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EVOLUTION OF HIGH-REPETITION-RATE INDUCTION ACCELERATORS THROUGH ADVANCEMENTS IN SWITCHING*

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Abstract

Future applications of linear and recirculating induction accelerators include microwave sources for plasma heating and linear colliders, industrial manufacturing processes, and heavy-ion fusion. These applications require pulsed sources capable of sustained operation at high pulse-repetition rates. Powering these new accelerators places severe switching demands on the source that often can not be met with commercially-available technology. Consequently, several new accelerator switching schemes have been developed at Lawrence Livermore National Laboratory (LLNL). Our transition from spark-gap technology to magnetic switching has merged the formerly independent roles of source and cell into a single system and reshaped our design methods to emphasize high efficiency. Treatment of the accelerator as a system has also enabled us to optimize new accelerator designs based on cost considerations. Presently, we are developing a technology for driving a heavy-ion induction recirculator at pulse rates exceeding 100 kHz. In this case, the switching method is all solid state and the source and cell have evolved into a unified device.

Introduction

We have encountered many intriguing applications for induction accelerators, especially if the machine has a high average power capability. For example, microwaves that are generated from electron beam power can drive Tokamak plasmas via electron cyclotron resonance heating [1] or power a high-gradient rf structure for the next generation of linear colliders [2]. A high energy induction accelerator, when coupled to a free-electron laser (FEL), can transmit large amounts of optical radiation from the ground into space at wavelengths with low atmospheric attenuation. This powerful radiation could then be directed to high efficiency photovoltaic cells that would power a spacecraft or a lunar base [3]. Electron beams have been applied to diverse environmental and industrial processes including the cleansing of flue gasses, waste sterilization, welding, and mineral identification in ore samples [4].

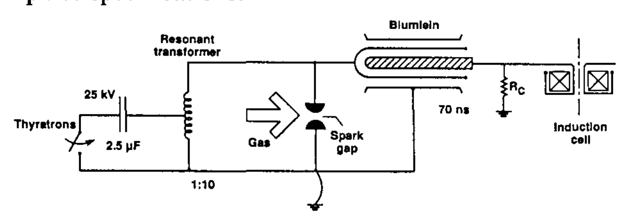
Heavy-ion fusion research in the U.S. has also focused on the linear induction accelerator as a driver candidate for inertial fusion [5]. A variation of this concept was investigated in a recent study that suggests bending the induction accelerator components into a closed path to form an ion "recirculator" [6]. The closed ion path recycles the most expensive accelerator components to attain the desired ion energy at a lower capital cost.

All of the induction accelerator applications mentioned hare a common need for advanced, high power switching. It is switching that significantly influences the accelerator's design architecture, average power capability, beam quality, efficiency and overall cost. It is also switch research that opens the new gateways between present accelerator technology and the high average power machines we envision for the future.

In this paper, we will illustrate how switching has shaped and facilitated accelerator research at LLNL. We will review some past examples of switch development programs to show what we have learned and how that knowledge has changed our methods of accelerator design and costing. Results selected from our recent switch investigations will illustrate the continuing role switching plays in new accelerator designs.

Past Accelerators and Switching Systems

The Advanced Test Accelerator (ATA) is a burst-mode, high pulse-repetition-rate accelerator that was built by DARPA approximately 10 years ago to study the feasibility of propagating intense electron beams through the atmosphere. ATA is a 50-MeV, 10-kA electron accelerator that can deliver a 70-ns beam pulse at a 1-kHz burst rate [7]. The accelerating voltage is generated from a pulsed power system that is switched by thyratrons and gas-blown spark gaps [8,9]. The thyratrons are used to charge a water-filled Blumlein, and the spark gaps serve to discharge the Blumlein into an induction cell. Figure 1 illustrates the ATA switching circuit and lists the pulse specifications.



Specifications					
Beam current	Beam voltage	Cell voltage	Pulse width	Continuous PRF	Burst PRF
10 kA	50 MeV	250 kV	70 ns	1 Hz	1 kHz (10 pulses)

Figure 1 Schematic diagram of the ATA switching circuit and table of pulse specifications.

The switching system on ATA worked very well, but our emerging interest in high power FELs prompted a search for a switch that could live longer and pulse faster than the gas-

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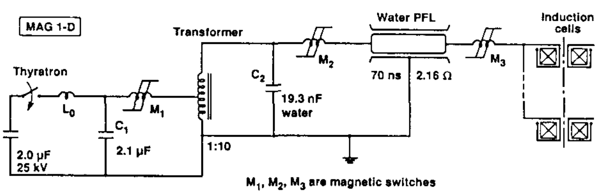
blown spark gaps we had at hand. Our first investigations began with low-pressure switches, which could perform at a high pulse repetition frequency (prf) but suffered from severe anode damage [10]. Experiments with magnetic and low-pressure switch combinations [11] eventually lead to a magnetically-switched prototype for the spark gap and Blumlein system on ATA [12]. ATA was never refitted with the new switching system. Instead, we built the Experimental Test Accelerator II (ETA II).

