DEVELOPMENT AND OPERATION OF THE SNS FAST CHOPPER SYSTEMS*

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Abstract

The Spallation Neutron Source (SNS) at Oak Ridge National Laboratory requires fast chopper systems to create a series of mini-pulses of H^- ions in the Linear Accelerator (LINAC) for injection into the accumulation ring. The fast chopper systems are in the front end of the accelerator with one chopper in the Low Energy Beam Transport (LEBT), immediately upstream of the Radio Frequency Quadrupole (RFQ), and another chopper in the Medium Energy Beam Transport (MEBT), downstream of the RFQ, where the beam energy is approximately 2.5 MeV. Clean bunching requires fast rise and fall time and low jitter to minimize the amount of charge in the ring extraction gap. The chopper systems operate at a burst frequency of 1 MHz and a burst width of greater than 1 ms and burst frequency of 60 Hz. The choppers have had historical reliability issues, especially in the LEBT system. This paper describes the development of reliable LEBT and MEBT choppers and the operational performance since SNS commissioning in 2006.

INTRODUCTION

A layout of the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory is shown in Figure 1. The SNS consists of a Linear Accelerator (LINAC) which injects H^- beam pulses into a proton accumulation ring where they are extracted and transported to a liquid mercury target to generate neutrons for studying neutron sciences. The ion source in the front end system [1] produces an H^- beam that is chopped into mini-pulses for injection into the LINAC. The beam is accelerated through the LINAC and transported through the high energy beam transport (HEBT) section where it is injected into the accumulation ring. More than 1000 turns can be accumulated before the beam is extracted from the ring for transport to the mercury target. Four bipolar high voltage pulse generators in the Low Energy Beam Transport (LEBT) [2-4] section and two unipolar high voltage pulse generators in the Medium Energy Beam Transport (MEBT) [5-8] section create the beam mini-pulses.

The pulse generators and the structures they drive have had many reliability issues which have required extensive research and development to rectify. This paper summarizes the LEBT and MEBT chopper systems function, failure history, and development of reliable modules. It is focused on the reliability of the LEBT high voltage pulse generators used to apply pulses to the lens segments. Detailed descriptions of the LEBT and MEBT structure improvements can be found in the references.

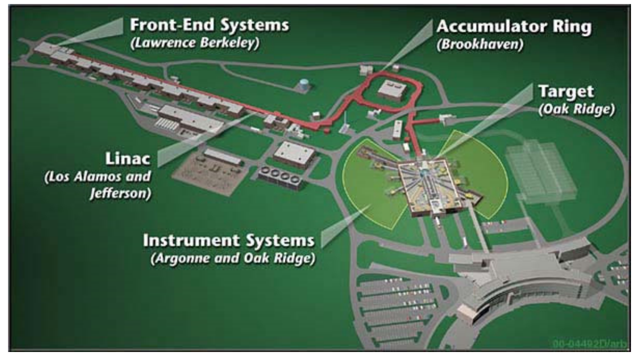

Figure 1: Layout of the Spallation Neutron Source in Oak Ridge, TN.

CHOPPER TIMING REQUIREMENTS FOR BEAM EXTRACTION

The choppers operate by generating fast rise/fall time high voltage pulses interspersed with periods of no high voltage, effectively deflecting the beam from the beamline to a target to generate gaps in the beam. The extraction kicker rise time sets the minimum gap required for the high voltage pulse generators used for chopping in the LEBT and MEBT. The beam gap in the accumulation ring must be clean and wide enough for the extraction kickers to fully turn on. If the head and tail of the beam in the ring are not sharp or the gap is not free of protons, the extraction kickers will partially deflect the beam during kicker turn on, causing activation of the extraction septum magnet.

The extraction kicker system consists of fourteen pulse forming networks (PFNs) located in the Ring Service Building, driving fourteen kicker magnets in the Ring Tunnel. Due to the design of the PFN, the rise time is fixed at approximately 200 ns. Figure 2 is a graph of the rise time of the extraction kicker magnet current.

