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LLNL-PROC-852425

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July 31, 2023

IEEE Pulsed Power Conference
San Antonio, TX, United States
June 25, 2023 through June 29, 2023

Bipolar Pulsed Power for Active Reset of Induction Cells

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***Abstract*— Linear induction cells driven by bipolar solid-state pulsed power have accelerated a kiloamp electron beam using active reset of the magnetic core material. Four 25 kV bipolar pulsers accelerated the FXR beam in double pulse mode, resetting the magnetic core between each pulse. The integration of the active reset system into a production facility enables continued development toward cinematographic radiography. The flexibility of the solid-state active reset system to generate an arbitrary number of pulses will allow access to more physics during a single experiment. The design and capabilities of the active reset system will be presented.**

Keywords—active reset, linear induction accelerator, solid-state pulsed power

I. Introduction

Active reset technology for Linear Induction Accelerator (LIA) based radiographic systems has the potential to revolution our diagnostic capability by providing a virtually unlimited number of x-ray pulses. This technology is enabled by bipolar solid state pulsed power (BSSPP). Four BSSPP units and two active reset cells were built to develop and test this technology. These pulsed power units and induction cells were successfully installed into the Flash X-Ray (FXR) radiographic system at the LLNL Confined Firing Facility (CFF) to test the integration into a production Linear Induction Accelerator.

The experiments measured acceleration of the FXR electron beams by the active reset induction cell. Most of the testing was performed with FXR in double pulse mode using two 60 ns wide electron beam pulses with 1.6-1.8 kA of beam current. Voltage measurements from the FXR accelerator cells and the active reset accelerator cells were compared to the electron beam energy measured by a scattering wire spectrometer in the FXR. These results show clear acceleration of the electron beam by the active reset hardware. Results are presented for 2 µs pulse spacing between the electron beams with the active reset induction cells time concurrent with the FXR electron beam or offset from the electron beam. In each of these cases the active reset cells are reset in between the two electron beam pulses. In a third test, the active reset cells were fired and reset four times with 1 µs spacing between the drive pulses and the FXR electron beam was accelerated during two of those pulses.

II. BiRX Experiment

In conventional Linear Induction Accelerators, an inductive core isolates the pulsed power from ground potential. The size of the inductive core defines the total number of volt-seconds of pulse (or pulses) that can be applied to accelerate charged particles. FXR [1] is powered by Marx bank driven Blumleins which produce a single pulse. The ferrite core in the induction cells is sized to accommodate that single pulse. The Scorpius [2] LIA will use Metglas® cores that are sized for four full length electron beam pulses. Increasing the volt-seconds of pulses that can be supported means adding more magnetic material, which increases the size of the machine (either in length, diameter, or both).

The Bipolar Reset eXperiment (BiRX) consists of 100 kV of active reset induction cells with core material for a single pulse, powered by bipolar solid state pulsers, installed onto the FXR Linear Induction Accelerator with three custom solenoid magnets. The scattering wire energy spectrometer installed in FXR measures the acceleration of the electron beam. The goal of the bipolar reset experiment was to demonstrate the

Figure 1: Stages in pulser (left) and pulser cabinets at FXR (right)

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. LLNL-PROC-852425

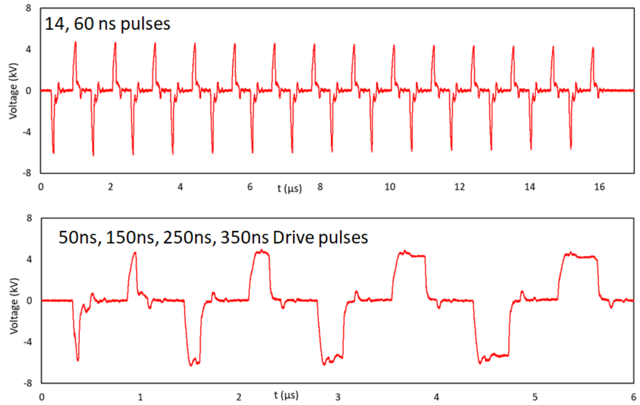

Figure 2: Pulse trains produced by the BSSPP driving an active reset induction cell. (Top) A burst of fourteen drive pulses interlaced with fourteen reset pulses. (Bottom) A set of four drive pulses of different widths interlaced with reset pulses.

integration of an LIA with active reset technology including both the induction cells and the bipolar pulsers.

