**Research on High Density Tomography
LDRD REPORT FOR FY93**

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June 26, 1995

Lawrence
Livermore
National
Laboratory

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Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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Research on High Density Tomography

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Abstract

The project goal is to define the beam transport system and pulsed power architecture for an advanced radiography machine that would permit obtaining a temporal sequence of multiple-line-of-sight views of a given dynamic event. A long (200ns-1000ns) beam pulse would be split temporally by fast kicker "coils" and made to travel down separate beamlines to illuminate a target from two to four different angles. The beam pulse could be repeated at intervals down to 1 microsecond. The beam transport system and pulsed power architecture for this machine have been scoped out.

Introduction

Radiography is a powerful tool for studying dynamic events, such as explosively driven implosions, explosively formed projectiles, or dynamic systems such as an operating diesel engine. One of the key radiographic devices now in use is FXR – a flash x-ray machine that was designed for imaging rapidly imploding objects at a critical moment in time [1]. The x-ray flash is generated by focusing a high energy electron beam from an induction accelerator onto a target made from high-Z material. The best radiographic image is obtained by a high quality electron beam that has high current, low emittance, and low transverse motion on the target. Further radiographic information can be obtained from multiple x-ray views of the object (tomography) and from multiple observations of the same hydrodynamic event in time. The result is a tomographic "movie" of the event, rather than a one-view snapshot.

Efforts are underway at LLNL and LANL to improve each laboratory's radiographic capability by the methods mentioned above. At LLNL, the FXR accelerator is being refurbished with new solenoid magnets that will focus the beam with less corkscrew motion [2]. Modifications to FXR are also proposed that will enable the accelerator to generate two beam pulses with a variable pulse spacing [3]. At LANL, construction is underway on the Dual-Axis Radiographic HydroTest Facility (DARHT) that will house two 16-MeV induction accelerators that face the object at a 90-degree included angle [4]. The DARHT Facility will obtain two radiographic snapshots of the same hydrodynamic event at different times or a single tomographic image of the object at a fixed time.

During the past year, a feasibility study was funded to examine a new accelerator and beam transport system that goes well beyond the capabilities of DARHT and FXR. The study concluded that the technology is at hand to construct a high current accelerator (~3-kA at 20-MeV) that can generate multiple pulses into multiple beamlines. The design adopted for technology evaluation will generate up to five, 200 ns beam pulses in rapid succession. Each beam pulse will then be cleaved by fast kickers into four, 50-ns beamlets that simultaneously illuminate the object from four view points. The study went on to

identify key elements of a concept for an Advanced Radiography Machine (ARM).

The following summary describes the general ARM architecture followed by a detailed description of the induction modulator element and fast kicker.

ARM: A Multi-pulse, Multi-view Accelerator System

Figure 1 is a schematic of the Advanced Radiography Machine concept showing a single induction accelerator generating five consecutive pulses with a minimum pulse width of 200 ns and a minimum pulse separation of 1 μ s. The attached beam-transport section is equipped with three fast kickers that are used to divide a single entry beam into two smaller exit beams. For example, the first kicker divides the original 200-ns pulse into two, 100-ns pulses that are directed along independent paths (see Figure 1; lower right-hand corner). The two additional kickers each cleave their 100-ns beam into two, 50-ns beamlets that travel to the object along independent pathways. The transport section is carefully designed so that each 50-ns beamlet simultaneously strikes its own tantalum target at the end of each beam path. All five accelerator pulses can be cleaved into four 50-ns beamlets resulting in five tomographic images of a rapidly evolving event.

Accelerator pulse rates to 1 MHz are achieved by an all solid-state power system that uses field-effect transistors (FETs) as the power switch. A large FET array is used to connect a charged capacitor to a small induction cell. By switching the array on and off from a central command, the induction cell will generate 15-kV, 3-kA pulses with the required pulse rate and width. The high voltage needed for the electron beam is formed by stacking 10 of the small induction cells and summing their voltages by a coaxial stalk. The new 150-kV source is called an induction adder and two of them are used to power the electron beam through the larger induction accelerator cell shown in Figure 1 (lower left-hand corner).

The multipulse accelerator is a very flexible beam source that allows pulse format alterations from pulse to pulse. Dynamic pulse-width formats are available so that the x-ray dose received by the object need not be fixed during the burst but can be tailored for sudden changes in object density. Variations in pulse spacing within a burst are available so that the image period can keep pace with sudden changes in object velocity. The extreme pulse width of 1 μ s is available so that a sub-microsecond observation window could be created by using an extra kicker to cleave several 200-ns pulses from a single 1- μ s pulse.