ETA II is a high average power electron beam accelerator that was designed and built to explore high average power accelerator technology and its benefits to FEL research [13]. ETA II employs a more mature version of the magnetically-switched power system developed for ATA and is capable of generating long bursts of electron beams at a 5-kHz rate [14,15]. Figure 2 illustrates the ETA-II magnetic switching circuit, known as a MAG1-D, and lists the pulse specifications.



Specifications					
Beam current	Beam voltage	Cell voltage	Pulse width	Continuous PRF	Burst PRF
2.0 kA	7.5 MeV	112 kV	70 ns	60 Hz	5 kHz (50 pulses)

Figure 2 Schematic diagram of the ETA-II switching circuit and table of pulse specifications.

A number of papers are available that describe the principles of magnetic switching [16,17] and the modern amorphous alloys used in switch construction [18].

Lessons from the Past

The ETA-II and ATA machines taught us several important connections between the switch, induction cell, and beam. First of all, we learned that the cell impedance of a low-prf accelerator can be well matched to a constant source impedance by an appropriate compensation resistor, as denoted by R_C in Figure 1. A resistively-dominated cell will yield a reasonably flat voltage pulse because the resistor masks any nonlinear impedance variations from the induction core or the beam. A flat voltage profile is generally an important goal because any variation of the beam's energy across the pulse contributes to an undesirable variation of the beam's center of mass position during the pulse through a mechanism known as "corkscrew" [19]. Corkscrew and beam-energy variations are important for FEL work because the beam will not contribute its energy to the radiation field if certain limits are exceeded for beam-centroid position or beam-energy spread [20].

We also learned that a high-prf induction accelerator needs to be electrically efficient and that high efficiency implies a tight coupling between source and beam. Specifically, the absence of a compensation resistor increases the cell's electrical efficiency but leaves the beam and cell magnetization currents as the only pulsed power load. In this arrangement, the shape of the cell's voltage pulse strongly depends upon the relative timing between the voltage pulse and the beam current. Therefore, precise switching is essential so that a flat voltage pulse is maintained [21].

The absence of a compensation resistor R_C also had an interesting social result: we became an integrated team. The compensation resistor in ATA allowed the source designers to regard the beam and cell as a simple resistor. Likewise, the researchers interested in cell-beam dynamics could also regard the source as an ideal pulse generator. We no longer enjoy the luxury of those innocent and somewhat isolated viewpoints. Our experience with ETA II taught us that high-prf machines require a well-integrated team to provide an integrated cell and source design [22]. We also discovered that designing a marriage between a nonlinear source (magnetic switches) and a nonlinear load is a formidable problem requiring advanced modeling techniques.

Our integrated thinking now goes beyond the source and cell to encompass the whole accelerator. In recent work, we developed a code to evaluate the relative costs of induction accelerator driver systems for relativistic klystrons (RK). The code serves as an integrated design tool by observing the interdependences between beam generation, beam transport and pulsed power. Results of this code work are presented in these proceedings [23].

Lastly, we found that switching dictates the accelerator's architecture and is a driving factor in the overall system cost and efficiency. Our appetite for high average power constantly bears against available switching technology. Consequently, advancements in accelerator capacity, as in ETA II, are achieved by advancements in switching.

Induction Accelerators for Linear Colliders

It is proposed, that microwaves from a relativistic klystron can provide power to a high-gradient accelerator structure for linear collider development [2]. Experiments are underway at LLNL to evaluate the microwave production from an RK powered by the modified ATA injector. Results of this investigation are presented in these proceedings [24].

Switching becomes a concern in this research when we consider the electron source needed for large-scale combinations of RKs and high-gradient structures. Previous work [25] indicates that the RK will require a nominal 3-MeV, 3-kA beam with a flat top exceeding 100 ns. A high average power source is needed that is rugged, efficient, and will generate pulses at a 300-Hz rate. We selected a source architecture that combines the best technologies of past accelerators [23]. Magnetic switches were chosen to charge a water-filled Blumlein (elements from ATA and ETA II), but discharging the Blumlein required a switch that was commercially unavailable.

Faced with the need to develop our own switch, we initiated a experimental study of a magnetically-delayed low-pressure switch. The scheme makes good use of our previous switching experiences by connecting a low-pressure switch in series with a magnetic switch. The magnetic switch delays the Blumlein's discharge long enough for the trigger plasma in the low-pressure switch to fully develop. The delay aids the low-pressure switch by reducing electrode erosion and increasing switch efficiency. Based on good results obtained by other researchers with magnetically-delayed vacuum switches [26], we established the test apparatus shown in Figure 3.