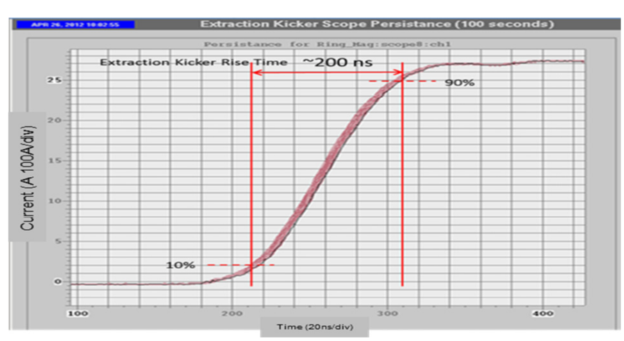

Figure 2: Extraction kicker rise time.

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The LEBT chopper structure is an electrostatic einzel lens split into four quadrants to deflect the beam to a diagnostic plate for a minimum of 200 ns to a maximum of 1000 ns, depending on the percentage of ring fill desired. [3] The chopping pattern rotates the beam around the diagnostic plate to limit heating. Figure 3 shows the timing sequence used to move the beam from one segment to another during either beam on or off time.

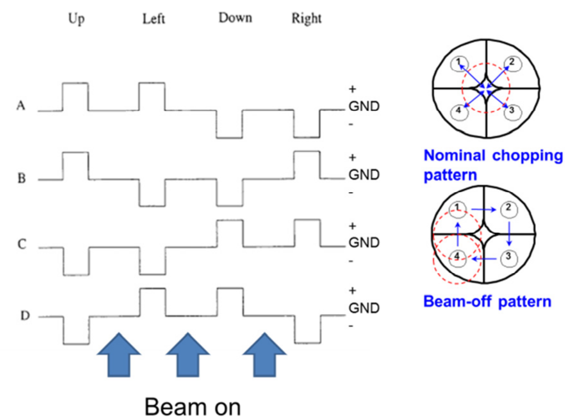

Figure 3: Four phase timing of LEBT chopper.

The LEBT chopper specifications require +/- 3 kV pulses with rise and fall times of < 50 ns and pulse widths varying from 200 ns to 1000 ns. The variable pulse widths provide for the ability to change the beam fill in the ring, beam ramping at the beginning of the macro-pulse and permits accelerator physics studies. See reference [4] for a discussion of the timing limitations of the LEBT high voltage pulse generators.

The MEBT chopper system consists of two high voltage pulse generators of opposite polarities to deflect the beam vertically. MEBT rise and fall times are specified to be less than 10 ns. The MEBT high voltage pulse generators [7-10] are used for sharpening the edges of the pulse and to clean the gap to minimize losses during extraction.

LEBT CHOPPER

The LEBT chopper system consists of four high voltage pulse generators each driving a segment of the einzel lens to deflect the beam. The lens is biased at near -50k Vdc for focusing and each segment is independently offset by another fraction of a 3 kVdc supply for steering. Figure 4 is a simplified block diagram showing the connections within the LEBT chopper system. Capacitive coupling is used to isolate the ground referenced pulse generators from the bias and steering voltage. A 20k Ohm resistor and the inductance of the cabling are used to isolate the bias and steering power supplies from the pulsed high voltage. A relay is used to disconnect the high voltage pulse generator from the structure.