Induction Modulator Element

An exploding test object is truly a single-shot experiment that can be very expensive to repeat if the diagnostic system should fail. Consequently, the accelerator that generates the flash x rays must be reliable and somewhat redundant so that data can still be obtained despite some system failure. The accelerator system described in Figure 1 is a doubly-redundant system because it can continue to function with only 25% of the power system in working order. The 15-kV induction cell (or modulator) is the basic building block of the

accelerator's power system and therefore becomes the focal point for several critical system issues:

1. *Cost vs. System Redundancy* – the accelerator system in Figure 1 will still function with only half of the induction adders on line and only half of the FETs working in each remaining adder. Such latitude for a massive system failure is very expensive. Estimated accelerator costs will be reduced after laboratory tests indicate a level of modulator reliability.
2. *Peak vs. Average Power* – the peak power of each acceleration pulse is very high (60 GW) but the average accelerator power is very low because only five pulses are needed to diagnose a single-shot experiment. Consequently, each modulator must store more than enough energy to produce a five-pulse burst without recharging.
3. *Magnetic Reset* – beam voltages are generated by induction using a magnetic core material. The material undergoes magnetization during the acceleration pulse and must be rapidly reset (remagnetized to prepulse conditions) between pulses. The modulator element is responsible for both functions of acceleration and core reset.
4. *Timing* – each modulator pair makes a 15-kV contribution to the 20-MeV beam voltage. The end result of 20 MeV is achieved by the precise timing and control of 2,700 independent modulators.

The technology of FET-switched induction cells was first developed for the Heavy Ion Fusion (HIF) Project to power an induction recirculator [5]. The experimental results from our HIF work evolved into the ARM power system we propose here. The two investigations differ in scale and particle species but the general induction modulator circuit, shown in Figure 2, remains the same for both. One of the principal challenges will be to extend the repetition rate capability of the pulser to 1 MHz.

We selected the circuit in Figure 2 because it generates the voltages needed for acceleration and core reset with a single on/off switch command. When the switch S_1 is closed, the precharged capacitor C_1 is connected to the Metglas induction cell and provides the energy for five acceleration pulses. Once the acceleration pulse has ended, the FET switches open and cell magnetization current is automatically diverted from the switches to the precharged reset capacitor, C_2 . The reset voltage determines the rate of cell current decay and resets the magnetic core material by returning the magnetic flux density back to its original value. Additional core reset is provided by snubber capacitors across the switch (not shown) and current from the external charging supply. The capacitance of C_2 is selected large enough to absorb the magnetization energy of five pulses while maintaining a reasonably constant voltage.

FETs were selected as the switching element because they have fast rise and fall times, low gate-drive power requirements, low on-state impedance, and a high pulse rate capability. The FETs are arranged in a series-parallel array of independent switching circuits that are powered from a dc/dc converter and

commanded on and off by a fast optical link. Each FET is controlled by a commercial gate-drive circuit that receives information from the optical link and responds by quickly charging or discharging the FET gate capacitance. During FY 93, we conducted bench-top tests of a power FET and drive circuit combination shown in Figure 3(a). The tests determined that a drive circuit from Micrel will switch a pair of power FETs at a 1-MHz rate for a five-pulse burst, as shown in Figure 3(b) [6].

Transport Section, Fast Kicker and Pulser

The four-path beam transport section is a collection of kicker, bending and focusing magnets that receives a 20-MeV, 200-ns input beam and chops it into four 50-ns beamlets. Figure 4 is an illustration of the transport section as viewed from above. The area dimensions are in meters and the various beam lines are co-planar, except for a small jog where one beam line crosses another. The box surrounding the converging beam lines represents a firing containment building measuring 12.2 meters on each side. The accelerator delivers a beam that enters the diagram from the left and is split by kickers located at each Y junction. Figure 5(a) through (f) shows the action of each kicker as they divide the beam into 50-ns beamlets, where each beamlet occupies about 15 meters of beam line. The figures depict the relative locations of the beamlets as they all converge to a single point. Each kicker has a constant magnetic bias field that automatically deflects the beam into one of the two paths. When a kicker pulse is applied, the bias field is overcome by the pulsed fields and the beam is switched to the adjacent path.

