enters the module (sometimes referred to as the cell or cavity), the ferromagnetic core is magnetized to a maximum magnetic field. Then, a voltage pulse from the coaxial transmission line is impressed upon the acceleration gap. The ferrite torus acts as a lossy inductor which prevents a large current from flowing through the structure and keeps the coaxial line from shorting to ground. The cell geometry is designed and ferromagnetic materials chosen to keep the induced current a small fraction of the total beam current, hence, contributing to the inherently high energy-transfer efficiency of the LIA. In accordance with Faraday's law, the cell is designed such that the cross-sectional area of the ferrite is sufficient to keep the magnetic flux from saturating it.

In addition to satisfying the law of magnetic induction, the cell must be designed to satisfy the dynamics of beam transport. Much like rf accelerators, the geometry of kiloampere electron beam accelerators must be such that beam motion through the cell does not lead to instabilities and beam breakup (BBU). The LIA cell, unlike rf accelerators, consists of a simple low Q (<4) structure with minimal coupling to the electron beam. Fig. 1(a) shows the cross-section of the ATA cell with 20 kA of drive. Although this cell displays the low Q required, it is not adequate for acceleration and transport of high-current beams to energies greater than a few tens of mega-electron volts. The cell shown in Fig. 1(b) is the new design used in ETA II. This design incorporates the low Q and geometry required to stably accelerate a 3-kA beam to 10 MeV. This cell is also designed to minimize gap capacitance so that risetime can be preserved and that the load to the high-impedance drive can be minimized.

Switching Requirements

Nearly all accelerators require some form of pulse shaping. The LIA is very efficient at high currents (>1 kA), low energies (1 MeV/m), and short pulses (<100 ns). The requirement, therefore, is to generate short, high-voltage pulses from a dc power supply with a rate of rise in current greater than 10^{13}A/s.

Invariably, such a pulse cannot be generated directly but is achieved by one or more stages of compression. The spark gap is a perfectly acceptable method of compressing a pulse in a single stage when the average power requirement is low. The Advanced Test Accelerator (ATA), which operates at 1 Hz, uses a thyratron to generate a 20-μs, 250-kV pulse and a spark gap to compress it to 70 ns at the same voltage (Fig. 2). The life of such a device is less than 10^7 pulses, at which time electrodes must be replaced. Recovery time and wear make spark-gap devices unacceptable for high repetition rates (high average power). Even if such a device could operate at kilohertz repetition rates, its life would be measured in minutes.

Magnetic Pulse Compression

It was recognized that future needs for high average power would require alternative solutions. Even before the first spark gap went into operation, a development program was started to achieve the same pulse shapes at high repetition rates.

The scheme we chose, magnetic pulse compression, has been utilized for decades at much lower power levels and longer pulse durations. The fundamental principle involved is to use the large changes in permeability exhibited by saturating ferromagnetic materials to

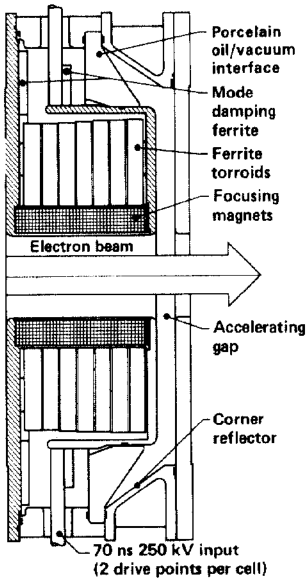

Fig. 1a. Cross section of old ATA induction accelerator.