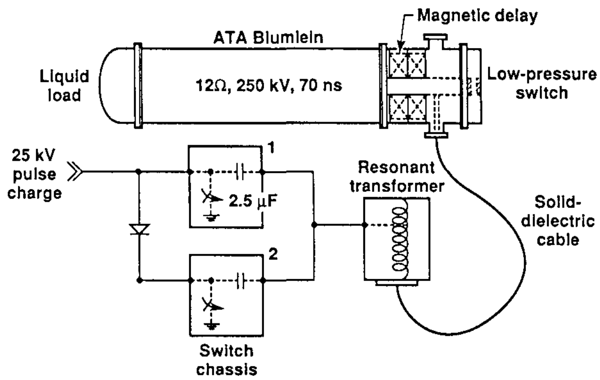


Figure 3 Circuit diagram of the two-pulse test apparatus for magnetically-delayed low-pressure switch experiments.

The test stand consists of an ATA Blumlein, resonant transformer and two thyratron switch chassis. The traditional ATA spark gap is replaced by a low-pressure gas switch in series with two magnetic cores constructed from 2605-CO Metglas alloy and mylar film. Switch recovery is tested by discharging the Blumlein through the switch combination and then recharging the Blumlein shortly thereafter. Typical voltage and current waveforms for the low-pressure switch are shown in Figure 4.

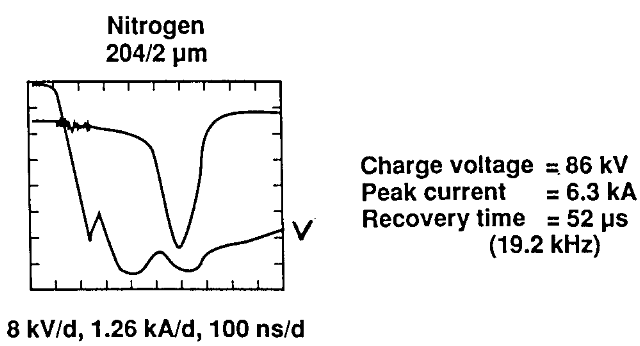


Figure 4 Voltage and current waveforms for a low-pressure switch closure in nitrogen. Electrodes are flat with a stainless-steel anode and aluminum cathode. N_2 flows into the gap region via an axial trigger electrode. Gas pressure in the cathode trigger plenum is 204 µm while the pressure at the chamber wall measures 2 µm. Radial pressure distribution in the 1-cm gap region is unknown.

The current pulse shown in Figure 4 follows the switch voltage fall by a delay that depends upon charge voltage and magnetic core size. A two-pulse recovery test indicates that full voltage can be re-established across the test switch in 52 µs (19.2-kHz prf), under specific conditions for gap spacing, gas species and pressure. The data presented is still preliminary. Work continues on the test stand to thoroughly determine the relationships between delay time, electrode erosion, recovery time and conduction characteristics.

Induction Accelerators for Heavy-Ion Fusion

The idea of using heavy ion accelerators as drivers for inertial fusion has been around for some time and is considered to be one of the promising alternatives for inertial fusion [27]. Methods for accelerating heavy ions are varied and include rf accelerators, linear induction accelerators and several derivatives of both. In the U.S., induction accelerators are preferred and linear induction accelerator experiments have been conducted at Lawrence Berkeley Laboratories (LBL) for several years. A recent study by LLNL and LBL researchers concluded that a significant cost savings is possible if the induction accelerator components can be arranged in a closed path [6]. This cost savings can only be achieved however, if low-cost, agile modulators can be developed to drive the induction accelerator cells at repetition rates exceeding 50 kHz. In addition, these modulators must have the ability to vary their repetition rate and pulse width during an acceleration sequence [28,29].

It is proposed that a recirculator experiment be added to the next set of induction accelerator experiments planned at LBL. The recirculator will be a part of the Induction Linac Systems Experiment (ILSE) — a 40-m long, 10.5-MeV linear induction accelerator for argon ions. Modulators for the 30-m diameter recirculator experiment must operate at repetition rates that exceed the requirements for an inertial fusion driver due to the low ion mass and small recirculator circumference. Table 1 lists the pulse specifications for the ILSE recirculator.

TABLE 1

Pulse Width	1.0 µs (nom.)
Pulse Amplitude	5.0 kV
Minimum PRF	70 kHz
Maximum PRF	200 kHz
Minimum Reset Time	4 µs

Solid-state field-effect transistors (FETs) were selected as the switch best able to achieve the voltage, pulse width and high-prf specifications. The FETs switch the modulator circuit shown in Figure 5a.