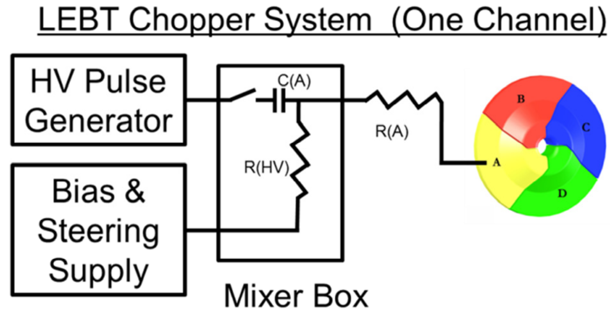

Figure 4: Block diagram of one channel of the LEBT chopper system

LEBT Structure

After very high arc rates in early 2007, the lens was redesigned with glue-free joints and 32 intersegment spark gaps to limit intersegment voltages to about 10 kV and to divert the energy away from the intersegment insulators [11]. In addition, the operational arc rate was reduced with high voltage conditioning and the addition of an automatic disconnect when more than 5 arc events occur in a 6 minute period.

LEBT High Voltage Pulse Generators

The LEBT high voltage pulse generators are a ¾-H bridge design where the capacitive load of the LEBT lens segment is either switched to the positive 3 kV rail, ground, or the negative 3 kV rail. The design uses eight high voltage metal oxide semiconductor field effect transistors (MOSFETs) stacked in series to create a single high voltage switch with enough voltage hold off to permit reliable operation during normal switching operation.

LEBT High Voltage Pulse Generator Failure Analysis

The high voltage pulse generators have experienced high failure rates since commissioning in 2006 with over 180 failures after 30,000 arc events since recording started in 2007.

Normally, a segment of the second lens arcs to ground, which is followed by intersegment arcs. Improvements to the LEBT structure reduced the number of arc events from approximately 8000 to 1000 per ~20 week long accelerator run cycle. The initial high voltage pulse generator failure count was 80 failures per run cycle. Failures of pulse generators only occurred when accompanied by an arc. Figure 5 is a chart of the LEBT high voltage pulse generator failures and arc event counts per run cycle. The rise in 2009 was likely caused by the aggressive increase in duty factor and beam current.

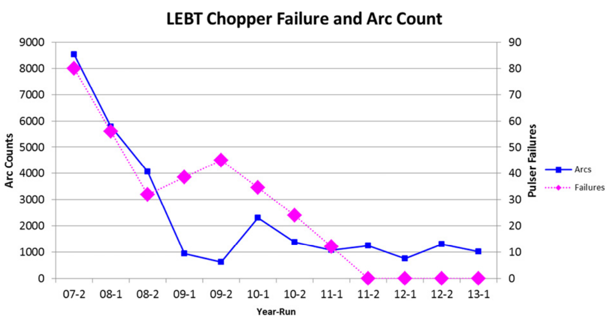

Figure 5: LEBT high voltage pulse generator MOSFET failures and arc events verses run cycle.

SNS has only six of these custom pulse generators in stock and four are used during operations. The two spares were enough to keep SNS running but repeated repairs of the MOSFETS and supporting components has irreparably damaged the printed circuit boards. The replacement time for a failed pulse generator is, at best, 1 hour when the failure occurs during normal business hours and up to 4 hours if it occurs when personnel are not already on-site.

LEBT Chopper Improvements

Multiple improvements to the high voltage pulse generators were tried up to 2011: the existing MOSFET snubber circuits were improved, transorbs on the output node and MOVs in the mixer box were added, and the series resistance was increased to limit the current. All of these resulted in limited improvements as seen in the failure rate in Figure 5.

Changes made during the summer shutdown of 2011 essentially eliminated failures. There have been three failures since 2011. None of these were for high voltage MOSFET failures: a diode isolation board had underrated parts installed, a timing logic board had a bad 1/4W resistor and a control voltage power supply failed after a lightning strike near the facility.

Failure Mode Analysis

MOSFETs can fail by two principle methods: over voltage or over current (thermal overheating). Our HV MOSFETs usually failed as a short. This implies that over voltage or punch through of the wafer was occurring. If the device failed from over current, it would fail as an open circuit when the wire bonds from the leads of the drain or source or the bulk semiconductor fuse open. Over voltage can be caused by the amplitude of the coupled arc voltage exceeding the individual MOSFET's high voltage hold-off rating.

