Development of a 100 kV Pulse Generator for Driving an Electron Scanner used in Proton Beam Profile Measurements*

B. Morris[ξ], W. Blokland, V. Peplov, R. Saethre
Oak Ridge National Laboratory (ORNL),
Spallation Neutron Source (SNS)
1 Bethel Valley Road, Oak Ridge, TN 37831 USA
R. Ness
Ness Engineering Inc.,
P.O. Box 261501
San Diego, CA 92196 USA

Abstract

The Spallation Neutron Source (SNS) utilizes an electron scanner in the accumulator ring for non-destructive transverse profiling of the proton beam. The electron scanner consists of a high voltage pulse generator driving an electron gun, a medium voltage ramp generator, and a CCD camera. A new high voltage pulse generator that provides negative 100 kV pulses with rise times of less than 200 ns, +/-0.5% flattop of greater than 100 ns has been designed, delivered, and undergone extensive testing. The pulse generator has been operationally verified with the existing control system and simulated loads. Full system testing with the actual electron scanner is planned. This paper details the requirements, design, setup, and test results of the high voltage pulse generator.

I. INTRODUCTION

The Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory has a need for a High Voltage Pulser (HVP) to drive an Electron Gun within the Electron Scanner System. The system consists of a controller, HVP, electron gun, a ramp generator attached to the deflector plates, and a CCD camera screen as shown in Fig. 1 [1]. The Electron Scanner is to be used in the accumulator ring of the SNS for non-destructively measuring the proton beam's transverse profiles.

The HVP operates by providing up to 100 kV, 100 ns pulse flattop to the electron gun. The HVP's pulse generates a high intensity electron beam which is deflected by the ramp generator to slew through the proton beam onto the screen. The design specifications are listed in Table 1.

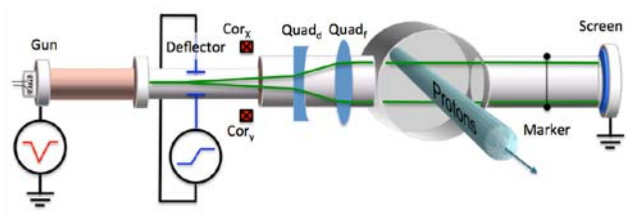

Figure 1. Electron Scanner System Diagram

Table 1. HVP Design Specifications

Maximum voltage	100 kV
Rise/fall time	200 ns max
Flat top time Ripple	100 ns min +/- 0.5% (99.5-100.5 kV)
Overshoot at flattop	5 kV max
PRF	1 Hz
Load Capacitance	100 pF
Load Current	~ 30 mA @ 100 kV
Filament current	15 A max
Filament voltage	4.5 V max
Filament resistance (cold)	0.1 Ohm

II. DESIGN

The HVP was designed by Ness Engineering, Inc. The goal was to eliminate high voltage breakdown issues that are present in the existing pulser (provided by a different vendor) that prevents reliable operation above 65 kV [1]. This limits operation of the scanner to low electron beam intensity. The system block diagram is shown in Fig. 2.

**This manuscript has been authored by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).*
ξ email: morrisb@ornl.gov

The major components of the system are the control, power, and shunt circuit boards, the pulse transformer, the 24 Vdc, and filament heater power supplies.

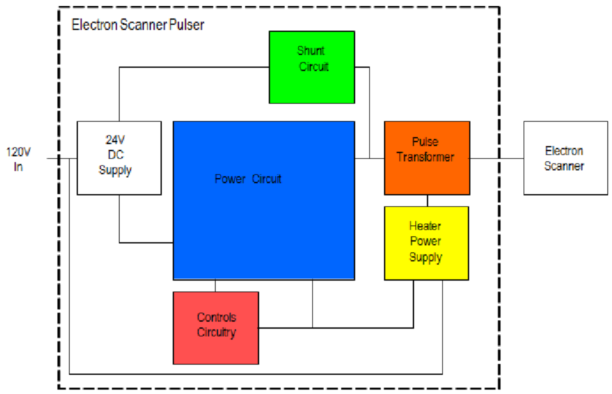

Figure 2. HVP System Diagram

The power and shunt circuit boards are shown in the right side in Fig. 3. The transformer is the black module in the middle and the heater is behind the 24 Vdc power supply on the left. A high voltage divider for monitoring the output voltage is shown above the transformer. The output connector is on the back wall.