A. Bipolar Solid State Pulsed Power (BSSPP) design and operating parameters

The Bipolar Solid State Pulsed Power (BSSPP) is a high current pulser (kiloamps) that can produce both positive and negative high voltage pulses. This unique design, shown in *Figure 1*, is a proof of principle for active reset linear induction accelerators and produces kA scale currents with rise and fall times of 10s of nanoseconds. High voltage is achieved by producing an induction voltage adder with multiple stages of circuit boards, each operating at a fraction of the full voltage. The high current is produced by using many field effect transistors (FETs) in parallel on each stage of the pulser.

We refer to the portion of the output pulse that applies the high voltage to the induction cell to accelerate the electron beam as the drive pulse and the portion of the pulse that resets the magnetic core in the induction cell as the reset pulse.

Figure 2 shows two examples of pulse trains from the BSSPP. In this example, the negative going pulses are the drive pulses and the positive going pulses are the reset pulses. The BSSPP can produce an arbitrary pulse format with the total duration of pulses limited only by the energy storage in the pulser. The primary diagnostic is a resistive voltage monitor (RVM) installed at the top of the pulser used to measure the output voltage, which is done using a Pearson model 110 to measure the current going through a 1 kΩ, 1% resistor.

III. Active reset induction cell design and operating parameters

Active reset induction cells were built and installed at FXR as shown in *Figure 3*. The cell design is optimized for use with the bipolar pulsers and care was taken in evaluation of the high voltage operation at both positive and negative potentials as well as to minimize the transverse impedance (which affects the growth of the beam breakup instability in linear accelerators).

The active reset cell is powered using two bipolar pulsers. A negative drive pulse is applied to the cathode while a positive drive pulse is applied to the anode creating a potential difference of 50 kV when the pulsers are charged to full voltage The outer diameter of each cell has ports for cables, resistors, and diagnostics. The cathode is the field emission surface during the drive pulse and the anode is the field emission surface during the reset. The insulator in the cell is also the vacuum seal so the gap is insulated by vacuum on the inner diameter of the insulator and by dry air on the outer diameter of the insulator. The field stress analysis needs to consider both the vacuum insulated and air insulated sections of the geometry in both voltage polarities. DC voltage breakdown characteristics were assumed for the air insulated electrodes. The surface area of the anode and cathode, pulse duration, and pulsed breakdown data drove the design of the cell gap geometry.

To measure the cell voltage, a D-dot and Resistive Voltage Monitor (RVM), were inserted into each half of the cell. The two devices, once calibrated, have excellent agreement with each other, indicating that the errors in the diagnostics are small. The diagnostics in the Active Reset cell provided the information that was required to perform the BiRX experiment and determine the properties and operation of the cell.

IV. Description of FXR

The Flash X-Ray (FXR) Linear Induction Accelerator can be operated in either single pulse or double pulse mode producing up to 3 kA of electron beam current accelerated to a maximum of 18 MeV then focused down to a mm sized spot on an x-ray conversion target.

For the BiRX experiments, the FXR is operated in double pulse mode [3] by firing half the machine for the first pulse and the other half for the second pulse. This produces two 1.6 kA electron beams with an endpoint energy of 9 MeV. The pulse spacing is fully adjustable from 1 – 4 µs.

A. Electron beam energy measurement & calibration

The electron beam energy in the FXR was measured using a scattering wire electron energy spectrometer. The spectrometer is adapted from the design performed for the DARHT-2 machine [4] and is part of the permanent diagnostics suite at FXR. Electrons are scattered off a 0.004" diameter Rhenium wire and focused onto a 32-channel PIN detector array. The position of the electrons on the detector corresponds to the energy of the electrons (E) and is proportional to the difference/sum of the signals measured at each end of the array (V_a and V_b). The energy is calculated digitally according to the following equation:

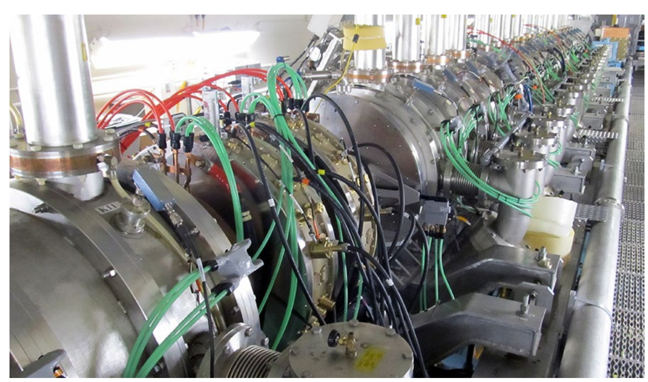
Figure 3: Active Reset cells installed at FXR.

$$E = G\left(\frac{V_a - V_b}{V_a + V_b}\right) + E_{center} \qquad (1)$$

where G is the gain and E_{center} is energy of an electron that strikes the center of the detector.

The energy analyzer response was calibrated by setting the magnet center energy to the center of the sensor. The electron beam energy for each of the two electron beams was then adjusted to be the same by adjusting the charge on the Marx banks. To confirm calibration, the beam energy was adjusted downwards by a small amount and the expected change was measured correctly by the energy analyzer.

V. Results

A set of experiments was conducted to compare adding energy to the electron beam by adjusting the charge voltage of the Marx bank powering L40 block and by adjusting the voltage in the BiRX cells. For all these shots, the cell voltage monitors measured the voltage on each FXR induction cell, a resistive voltage monitor measured the voltage on each of the active reset induction cells, and the energy analyzer measured the electron beam energy.

A baseline energy profile of the FXR beam without BiRX was established by averaging seven identical shots that were taken while the BiRX cells were shorted out. Any amount of energy measured above that baseline for any given shot is added energy. The added energy can be plotted by taking the difference of the energy analyzer data for a shot with the baseline energy subtracted. This is the energy added by the active reset cells.

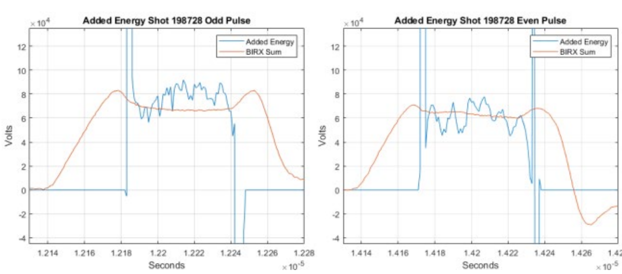

Figure 5: Overlays of the sum of the active reset cell voltages with the added energy in the electron beam measured by the energy analyzer for the first and third drive pulses from shot 198728.

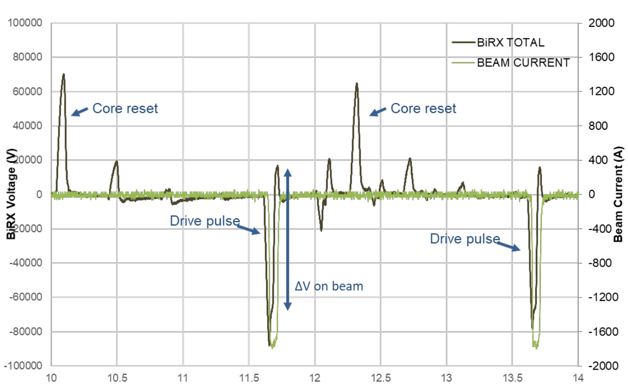

Figure 6: Offset timing of BiRX cell voltage induces a change in beam energy during the pulse.

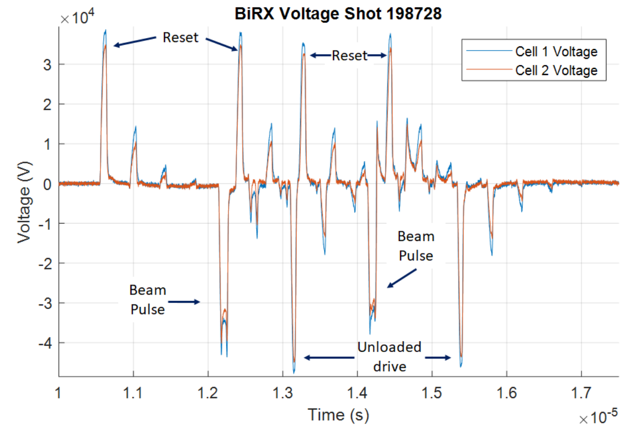

Figure 4: Voltages of each of the two active reset cells for a four-pulse burst with FXR fired concurrent with the first and third pulses.