An oscilloscope was added to capture and store every arc event. After more than 300 arc events a pulse generator failed. The oscilloscope traces in Figure a are examples where all high voltage pulse generators survived and Figure b where one did not. There is no significant difference between an event that caused a failure and one that did not. The amplitude, frequency, and shape of the arc voltage appearing at the pulse generator were similar.

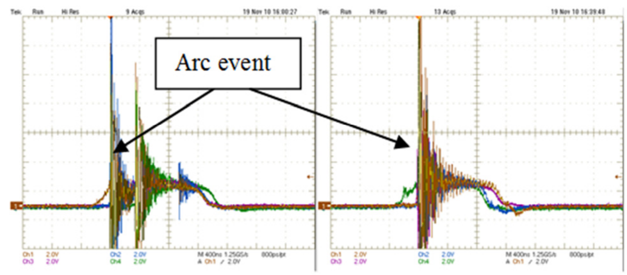

Figure 6: Examples of an arc event which did not result in a failure (Figure 6a) and one that did (Figure 6b).

The output voltage traces for all four pulse generators are shown overlaid to demonstrate the similar amplitude, duration and shape of an arc event. A detailed analysis of the energy transfer during an arc event is given in [5] and summarized here. Figure is a simplified schematic for analysis of the arc event equivalent circuit.

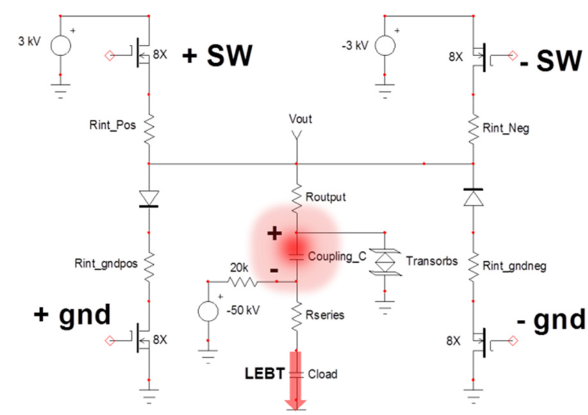

Figure 7: Simplified Schematic demonstrating an arc in the LEBT Structure and voltage reversal on the Coupling Capacitor.

The high voltage pulse generator 3kV power supplies do not supply enough voltage to exceed the 8kV rating of the stack and are therefore not a source of overvoltage failure. The 50 kV bias supply, however, could.

The coupling capacitor (Coupling_C) in the Mixer Box is charged to the dc bias voltage through the impedance of the pulse generator's high voltage circuit. LEBT structure arcing causes the load capacitance (Cload) to short, pulling the series resistor (Rseries) to ground. This causes the coupling capacitor's voltage to appear at the output of the pulser. The Transorbs and MOVs were sufficient to limit the voltage seen by the MOSFETs. Arc event simulations with a spark gap used in place of the LEBT structure showed that the voltage across the stack did not exceed the rating.

Gate Drive Latching

Another discovery was the realization that the fault could be in the gate drive circuit. The gate is turned on with a pulse through an isolation transformer and held on with a diode (D1) as shown in the schematic in Figure .

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This circuit is identical for all MOSFETs in each of the four legs of the ¾-H bridge. Another short pulse of negative polarity is sent to turn OFF the gate. The diode does not latch OFF the gate so the voltage decays back to zero after a few microseconds due the RC time constant of the gate capacitance and the series resistance.

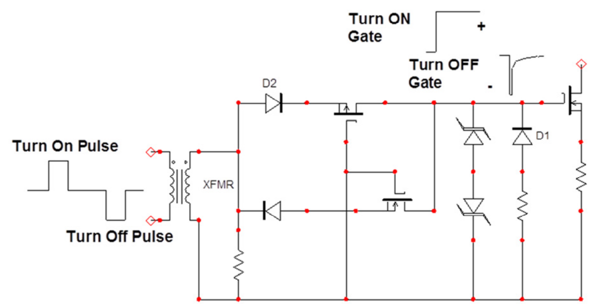

Figure 8: Gate drive schematic.