Figure 3. Layout of the HVP components inside the chassis.

The HVP power input of 110 Vac supplies a variable output 4 kV dc power supply which charges a capacitor bank. An array of IGBTs is used to resonantly transfer energy from the capacitor bank through a diode assembly into the primary of a pulse transformer. The transformer, with the secondary connected to the electron gun, steps up the pulsed voltage from 2.3 to 100 kV. An array of IGBTs in parallel to the primary of the transformer is used to sharpen the trailing edge of the pulse by shunting the voltage into a 4 Ω load.

A. Control Circuitry

The control circuit board performs fault diagnostics and logic control for IGBT triggering. It also sets the delay between the trigger input, charge enable, and shunt enable signals. Fiber optic cabling between the control board and the power board isolates the floating gate of the IGBTs.

B. Power Circuit

The schematic of the power circuit board, shown in Fig. 4, contains a 1-μF capacitor bank that is switched into the transformer primary winding with a parallel network of 10 IGBT switches and a network of 30 diodes (10x3 parallel/series). High voltage isolation of the IGBT gate drivers is accomplished with an isolated DC-DC converter.

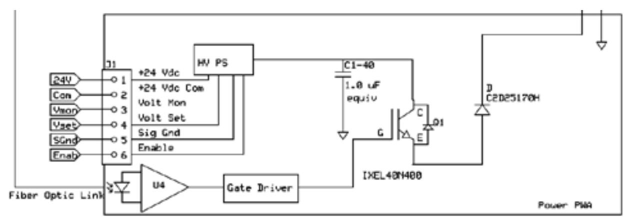

Figure 4. Power Circuit Board Schematic

The power circuit board also includes a simple resistive voltage divider which serves as a diagnostic of the transformer primary voltage. The 2 MΩ resistance of the voltage divider also functions as a bleeder resistor for the 1 μF capacitor bank when the high voltage is turned off.

C. Shunt Circuit

The electron gun pulser output voltage must be less than 10 kV prior to the deflector ramp pulser voltage falling. If the electron gun is still producing electrons when the ramp generator's output decays the captured image on the screen will be blurred. The system was originally designed with a shunt switch to terminate the electron gun pulse in less than 200 ns. The shunt circuitry, shown in Fig. 5, includes the shunt switch network of a 16 (2x8 series/parallel) IGBTs. High voltage isolated dc/dc converters are used to provide power to the IGBT gate drive circuits. The shunt switch acts as a "tail-biter" to terminate the output pulse once a sufficient duration has been obtained. The peak current through the shunt current is limited by a 4 Ω resistor.

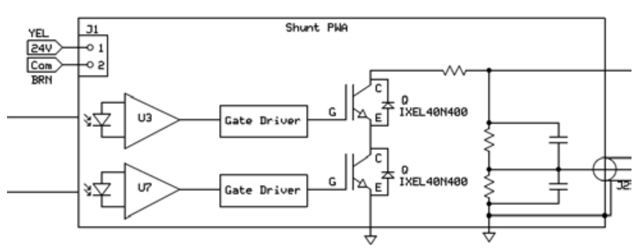

Figure 5. Shunt Circuit Board Schematic

D. Transformer

The transformer, shown in Fig. 6, was designed by Stangenes Industries, Inc. and is a transformer with a 1:25 ratio and two identical sets of secondary windings. The primary is fed from the 1 μF capacitor bank charged to 2.3 kV. The capacitor bank voltage resonantly rings up the primary through the stray and leakage inductances to 4 kV (~1.7x2.3 kV) to produce approximately 100 kV on the secondary in less than 200 ns. The second set of terminals on the transformer secondary low side accepts the heater input.