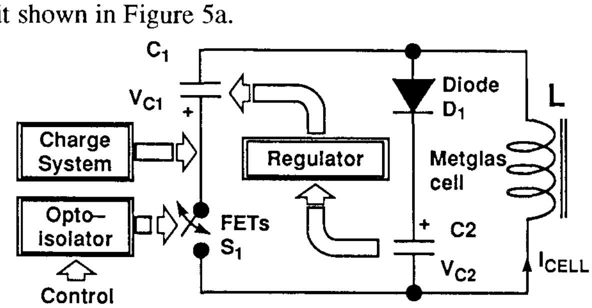
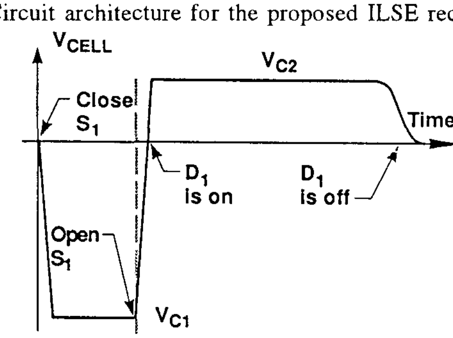


Figure 5a Circuit architecture for the proposed ILSE recirculator.



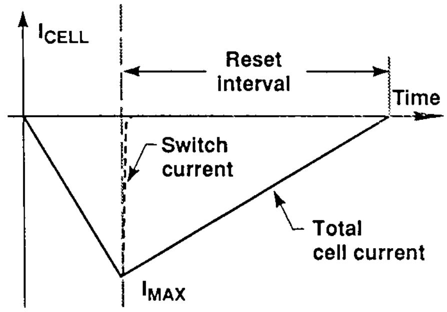


Figure 5b Idealized waveforms for the circuit in Figure 5a.

A series-parallel array of FETs connects the energy storage capacitor C_1 to the Metglas recirculator cell. Once the acceleration pulse has ended, the FETs are commanded to open and the cell current is diverted from the switches to the reset capacitor C_2, as shown in Figure 5b. The reset capacitor is precharged to a value that dictates the rate of cell current decay. This interval also helps to reset the induction core material by returning the flux density back to its original value. Additional core reset is provided by the charge system.

The capacitance of C_2 is large compared to C_1 so that the voltage on C_2 increases only slightly from each pulse. Likewise, the charge system replenishes only a small voltage deficit between pulses because C_1 contains far more energy than the ion beam and core material consume per pulse. The regulator element shown in Figure 5a returns the energy recovered by C_2 to C_1 [30].

We constructed a full-scale recirculator core using 2605S-3A Metglas magnetic alloy insulated with mylar film. Recent small-scale modulator tests were conducted by connecting the Metglas core to a capacitor bank and FET array containing two parallel strings of two switches in series. A diode and reset capacitor were also included in the test, but a regulator circuit was not. The results of a two-pulse test are shown in Figure 6 to illustrate the waveforms previously described and to show the high prf capability of the circuit architecture.

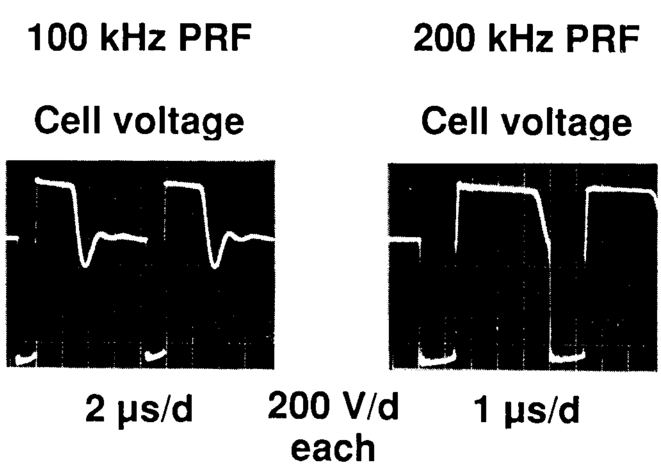


Figure 6 Two-pulse test of the modulator circuit with a small FET array. Voltages shown are measured across the Metglas induction core for a 100-kHz and a 200-kHz repetition rate.

Laboratory work continues toward a prototype recirculator cell and modulator. Our present development efforts are focused on a high-power FET array combined with a robust, optically-coupled control system.

Summary

Our past and recent experiences both reinforce the proposition that new applications of high-average-power induction accelerators are intimately tied to high-prf switch research. Furthermore, high-prf accelerators require a design approach that treats the machine as a system of co-dependent elements.

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