A. *Double pulse with beam and 4 pulses with BiRX*

Testing the multi-pulse performance of the system is integral to understanding the behavior of the cell. The existing setup of the pulser timing system allows for 4 independently timed pulses from the drive and reset. To test the 4-pulse operation, FXR was set up to deliver 2 beam pulses, 2 us apart and the pulsers were timed to provide 4 reset and 4 drive pulses, as shown in *Figure 4*. The reset pulses and the unloaded drive pulses introduce reflections in the system that influence the shape of the pulses and change the loading in the pulsers. Because the pulsers are not capable of modulation, the timing was defined so that the reflections appear in between the programmed pulses. The added energy measured by the energy analyzer for the beam pulses (*Figure 5*) is consistent with the results from the 2 pulse tests.

B. *Offset timing between beam and BiRX pulses*

In this set of experiments, the bipolar pulsers were timed to be offset from the FXR electron beam. The active reset cells were at full voltage prior to the arrival of the electron beam and turned off while the electron beam was still passing through the cell. This produced a relative difference in the acceleration of the electron beam during the pulse.

Figure 6 shows a shot that was fired with BiRX turning off midway through the beam of the first pulse so that energy was only added to the first half. The increase at the first half is apparent when plotted against the baseline. This is shown in *Figure 7* for the first pulse comparison between the total BiRX cell voltage and the change in energy compared to the baseline. The plot confirms that approximately 80 kV was added to the head of the beam and 20 kV removed from the tail of the beam. When the active reset cells were turned off for the second half of the pulse, the beam energy is reduced as a result of the beam coupling energy back into the undriven cells.

VI. Summary

The BiRX experiment accelerated electron beams on a production Linear Induction Accelerator based radiographic system for the first time. These experiments were a successful integration of the active reset technology into the LIA. The active reset cells, the bipolar solid state pulsers, and the FXR accelerator all performed as expected.

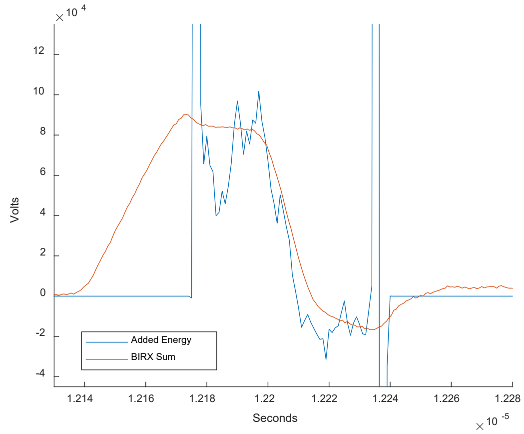

Figure 7: Total voltage from the active reset cells overlaid with measured energy change from the energy analyzer for offset timing.

Measurements from a scattering wire spectrometer were compared to the measurements of the active reset cell voltage monitors and showed good agreement for shots with active reset cells co-timed and offset-timed with the FXR electron beam pulses.

These experiments demonstrate the technology readiness level of seven (TRL-7) for the active reset technology because full scale prototypes were integrated into a production system.

REFERENCES

[1] Multhauf, L. G., Back, N. L., Simmons, L. F., Zentler, J.-M., & Scarpetti, R. D., "The LLNL flash x-ray induction linear accelerator (FXR)." *Proceedings Volume 4948, 25th International Congress on High-Speed Photography and Photonics.*2003 doi:10.1117/12.516922

[2] Crawford, M., & Barraza, J., "Scorpius: The development of a new multi-pulse radiographic system." *IEEE 21st International Conference on Pulsed Power (PPC)*. Brighton, UK. 2017 doi:10.1109/PPC.2017.8291266..

[3] Parker, A, "FXR Machine Does Double Duty." *Science and Technology Review* July/August 2018. Retrieved from https://str.llnl.gov/2018-07/mcallister.

[4] Paul, A. C., et al., "DARHT-II Energy Analyzer." *Particle Accelerator Conference.* May 2003, Portland, OR.