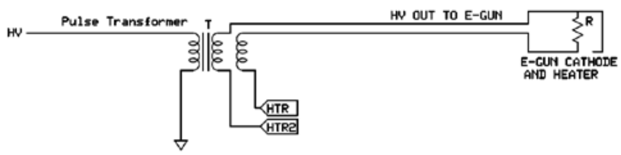

Figure 6. Pulse Transformer schematic

E. Electron Gun Filament Heater Power Supply

The heater circuit provides isolated filament power to the electron gun via the second set of bi-filar windings on the pulse transformer. The heater circuit is configured as a half bridge inverter as shown in Fig. 7. Rectification of the 110 Vac input charges four parallel 220 μF capacitors. The output of the inverter is filtered through a 100 μH inductor and is connected to a 1:1 isolated output transformer that induces voltage and current on the low side of the 1:25 high voltage transformer secondary. As a result, current flows to the filament of the electron scanner. The inverter is pulse width modulated to obtain the proper RMS current and voltage for the filament.

Figure 7. Filament Heater Circuit Board

III. TEST RESULTS

A. Testing at Ness Engineering, Inc.

Initial testing of the High Voltage Pulser at Ness Engineering Inc. was performed with a 5,000:1 oil immersed capacitive voltage divider probe. Successful operation was demonstrated up to 100 kV prior to shipment to ORNL. Utilizing the scope offset feature and expanding the view, the +/- 0.2% pulse flattop width was measured to be 100 ns at a pulse amplitude of 100 kV (Fig. 8).

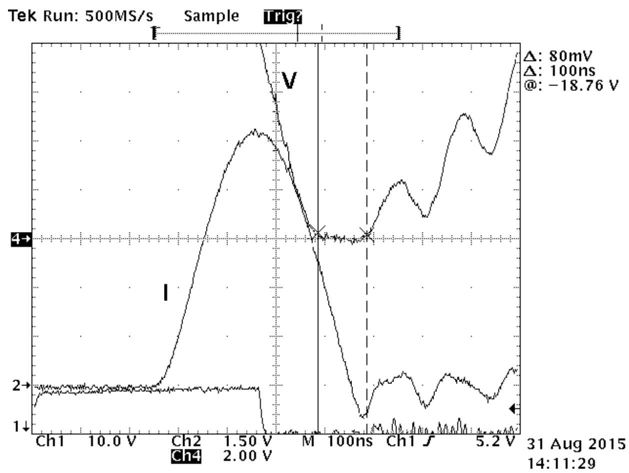

Figure 8. Typical Waveforms from the ORNL Electron Scanner Pulser Showing a Peak Output Amplitude of ~100 kV. (Ch1: Trigger In at 10 V/div; Ch2: Output Voltage at 7.5 kV/div and offset by 19 V; Ch4: Current Mon at 150 A/div).

B. Testing at ORNL

The initial design placed the HVP directly below the electron gun terminals in the ring tunnel. A short wire was to be used to connect the transformer output to the gun. Initial testing at ORNL was conducted in a lab utilizing a 150 kV rated 20,000:1 high voltage divider as a simulated load located on the top of the transformer shown in Fig. 3. The capacitance of this divider was approximately 100 pF, simulating the load of the electron gun.

The high voltage divider was determined to be beneficial for remote diagnostics and will be permanently installed adding additional load capacitance which sacrifices rise time but lengthens flattop. An external housing was fabricated to cover the HVP assembly with the high voltage divider and minimize any field enhancement points near the transformer. With the high voltage divider installed the HVP needs to have an output cable to the gun. This six foot cable also adds approximately 180 pF of capacitance. A second voltage divider was added to simulate the electron gun load. The assembly within the test stand is shown in Fig. 9.