The achromatic transport system was designed using the TRANSPORT and LATTICE code groups installed at NERSC. While the system contains over 150 bending and focusing magnets, the construction task has been greatly simplified by using a kicker and only six magnet types to make up the whole system; an expander magnet, expander symmetry magnet, dipole magnet, jog magnet, quadrupole and final focus solenoid. Basically, the beams are transported to the targets by connected segments of straight and curved vacuum pipe that pass through several combinations of the same six magnets.

Among the different transport elements, the kicker design has received most of our attention. The kicker steers the beam by two wide deflection plates that are slightly curved to follow the beam trajectory. A hard-tube pulser and two 50- Ω drive cables launch a wave onto the plates that deflect the beam by both electric and magnetic field contributions. The wave is terminated at the upstream end of the plates by two 50- Ω resistors. Figure 6(a) is a schematic sectional view of the kicker showing the plates connected to high-voltage bushings for cables and resistors. Figure 6(b) is a compressed graph showing the curved relationship between the plates and the beam envelope.

A similar arrangement of pulser and kicker was first developed for the Advanced Test Accelerator (ATA) as a means to dynamically compensate for transverse beam motion [7,8,9].

The kicker designed for ARM deflects the beam centroid about 30 mm by using a 15-kV pulse applied between 1.2 meters of deflection plates (see Figure 6). The shallow deflection angle is adequate to shift the beam from one beam line to another, but the two beam lines do not spread apart quickly enough to

accommodate the need for a simple focusing magnet near the kicker exits. A solution was found by using permanent magnets and iron pole pieces to generate a uniform magnetic field at the kicker exits. This so-called septum magnet applies a field perpendicular to the beam path and oriented so as to dramatically increase the beam deflection angle. Consequently, the exit beam lines spread quickly and allow individual focusing magnets for each line. Figure 7(a) is a diagram of the septum magnet showing the Neodymium-Iron-Boron (NdFeB) segments flanked by soft iron pole pieces [10]. The angular arrangement of three NdFeB magnets is designed to increase the magnetic flux density near the longitudinal midline and thereby increase the uniform field region. Figure 7(b) shows the calculated magnetic flux lines generated by the NdFeB magnets. The flux circulates between the pole pieces in a clockwise direction so that a beam entering the field is deflected away from the midline for either pathway. The circles in the flux field indicate the two nominal beam positions through the septum magnet.

Summary

The multipulse, multiview radiography machine is made possible by an all solid-state accelerator power system. The power system is made possible by recent advances in FET switching technology coupled to an aggressive computer-based control system. The marriage of advanced on/off switching with computer control is a rapidly growing field within the power electronics industry and is called "smart power management" [11]. The power of computer-controlled switching enables a large system, such as an accelerator, to rapidly adapt to dynamic performance objectives by providing just the right amount of power (pulse width) at just the right time.

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Figure Captions

1. Advanced radiography machine concept is depicted. The main elements are an induction linac which can produce a rapid burst of pulses of several kiloamperes at approximately 20 MeV, the pulse power chain which drives the accelerator and a downstream "switchyard" which divides each pulse and directs the resulting "beamlets" to their different x-ray targets. The individual 200 ns pulses are split in half along their length by a fast kicker and directed through different beamlines. In the figure each split pulse is split again by another kicker resulting in four 50 ns beams converging on the target. The pulse power chain consists of induction adders which sum the voltages of 10, 15 kV cells to produce

Advanced radiography machine concept

- A single accelerator to provide a temporal sequence of views of a given hydrodynamic event from multiple lines of sight

Figure 1. Schematic diagram of the Advanced Radiography Machine

A general network architecture has been selected for study

Figure 2. Induction modulator circuit

Idealized waveforms

Figure 3(a). Optically-coupled gate drive circuit

Gate-drive tests demonstrate a 1-MHz pulse repetition rate

Gate Voltage

5 V/d 50 ns/d

5-Pulse Burst (Vds)

250 V/d 500 ns/d

Figure 3(b). Switching tests for a five-pulse burst

Figure 4. Transport section schematic

Figure 5. Kickers acting on a 200-ns beam

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Figure 6(a). Sectional views showing klicker plates

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Figure 6(b). Relationship between curved plates and beam envelope

Figure 7(a). Diagram of the septum magnet

Figure 7(b). Magnetic flux lines