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THE LEB TO MEB TRANSFER KICKER SYSTEM PROTOTYPE*

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Abstract

The design requirements for the Low Energy Booster (LEB) extraction kicker system at the Superconducting Super Collider Laboratory (SSCL) were to deflect a 12 GeV/c beam through an angle of 1.5 mrad. The circumference of the LEB was 540 m. This resulted in a 0.06 T-m integrated field, of 1.8 μ s width with a 1% to 99% rise time of less than 80 ns and allowable pulse ripple of less than $\pm 1\%$. The repetition frequency was 10 Hz and the allowable timing jitter was 2 ns. The field was required to be uniform over a 2x4 cm area to $\pm 2.5\%$. The requirements for the Medium Energy Booster (MEB) injection kicker were similar except that a 99% to 1% pulse fall time of less than 2 μ s was needed. Prototypes of the pulsed power system and magnet to meet these requirements were built and tested at the SSCL. This paper describes the results of that testing.

Introduction

A traveling wave, ferrite C core, magnet with an aperture of 5x7 cm and 25 Ω impedance was designed, built, and tested at the SSCL for extraction of the beam from the LEB. The magnet impedance was established by interleaving capacitive plates connected to the high voltage and low voltage conductors [1]. A photograph of the magnet built at the SSCL is shown in Figure 1. This magnet has 28 interleaved cells of 25.1 mm length, and has a magnetic gain of 22.6 μ T/A. Calculated values for the magnet inductance were 53.3 nH/cell, and capacitance of 85.3 pF/cell. The electrical length of the magnet is therefore 59.7 ns. The rise time of the magnetic field is approximately the sum of the modulator rise time and the magnet electrical length, so the modulator must have a 1% to 99% rise time of less than 20 ns. The magnet is designed to operate in beam vacuum for voltage insulation.

Figure 1. Photograph of travelling wave magnet.

The total magnetic length available for LEB extraction was 5 m. This yields the modulator design requirements of 585 A output current, and 29.25 kV charge voltage to achieve 110% of the rated kick. A 12.5 Ω modulator was built at the SSCL which employed four 254 m parallel connected spools of RG-220 cable as the pulse forming line (PFL) [2] [3]. Each modulator was designed to drive two parallel connected magnets. A single gap, hollow anode thyatron was used as the switch tube. Charging of the PFL was accomplished by a command, resonant charging system which used a low voltage DC power supply and capacitor bank switched by an SCR through a 147:1 step-up transformer. A photograph of the charger and modulator is shown in Figure 2.

Figure 2. Photograph of power modulator.

Modulator Testing

The modulator was tested to optimize the effects of grid bias, grid trigger voltages, delays between grid pulses, and reservoir and cathode heater supply settings on the rate of rise of current and timing jitter. Rise time was measured with a 0.1 V/A current viewing resistor. Timing jitter was measured with an H-P 53310 Modulation Domain Analyzer by taking 1000 shots, plotting a histogram of the delay times and computing the standard deviation of the distribution. Timing jitter from the SSC built, thyatron based, grid drivers was measured and had a standard deviation of approximately 160 ps. All of the data that follows is from testing with a EEV model 1154G switch tube. Tubes from other manufacturers were purchased, but were never tested due to time constraints and ultimate project cancellation. The effects of varying the reservoir voltage on rise time and jitter are shown in Figure 3. The tube began to prefire when the reservoir voltage was increased to 5.7 V. The recommended reservoir setting for this tube is 5.6 V.

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Figure 3. Timing jitter and rise time
vs
reservoir voltage

Effects of control grid voltage amplitude on rise time was investigated with the screen grid voltage pulsed to 2.5 kV and the reservoir voltage set at 5.6 V. The results of this testing are shown in Figure 4. Timing jitter was not significantly affected by changing the grid drive voltage. Voltage levels for the screen grid pulse had no significant effect on either current rise time or timing jitter. Rise time and jitter as a function of delay between the screen grid pulse and the control grid pulse are shown in Figure 5.

Figure 4. Rise time vs control grid voltage.

Figure 5. Timing jitter and rise time
vs
grid trigger delay

Pulse to pulse ripple was measured by digitizing ten points with an H-P 54510 digital oscilloscope. The ten data points were taken after any high frequency ringing had decayed, approximately 2 μ s into the pulse. The data was written to a file, and the average of the ten data points was found. One thousand pulses were measured, and the average of all pulse amplitudes was computed. The maximum deviation from the mean for all one thousand shot was $9.67 \times 10^{-3}\%$. The mean current for all shots was 660 A with a standard deviation of 0.84 A. The measurement was repeated in a burst mode with ten shots per burst at 10 Hz. Again, one thousand shots were recorded, and the average was computed for the first, second, third, etc. shot of the burst. The mean amplitude for each shot in the burst is shown in Figure 6. The second shot has the largest deviation of 0.172%. This deviation is the result of the transient response of the switch mode power supply, and is well within the system design specification.