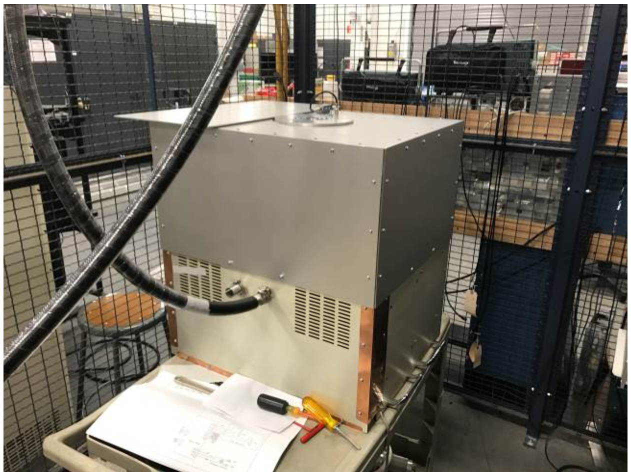

Figure 9. HVP assembly installed in test stand

The transformer initially arced at 65 kV. Investigation determined that the arcing was occurring inside the transformer near the primary and secondary windings overlay. The high reversal is likely the source of flashover in the transformer windings and subsequent damage to the insulation. Fig. 10 shows breakdown on the reversal.

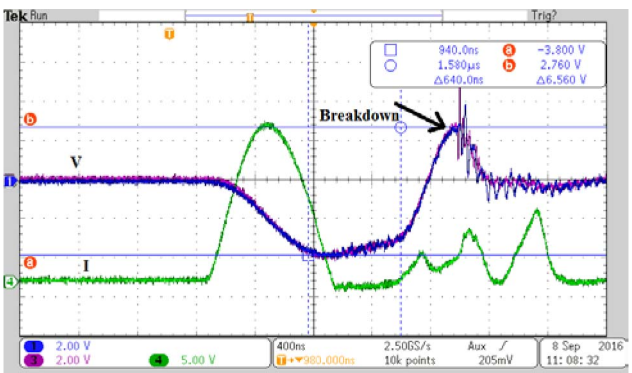

Figure 10. 76 kV operation, breakdown at 55 kV reversal indicated at arrow (Ch1&3: Output Voltage at 20 kV/div; Ch4: Current Monitor at 100-A/div)

A series diode stack was added across the secondary side of the transformer output leads to clamp the reversal to approximately 15 kV. With the diodes installed, the pulser operated up to 99.6 kV without regular arcing (Fig. 12).

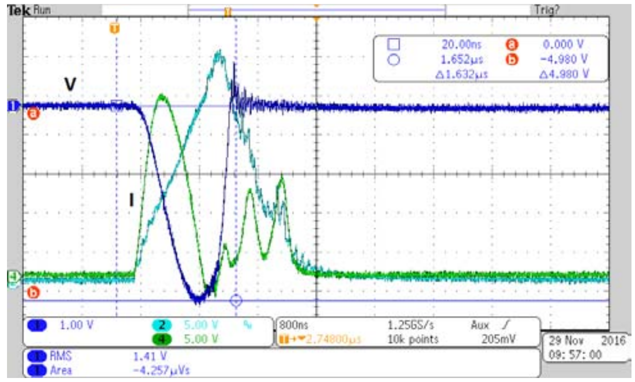

Figure 11. 99.6 kV, diodes installed, no breakdown (Ch1: Output Voltage at 20 kV/div; Ch4: Current Monitor at 100 A/div)

In Fig. 11, channel 4, a noticeable amount of current was observed flowing through the primary of the transformer after discharge. Analysis of the circuit determined that the extra current was flowing through the shunt circuit's IGBT anti-parallel diodes. The fall time of the output was determined to be fast enough without the shunt board so it was eliminated. The tests were re-run without the shunt circuit board and this verified the current ringing had been reduced as shown in Fig. 12.

