DESIGN AND PERFORMANCE OF THE DARHT SECOND AXIS INDUCTION CELLS AND DRIVERS*

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Abstract

The second axis of DARHT, a Dual Axis Radiographic Hydrodynamic Test facility at Los Alamos National Laboratory, is currently in production with a scheduled completion date of August 2001. This linear induction accelerator, designed by Lawrence Berkeley National Laboratory, consists of 88 induction cells and drivers which provide a total acceleration of 20 MeV to a 2 kA electron beam which has a flattop pulse width of 2.02μs. Major induction cell components include high flux swing magnetic material (Metglas 2605SC) and a Mycalex insulator. The cell drivers are pulse forming networks (PFN's) which are tuned to provide voltage regulation of $\pm$0.5% during the flattop. This paper will describe the design and performance of the cells and cell drivers.

1 INTRODUCTION

A LANL DARHT committee investigated several options for the generation of four sequential pulses for the second axis of the flash radiography facility. In order to achieve the required radiographic parameters, the four pulses were to occur within a 2.02μs window. Each pulse was to have a duration of approximately 70ns, an energy variation of $\leq \pm$0.5%, a peak current of 2-4 kA, and a final beam energy of 20 MeV. The nature of the experiments dictated extremely high reliability of the accelerator. The ultimate choice of the accelerator would be based on technical performance and the approach with less inherent risk. After a lengthy study, the committee chose the long-pulse accelerator proposed by LBNL as the best approach to achieve the required parameters. This approach generates a 2.02μs pulse that is accelerated to 20 MeV and then chopped by means of a kicker magnet to select the four individual pulses to be delivered to the target.

2 INDUCTION CELL DESIGN

The building for the DARHT facility was under construction when the decision was made to use the long pulse accelerator for the second axis. As a result, the DARHT team had the difficult task of fitting an accelerator with thirty-three times the energy of the first axis into an existing building that was designed for a short-pulse (60ns) accelerator. This limitation led to a non-optimal design of the induction cells. Since the cell axial length was fixed by the building, the only way to achieve the required energy (i.e. volt-seconds) was to increase the outer diameter of the cells and use a magnetic material with a much greater flux swing than ferrite. The non-linearity of the Honeywell (Allied Signal) 2605SC B-H loop is exacerbated by the fact that the ratio of core OD to ID is so large that saturation effects cause the cell impedance to be even more nonlinear. The drive impedance of the pulse forming network must likewise be a nonlinear function of time in order to maintain a $\pm$0.5% energy variation.

2.1 Standard Cells

The standard cells have a 10" beam pipe, a conical Mycalex insulator, a water- cooled DC solenoid magnet, damping ferrites, and four Metglas cores in insulating oil to provide 0.48 volt-seconds (Figure 1). The cell housing OD is 73" and the axial length is 20.25". Each standard cell is driven at –193 kV by four high voltage cables which are connected to the acceleration gap by four symmetric high voltage feedthroughs. In each high voltage feedthrough box, there are compensation resistors to ground. These resistors, in addition to the beam flattop, provide a linear load which is used to outweigh the nonlinear load of the magnetic material. The highly nonlinear magnetizing current is limited to < 20% of the total drive current. The ability to change the value of the compensation resistors allows for a beam current upgrade from 2 kA to 4 kA. These resistors are manufactured by HVR Advanced Power Components and are critical to better match the driver and cell impedances and to make the high degree of voltage regulation possible.

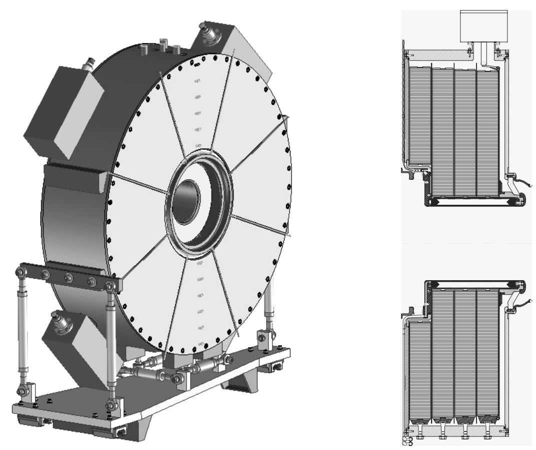

Figure 1: Cell Architecture

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2.2 Injector Cells

The first eight cells of the accelerator are called "injector cells" and are the same as the standard cells except for that they have a beam pipe diameter of 14" instead of 10". The larger beam pipe is used to lower the transverse mode impedance and decrease the possibility of a gap breakdown as a result of spilled beam [1]. These cells have less magnetic material (0.43 volt-seconds) and thus are run at a lower voltage of –175 kV. The drivers for these cells are the same as those for the standard cells.