Figure 6. Burst mode ripple

Magnet Testing

Low voltage testing of the magnet was performed to confirm the magnet design. Integrated B-dot probes which were designed to be matched at both the oscilloscope input and the shorted end were fabricated and calibrated. These probes were flipped in both polarity and axially to cancel the effects of capacitive coupling to the probe and propagation times through the magnet. The four resulting signals

were then averaged for each measurement. A pulse with a 1% to 99% rise time of 55 ns was used to pulse the magnet and the 1% to 99% integrated field rise time of 84.0 ns was measured. Direct measurement of the electrical length of 65 ns for the magnet was also performed by measuring the delay time between a magnet input and output pulse. Delay times between cells was measured to be 2.38 ns. Total magnet inductance and capacitance were also measured with an H-P 4284A LCR meter. After correction for fringe field effects these measurements show a cell inductance of 66.4 nH and cell capacitance of 92.7 pF. All of these measurements are in good agreement with the magnet design parameters.

Field uniformity in the good field region was mapped by positioning the probes in the magnet with an optical x-y positioner. The magnet was driven with a 1 MHz sine wave generator which was matched to the 25 Ω magnet by an impedance matching network. The amplitude of the integrated magnetic field was then measured with a digital oscilloscope with a vertical accuracy of $\pm 1.5\%$. The measurement was repeated with the magnet input and output reversed, and the two signals were averaged and divided by the input voltage amplitude. The 2 cm $\times$ 4 cm good field region was mapped with a resolution of 1 cm. The percent deviation from the center of the aperture is shown in Figure 7.

Figure 7. Deviation of field from center of aperture

The magnet was connected to the modulator for high voltage and system testing. A schematic of the test set-up is shown in Figure 8. Only the first 780 ns of data taken with this set-up was valid because the load at the end of the 390 ns cable was not well matched. A matched resistive load was designed and was scheduled for fabrication in 1994. Compensation ports on the input and output of the magnet were designed into the high voltage vacuum feedthrough to accept series networks of ceramic disk capacitors and carbon or metal film resistors.

Figure 8. Schematic of test circuit.

The first set of data taken is shown in Figure 9. The top trace in this oscillograph is the cathode voltage measured with a Tektronix P6015 high voltage probe. The lower trace shows the response of a D-dot probe located approximately 18 m down the transmission line between the switch tube and the magnet. The middle trace is the integrated D-dot response. These traces clearly show severe impedance mismatches in the system. SPICE analysis was performed to locate the source of the mismatches. It was found that the ringing on the rising edge of the waveforms could be duplicated by adding capacitance to ground from the cathode of the tube. The only source of capacitance from the tube cathode to ground came from the heater and reservoir high voltage isolation power transformer, and the pulse transformers for the grid drives. Two inductors of 5 mH each were wound on ferrite cores to isolate the pulse from each end of the high voltage power isolation transformer. Coaxial transformers were fabricated by winding 35 turns of RG-174 around a ferrite core to isolate the grid drivers. These transformers had over 7 mH of inductance each, enough to keep the current pulse droop within specification. The system was then compensated with the components listed in Table 1. The last integrated field measurement made is shown in Figure 10. The rise time here is 78.48 ns and the top of the pulse is flat to within $\pm 1.093\%$. This is very close to meeting the design requirements.

Figure 9. Early data showing impedance mismatches. Top trace is cathode voltage.

C_{cathode}	R_{cathode}	C_{cathode}	C_{in}	C_{out}	R_{out}	R_{load}
700pF	6.4 Ω	700pF	140pF	200pF	5.4 Ω	26.8 Ω

Table 1. Network compensation components.

11403 U1611ZING OSCILLOSCOPE
date: 9-NOV-93 time: 18:37:17
exp: 2.2, dig: 2.1, day: 2.0
Instrument ID# 8010510

Figure 10. Integrated magnetic field measurement.

Unfinished Testing

Testing of the system was stopped by the end of 1993 as people left the SSCL after project cancellation. Further testing was planned, but not realized. Thyratrons were purchased from both IT&T and EG&G, but were not tested. The travelling wave magnet was high-potential tested to 22 kV in vacuum, but was not pulsed at full voltage. Fabrication of a matched load, and measurement of the pulse flat top for the entire pulse width was planned for Fiscal 1994. Measurement of pulse fall time was also planned with the matched load. A solid core magnet was fabricated, and low voltage testing had begun. This magnet looked promising, and would have been much cheaper to fabricate than the travelling wave magnet. The hardware for a VME based data acquisition and control system had been designed, and software design had begun. The data acquisition and control system was to be procured and tested in Fiscal 1994. Unmanned modulator operation was under development to investigate reliability and lifetime. Some reliability data was taken, with the modulator operating for over 7×10^6 shots.

Conclusions

The basic design of the LEB to MEB transfer kicker systems was shown to be sound although full system testing was not completed. The rise time and flat top requirements were very close to being met when testing stopped. Pulse to pulse ripple, and timing jitter were well within design requirements and did not require prefiring the switch tube. The major challenges for this system which were under investigation at the time of project cancellation were reliability, maintainability, and cost.

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