Recent Advances in Magnetically Driven Induction Linacs

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Abstract

Increased interest in high-current, short-pulse electron beams for a wide variety of applications, including free-electron lasers, has generated a demand for high-performance, high-reliability induction accelerators. Advances in this technology will be reviewed.

Designing the drive pulse sources is particularly challenging because the sources must deliver multi-gigawatt pulses with rise times of a few nanoseconds and pulse lengths of a few tens of nanoseconds. Recent developments in all-solid-state nonlinear magnetic drivers will also be discussed.

Introduction

Induction accelerators at the Lawrence Livermore National Laboratory (LLNL) have undergone considerable development over the last decade. Because the early applications required only low repetition rates (1-10 Hz), the LLNL Advanced Test Accelerator (ATA) used gas-blown spark gaps to generate a 250-kV, 70-ns pulse. With the advent of the Free-Electron Laser (FEL) program, which required repetition rates of several kilohertz, magnetic pulse compression devices were adopted. These devices evolved over a period of several years and have become a reliable and efficient way to generate 125-kV, 70-ns pulses at high average powers.

Current Technology

In any pulse compressor, a switch generates a pulse, which is them compressed to the required output length. The number of compression stages is usually minimized by using a switch with the highest possible rate of energy discharge. For the most recent generation accelerator, an EEV CX-1547 switch initiated the compression process. The pulse compressor, MAG-1-D, used three stages of magnetic material (Metglas) to compress a 5-μs pulse into a 70-ns pulse. The majority of the core losses occur in the last stage of compression, where the saturation time is the shortest. The cores are typically wound with an insulating layer of Mylar tape placed between turns. However, this winding method makes cooling the magnetic material difficult. The maximum CW repetition rate is therefore limited to less than 1 kHz. Higher repetition rates are feasible, but the run time is limited by the thermal time constants of the cores.

Future Requirements

Linear induction accelerators using current technology are quite adequate for use in present FEL drivers. Future LIA's, however, will need to produce lower energy per pulse at much higher repetition rates at a near continuous wave (CW) duty factor. These new parameters have required a complete redesign of the MAG-1-D and the switches to drive it.

Proposed Design

The LIA requires a 250-kV, 20 to 40-ns pulse with a 1-2 kA beam current. The energy per pulse is in the 50-100 J range. To maintain the same overall power, the repetition rate required will be in the tens of kilohertz. To achieve the higher repetition rate, a scheme known as branching is proposed (Fig. 1). This method allows the switches to be fired in sequence thus obtaining five times the repetition rate. A reduction in pulse energy has made solid-state devices a viable alternative to thyratrons. Use of relatively low voltage SCR's within their di/dt limits has required that we use additional compression stages and step-up transformers (Fig. 2).

Reductions in pulse duration and the need for additional compression stages impose a severe restriction on the allowable jitter. In a magnetic pulse compressor, the output pulse timing is a function of the input voltage because the propagation through the compression chain is a linear function of that voltage. The input voltage will, therefore, have to be regulated to a high degree, and a dejittering technique will have to be applied to the triggering of the final active switch. With the proposed dejittering technique, a sample of the uncompressed capacitor voltage biases a small ferrite core, which delays or advances the trigger pulse.

Difficulties in handling the core losses limited the MAG-1-D operation to less than 1 kHz at CW rates and a few tens of seconds at 5 kHz. Higher repetition rates and shorter pulses would result in much higher losses if amorphous magnetic materials were used. To reduce the losses, it has become necessary to use ferrites in

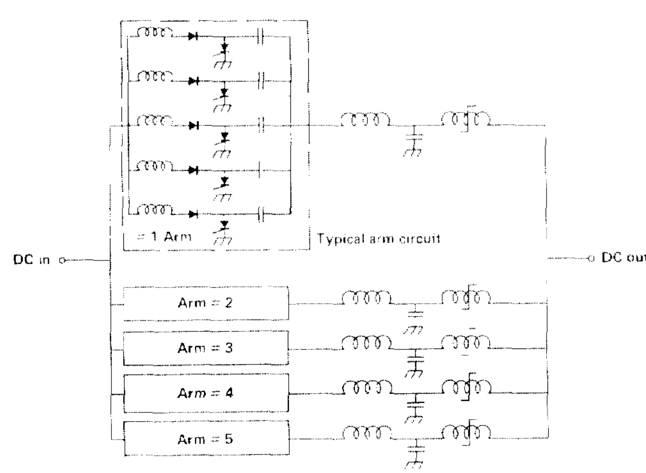

Fig. 1. Branched SCR's to achieve higher repetition rates.

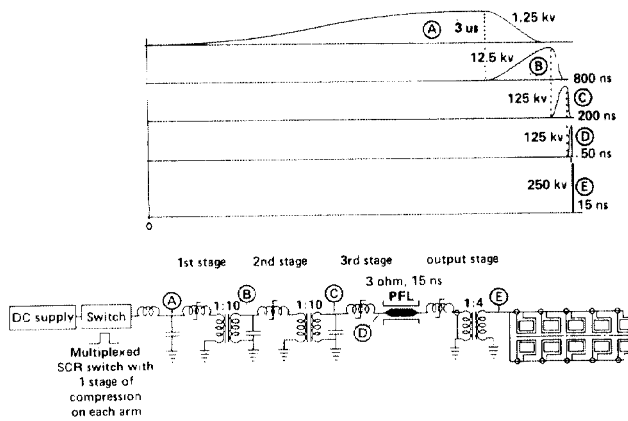

Fig. 2. Five stage magnetic pulse compressor driven by SCR's.

the latter stages of the pulse compressor (Fig. 3). The flux swing of ferrites is much lower than that of Metglas, so a larger cross-sectional area is necessary.