An arc event can cause a noise pulse in the low level drivers which results in a ringing pulse on the gate of each MOSFET. This places the switches in the high voltage legs at risk. One possibility is that a noise pulse turns ON all eight MOSFETs creating a shoot through condition where both the positive and negative MOSFETs are turned ON, resulting in high currents. This is not suspected as the cause of the failures because analysis of the failed devices determined the root cause to be due to over voltage not over current.

Another possibility is that the noise spike could latch ON only a few of the MOSFETs in a leg and leave OFF the others. This would force the remaining MOSFETs in the stack to hold off a higher voltage. During the normal operation each 1000 V rated MOSFET sees less than 750 V when the power supplies are charged to 3 kV. If two or more gates are latched ON the rest will have to hold off greater than the MOSFET's rating and fail. Transorbs were installed across the drain and source of the MOSFETs in the original design but the parasitic inductance of these devices likely made them ineffective snubbers for these fast transient events.

To simulate an arc event, a spark gap was used in place of the LEBT structure and triggered on command for multiple measurements. Measurements of the gate drive voltages during a simulated arc event showed many oscillations of the gate drive signal.

The oscillations could turn ON and OFF the device until they decayed lower than the gate threshold. If the last oscillation was above threshold for turn ON but lower than the turn OFF threshold the device would stay ON. In the summer of 2011 the diode was reversed in only the high voltage legs of the ¾-H bridge to latch OFF instead of ON. The decay rate was limited so as to exceed the maximum pulse width required for normal operation.

Rise/Fall Time Improvement

When the series resistance was increased during attempts to reduce failures, the rise and fall times on the LEBT structure increased to >100 ns, more than double the initial specification. By implementing the previously stated improvements, the series resistance of the circuit could be reduced, thereby decreasing the RC time constant. [6] The measured rise and fall times were reduced to less than 50 ns when measured on a simulated LEBT structure load as shown in Figure .

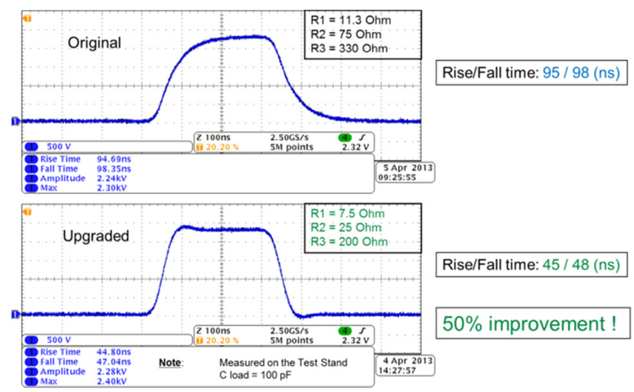

Figure 9: LEBT high voltage pulse generator rise/ fall time improvement chart.

The system with the reduced series resistance was installed during the summer 2013 maintenance period.

MEBT CHOPPER

The MEBT chopper system shown in Figure consists of two high voltage pulse generators of opposite polarities driving a transmission line structure into a 50 ohm load. The MEBT high voltage pulse generators were intended [7-10] to be used for both sharpening the edges of the pulse and to reduce the beam in the gap to minimize losses during extraction. The LEBT choppers were found to be more effective than anticipated so the MEBT choppers are primarily used for cleaning the gap.