2.3 Magnetic Material

The only type of accelerator which is applicable for a 2-4 kA electron beam is the induction accelerator. The first axis of DARHT is this type of accelerator where the energy is imparted to the beam at each cell by the voltage induced across the gap. Several short-pulse (< 100ns) induction accelerators have been constructed using ferrite cores. For the second axis which requires 2.02µs of acceleration, ferrite is impractical since the flux swing is limited to 0.7T and is therefore cost prohibitive. Investigations by the LBNL Heavy Ion Fusion program, which has requirements similar to those of the DARHT second axis, had indicated that the optimum material both from a performance and cost standpoint was the Honeywell Metglas Alloy 2605. Further investigations by the LBNL DARHT team led to the selection of the 2605SC material as having the squarest B-H loop, although improvements made in the last few years to the 60 Hz material 2605SA1 make it nearly indistinguishable from the 2605SC.

In order for the long-pulse accelerator to be economically feasible, the magnetic material had to cost below $20/kg as well as have the highest flux swing possible. After some initial startup difficulties on the 2605SC continuous casting line, Honeywell produced some excellent material for $16/kg.

The LBNL DARHT team also had to determine if the material should be used "as cast" with Mylar insulation or coated with recently developed proprietary coatings which could be annealed after winding and produce a squarer B-H loop. After months of investigation, the new coatings produced inconsistent magnetic properties and were marginal on holding off the volts/turn and were therefore deemed too risky. The "as cast" material with Mylar insulation was chosen which yielded a more rounded B-H loop. Although the induction cells would require more compensation to achieve the flattop in energy variation, this was considered the safest approach to achieve high flux swing and sufficient turn-to-turn insulation.

The magnetic properties of un-annealed Honeywell 2605SC Metglas are shown in Figure 2. The average magnetic flux swing (ΔB) is 2.7T for a change in magnetizing force (ΔH) of 1200 A/m. To get the maximum flux swing out of the cores, there is an active reset system. At the peak of an SCR-switched reset current (400-600 A) through the cell in the opposite direction of the main pulse, the cell driver is triggered. To insure that the total volt-seconds of each cell is the same, the cores are mixed and matched after the magnetic properties of each core have been tested. It is desirable for all of the cells to have the same volt-seconds so that the tuning of each cell driver is essentially the same.

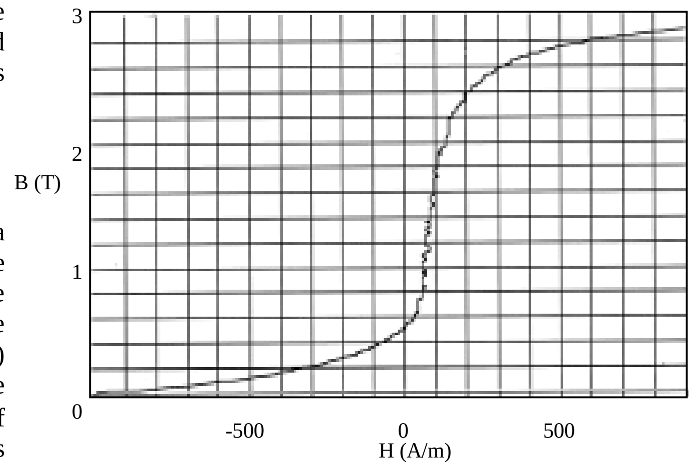

Figure 2: 2605SC Magnetic Properties

2.4 Insulator

The high voltage insulator, which is the vacuum-to-oil interface, is made of Mykroy Mycalex, a glass-mica composite which has a dielectric constant of 6.7. Early testing showed that this material was very resistant to tracking and had mechanical characteristics superior to traditional ceramics and plastics. The high impact strength was particularly attractive to avoid fracturing as a result of shock waves caused by possible arcs on the oil side. Because the second axis injector has a dispenser cathode, maintaining a good vacuum to prevent cathode poisoning is a primary concern. The outgassing rate of this insulator is lower than plastics such as Rexolite and approaches that of traditional ceramics.

3 CELL DRIVER DESIGN

The cell driver is a seven-section type-E network in a four-stage Marx configuration (Figures 3 and 4). This pulse forming network (PFN) is designed to provide a –193 kV pulse with a 2.02µs flattop with voltage regulation of $\leq \pm 0.5\%$. The required repetition rate is 1 shot/min. but testing is typically done at 12 shots/min. Each Marx stage has a tapered impedance to compensate for the nonlinearity of the core magnetizing current. A gradual lowering of the section impedances provides more current at the end of the pulse as the cores approach saturation and the losses increase. A coarse tune is provided by the default number of turns of the inductor sections. The fine tuning ($\pm 0.5\%$) is done by inserting copper pipes in the PVC pipe on which the inductor is wound to exclude the flux and lower the inductance, thus lowering the impedance for small sections of the pulse.

The average impedance of the PFN is 20Ω. The Gibbs network resistor value can also be varied to adjust the risetime and front corner of the pulse.