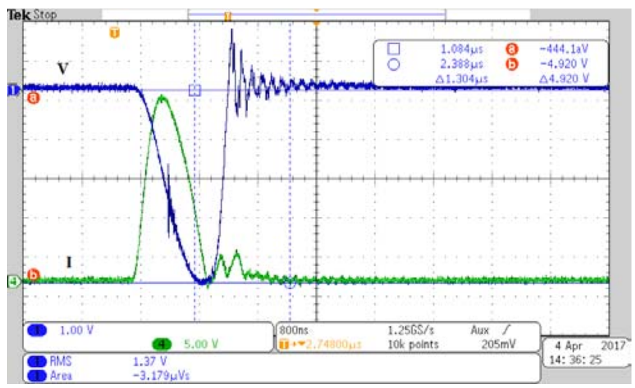

Figure 12. 98.4 kV, Shunt Board Removed (Ch1: Output Voltage at 20 kV/div; Ch4: Current Monitor at 100 A/div)

The transformer was sent back to the manufacturer to repair the insulation damage caused by previous arcing. It was re-wound with minor improvements to enhance high voltage reliability. The HVP was tested at 102 kV and up to 4 Hz without arcing or significant performance degradation.

The requirement for the +/- 0.5% flattop portion of the output pulse is to be greater than 100 ns. At a 101 kV operating point, +/- 0.5% of the high voltage pulse meeting the requirements was found to 125 ns. The flattop portion of the waveform is shown in Fig. 13.

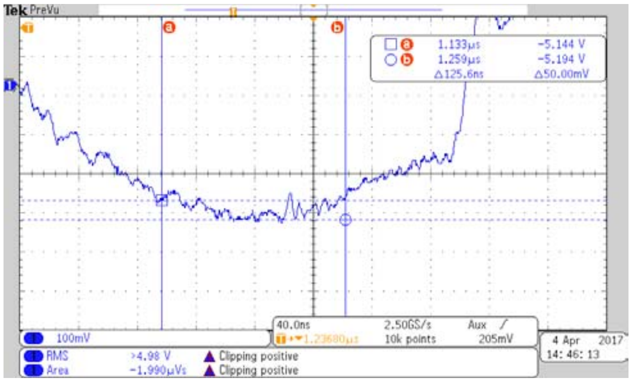

Figure 13. Flattop portion of waveform at 101 kV, +/- 0.5%, 125 ns width (Ch1: Output Voltage at 20 kV/div)

The filament heater circuit was tested with a simulated load and the current was measured with a 0.1 V/A current transformer on the low voltage side of the bi-filar secondary and also on the high voltage side at the load. The pulse width modulation of the heater current was adjusted and proper operation was verified. The system was verified to operate properly with high voltage pulsing.

IV. FUTURE WORK

The pulser will be tested with the electron scanner control system in the Ring Service Building to verify all control interfaces are operational. Once the system has been proven to function under the electron scanner control system without any issues, it will be installed in the ring tunnel for actual testing on the electron gun.

V. SUMMARY

For transverse beam profile measurements, an electron scanner is used which utilizes a high voltage pulser delivering a 100 kV pulse with a 100 ns flattop to an electron gun for non-destructively measuring the transverse profiles of the proton beam. A high voltage pulser has been designed and built that meets these criteria and has been tested with a simulated load on the bench, in a test cage, and with the electron scanner control system. The system is planned to be installed in the accelerator tunnel this summer and tested with the actual electron gun.

VI. ACKNOWLEDGEMENTS

The authors would like to thank Ken Fowkes and Joey Weaver for supporting the development and testing of the pulser. This research used resources at the Spallation Neutron Source, a DOE Office of Science User Facility operated by the Oak Ridge National Laboratory.

VII. REFERENCES

[1] W. Blokland, S. Cousineau “A NON-DESTRUCTIVE PROFILE MONITOR FOR HIGH INTENSITY BEAMS,” 2011 Particle Accelerator Conference, New York, March 28 –April 1, 2011