Designing an efficient magnetic switch hinges on controlling and understanding the magnetic flux in the saturable reactors. It is easy to underestimate the impact stray inductance places on driver operation. These stray inductances reduce the driver compression ratio, thus requiring a larger ferromagnetic core to achieve a given gain. This, in turn, adversely affects the achievable efficiency.

To understand this problem, it is instructive to compare the performance of some of the early LLNL designs to the present MAG-1-D. While materials have improved slightly, the major advance has been in the construction of the saturable reactors. The old designs, comprised of ferromagnetic cores housed in plastic covers and wound with RG-213 cable, have given way to fully coaxial structures with turns forming individual transmission lines around the core. Efficiencies have risen from 60% to nearly 95%.

A preliminary conceptual design for the proposed Advanced Nonlinear Magnetic Driver is presented in Fig. 3. Some of the techniques used to contain the magnetic flux within the core material can be visualized by examining this design in detail.

The proposed accelerator cell design is similar to the current LLNL design. Considerable effort has been expended in designing the gap region to minimize electric field enhancements and to provide a very low Q structure so as to minimize beam breakup mode excitation. In addition to the higher duty factor and average power that will be possible, the proposed design reduces the pulse length and, consequently, increases the potential gradient.

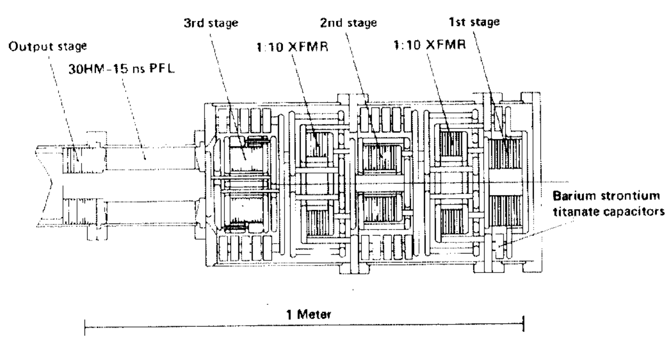

Fig. 3. Cross-section of magnetic pulse compressor with ferrite cores.

The gap width has also been increased somewhat to provide a higher impedance structure and to accommodate the higher voltage per cell. The proposed cell design would operate at 250 kV/cell, while the current LLNL design has been designed for 125 kV/cell. A cross section of the proposed four-cell block appears in Fig. 4. Each four-cell block would provide a total of 1 MeV of acceleration and would be driven by one cable from the 50-100 J magnetic driver.

Figure 5 compares 3-MeV accelerating sections constructed with the current and proposed technologies. Here, the proposed higher gradient modules are shown at the same scale as the modules based on the current LLNL design. The reduction in size is directly traceable to decreased pulse length and leads directly to a corresponding reduction in the size of the nonlinear magnetic driver. The lower per-pulse energy has also reduced the size of the driver. This energy reduction from 1000 J/pulse to 100 J/pulse is a significant change, which was realized by decreasing both pulse length and current.

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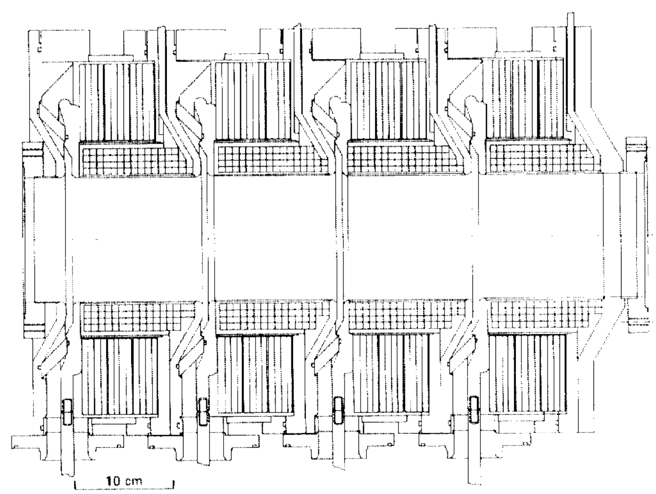

Fig. 4. Proposed 1 MeV four-cell block.

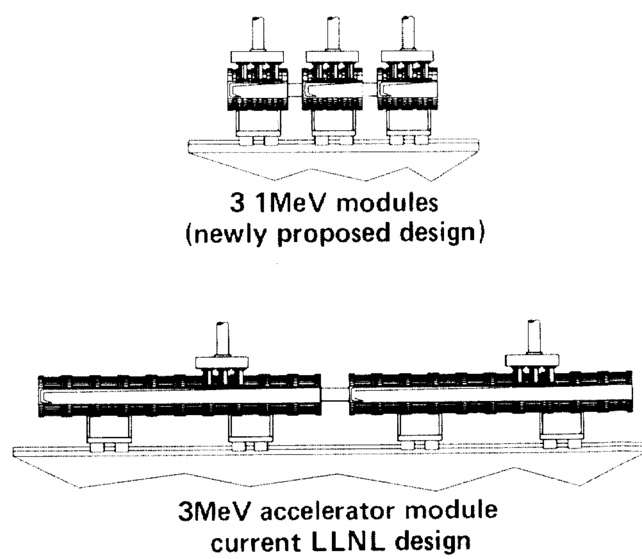

Fig. 5. Comparison of proposed 4-cell block with existing ETA-II 10-cell module.