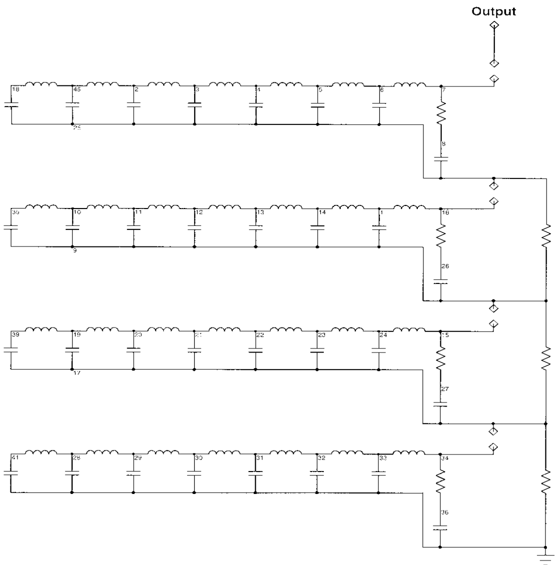

Figure 3: PFN / Marx Schematic

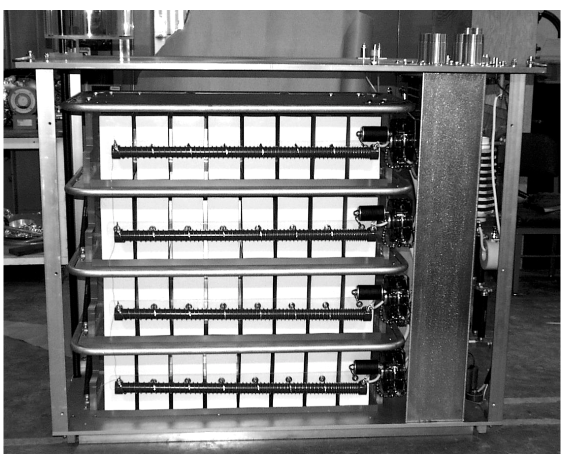

Figure 4: Pulse Forming Network / Marx

Four spark gaps are triggered simultaneously with a thyratron-switched pulse. These spark gaps, manufactured by Maxwell Physics International, are rated at 100 kV and have Schwarzkopf K33S electrode material to extend the lifetime to > 10^6 shots before maintenance is required.

The energy storage capacitors are manufactured by General Atomics/Maxwell and are rated at 40nF and 100 kV. Because of a slight impedance mismatch between the PFN and the cell, the capacitors will be charged to less than –90 kV to get the full –193 kV output, providing some safety margin in the capacitor lifetime.

4 CELL AND DRIVER PERFORMANCE

Before each cell and PFN are shipped to LANL, they are tested at the full operating voltage for 2,000 shots to confirm the voltage holding ability and volt-seconds. The cells are brought up to full voltage in several minutes and usually require no high voltage conditioning. Each cell design has also been overvoltaged to test the condition which occurs when there is no beam-loading on a powered cell (typically 30-40kV above normal operating levels). The voltage reversal becomes significant (> 50%) at these levels because of core saturation, and flashover does sometimes occur across the insulator vacuum surface, but these breakdowns do not track the insulator and do not effect the voltage holding at operating levels. This same scenario holds true for PFN prefires in which the cores are not reset and are therefore driven into hard saturation.

The first production PFN was tuned with a standard cell and was successful in delivering a –195 kV pulse which was $\pm$0.5% for > 2.02µs duration (Figure 5). At that time, the compensation resistance was too high and caused an impedance mismatch resulting in a 50% voltage reversal. After reducing the compensation resistance, the typical voltage reversal is 30-40%.

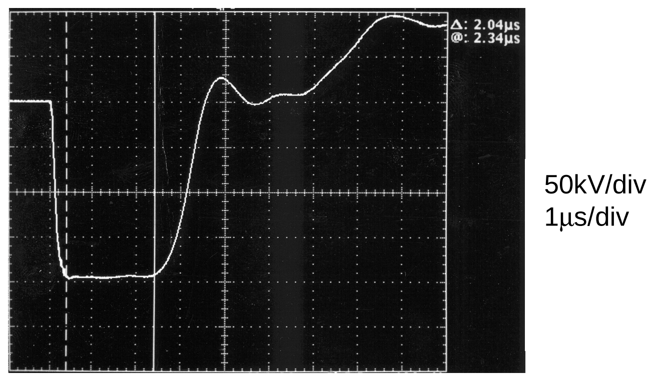

Figure 5: Full Voltage Pulse with Initial Compensation Resistance

5 CONCLUSION

Extensive testing on the first 8 standard cells and the first 2 injector cells has shown that all the required parameters have been met with a high degree of reliability. Virtually no high voltage conditioning is required to achieve the operating levels of –193 kV for the standard cells and –175 kV for the injector cells. The voltage flattop variation of $\pm$0.5% exceeds the required duration of 2.02µs. The life expectancy of all the components including the weakest link (spark gaps) should exceed 10^6 pulses before any maintenance will be required.

REFERENCES

[1] Rutkowski, H.L. et al, "A Long Pulse Linac for the Second Phase of DARHT", Proceedings of the 1999 Particle Accelerator Conference, New York, 1999