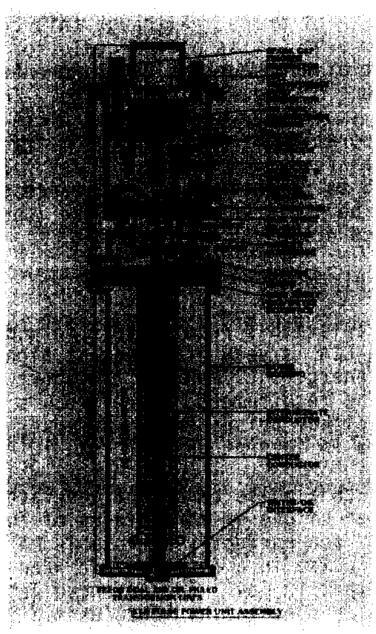

Fig. 2. Low average power spark-gap driven Blumlein.

produce large changes in impedance. The basic circuit for magnetic pulse compression remained essentially the same as originally conceived. What made this method attractive for very short pulses was the development of new, metallic glasses that could be mass produced in very thin (low loss) ribbons.

The goal was to couple existing thyratron technology to a minimum number of compression stages to produce a replacement for the existing spark-gap-driven Blumlein.

The first attempts were quite successful, and a two-stage magnetic pulse compressor took a 1-μs, 25-kV thyratron generated pulse, stepped it up and compressed it into a 70-ns, 250-kV pulse for the accelerator cell. The pulse compressor, MAG-1-A,

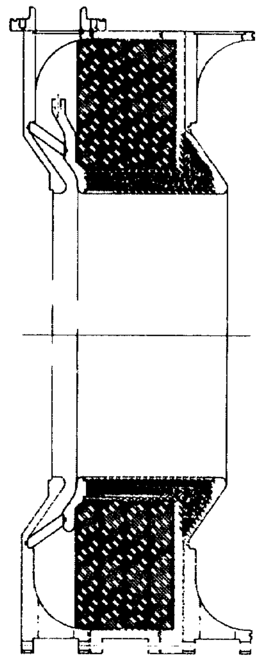

Fig. 1b. Cross section of advanced induction accelerator cell.

underwent several refinements to improve reliability and efficiency. Early devices were literally hand wound and did not withstand megawatt average power. Post-and-bar construction was later adopted to achieve reliability in voltage holding and high-current joints. Lower loss magnetic materials were also adopted as they became available. Operation of the two-stage device over several months showed that the lifetime of existing thyratrons was foreshortened considerably because of too high a di/dt. A precompression stage, which increased the thyratron discharge from 1 to 5 μs, was added to alleviate this problem. The simplified circuit schematic and wave shapes are shown in Fig. 3. A cross section of the latest device (MAG-1-D) is shown in Fig. 4. It consists of a precompression stage, a step-up transformer charging a water capacitor, one stage of compression to charge the water transmission line, and a second stage of compression which couples to the 20 induction cells through two parallel 4-Ω cables. Since this device was originally intended to replace the ATA Blumleins, its dimensions are very similar (about two feet longer). The comparison, however, ends there. The MAG-1-D provides twice the energy per pulse at an average power several orders of magnitude greater than the Blumleins. The continuous-wave burst-mode repetition rates are limited by the thermal time constants of the compression stages. Improvements in cooling of the magnetic material would extend these limits considerably.

This basic device was adopted for the new 7-MeV, 3-kA ETA II. The complete accelerator, shown in Fig. 5, consists of one MAG driving the injector and three other MAG's driving six additional ten-cell modules. This basic design can be modified if a different beam current or accelerator energy is desired.

Injector

A high-average-power accelerator requires an electron injector with the same capability and beam quality as that required by the specific application. For example, if the accelerator is used as a driver for a

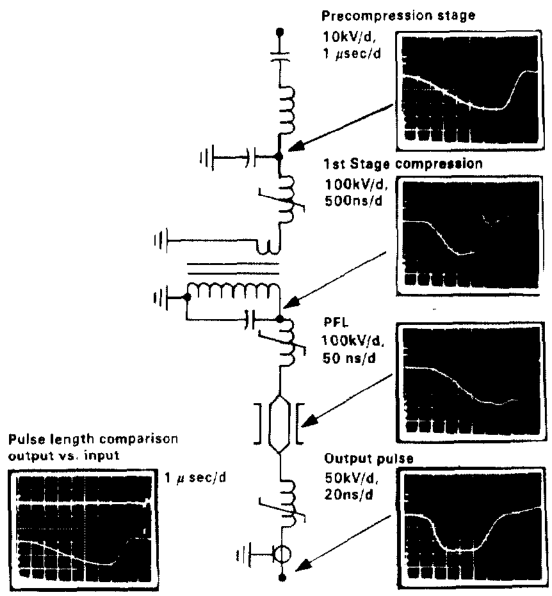

Fig. 3. Pulse compression sequence.