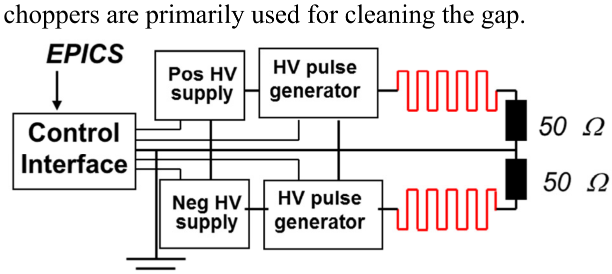

Figure 10: Block diagram of MEBT chopper system.

MEBT Structure

The MEBT rise and fall times were specified to be 10 ns. The pulse generators did achieve these from the start but the system was not impedance matched. The mechanical design of the structure [8] suffered failures due to water leaks, insufficient high voltage clearances and thermal performance issues.

In 2007 the structure was redesigned to eliminate these issues. [11] The new structure changed from the meander line design to a parallel plate transmission line type shown in Figure . The structure and HV pulse generators were impedance matched to reduce reflections of the fast HV edges from the pulse generators.

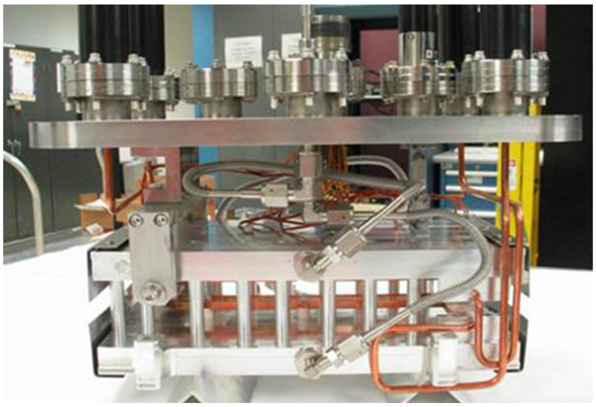

Figure 11: New MEBT structure design.

MEBT High Voltage Pulse Generators

The MEBT high voltage pulse generators are a two MOSFET series-switch design where the output resistive (50 ohm) load is either pulled to the high voltage rail or to ground. There is a positive pulse generator and a negative pulse generator that operate synchronously to assist the LEBT pulse generators in extraction gap formation.

Each high voltage pulse generator design uses five high-speed 1kV rated MOSFETs stacked in series for each leg to provide voltage hold off during normal operation. Improvements to the MEBT HV pulse generators include: matching the output impedance to 50 ohms by a custom cut copper bus (shown in Figure 12) upgrading the water cooled heat sinks and applying the LEBT gate drive latch technique described above.

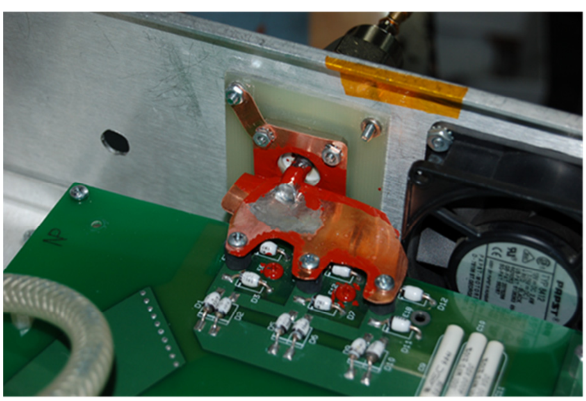

Figure 12: Matching 50 Ohm output impedance.

The pulse timing was changed so that the pulse generators were not ON during the pre-beam and beam OFF times to limit power dissipation in the MOSFETs.

SUMMARY

Continued development of and modifications made to the LEBT and MEBT fast chopper systems have greatly improved their reliability and therefore the availability of the SNS. The LEBT structure modifications and administrative controls to reduce arcing along with MOSFET triggering modifications have virtually eliminated high voltage pulse generator failures. This has permitted reducing the LEBT series resistance to values that meet the original rise and fall time specifications.

The improvements in the MEBT structure and impedance matching improved reliability of the structure. Additional development of the high voltage pulse generator cooling is still required.

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