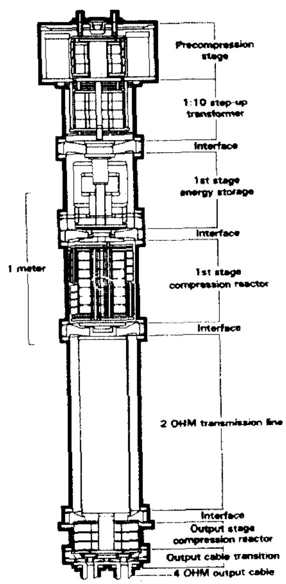

Fig. 4. Cross section of magnetic pulse compressor MAG-1-D.

free-electron laser, the beam brightness and pulse flatness must satisfy some very stringent requirements. The injector chosen to satisfy the requirements of the LLNL Beam Research Program is based on dispenser cathodes (Fig. 6). The cathodes are typically B-types with a layer of osmium alloy for operation at reduced temperatures. These cathodes have produced the current and brightness demanded by the program.

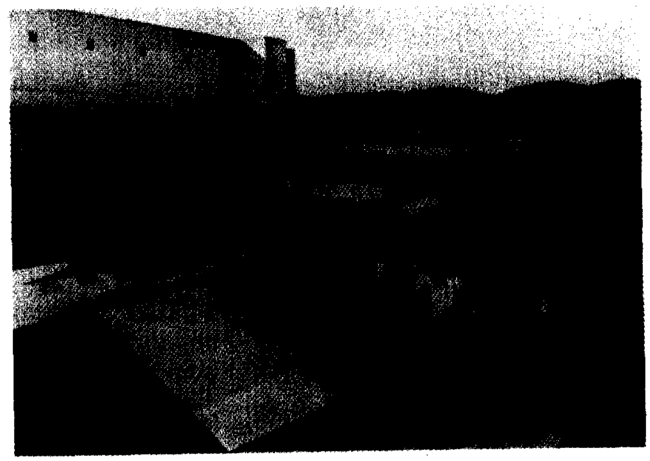

Fig. 5. Cut-away view of new ETA-II.

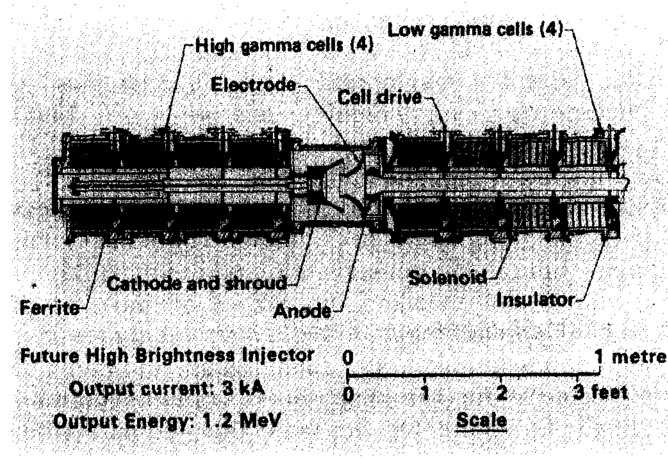

Fig. 6 Cross section of High Brightness Injector.

Conclusion

Induction accelerator technology coupled to magnetic pulse compressors offers a highly efficient and reliable method for accelerating kiloampere electron beams to several hundred mega-electron volts. This combination offers the physics community a powerful tool for studying free-electron lasers over a very broad wavelength and for applications such as beam propagation and food irradiation.

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