PERFORMANCE OF SNS FRONT END AND WARM LINAC

A. Aleksandrov, S. Assadi, W. Blokland, P. Chu, S. Cousineau, V. Danilov, C. Deibele, J. Galambos, D. Jeon, S. Henderson, M. Plum, A. Shishlo, M. Stockli, Y. Zhang,
Oak Ridge National Laboratory, Oak Ridge, TN 37830 USA

Abstract

The Spallation Neutron Source accelerator systems will deliver a 1.0 GeV, 1.4 MW proton beam to a liquid mercury target for neutron scattering research. The accelerator complex consists of an H- injector, capable of producing one-ms-long pulses at 60 Hz repetition rate with 38 mA peak current, a 1 GeV linear accelerator, an accumulator ring and associated transport lines. The 2.5 MeV beam from the Front End is accelerated to 86 MeV in the Drift Tube Linac, then to 185 MeV in a Coupled-Cavity Linac and finally to 1 GeV in the Superconducting Linac. With the completion of beam commissioning, the accelerator complex began operation in June 2006 and beam power is being gradually ramped up toward the design goal. Operational experience with the injector and linac will be presented including chopper performance, transverse emittance evolution along the linac, and the results of a beam loss study.

INTRODUCTION

The SNS Front End and warm linac consist of an H^- injector, capable of producing one-ms-long pulses with 38 mA peak current, chopped with a 68% beam-on duty factor and a repetition rate of 60 Hz to produce 1.6 mA average current, an 86 MeV Drift Tube Linac (DTL), a 185 MeV Coupled Cavity Linac (CCL), and associated transport lines [1]. After completion of the initial beam commissioning at a power level lower than the nominal, the SNS accelerator complex is gradually increasing the operating power with the goal of achieving the design parameters by 2009. Results of the initial commissioning can be found in [2]. In this paper we report the latest results of the Front End and warm linac performance with the focus on problems encountered and their short and long term resolution.

FRONT-END PERFORMANCE

The front-end for the SNS accelerator systems is a 2.5 MeV injector consisting of the following major subsystems: an RF-driven H^- source, an electrostatic low energy beam transport line (LEBT), a 402.5 MHz RFQ, a medium energy beam transport line (MEBT), a beam chopper system, and a suite of diagnostic devices. The front-end is required to produce a 2.5 MeV beam of 38 mA peak current at 6% duty factor. The 1 ms long H^- macro-pulses are chopped at the revolution frequency of the accumulator ring (~1 MHz) into mini-pulses of 645 ns duration with 300 ns gaps. The same front-end hardware has been providing beam for commissioning the rest of the linac since the initial commissioning at the SNS site in 2002. All commissioning goals have been achieved and results are published in [2]. The Front End Systems demonstrated reliable operation with more than 90% beam availability during the commissioning run but it became increasingly difficult to maintain beam availability with the average beam power increase.

Ion Source and LEBT

One of the major concerns is the RF antenna life time and the possibility of catastrophic antenna failures. We had two such events during the last run with one event resulting in a water leak into the LEBT chamber. We plan to use an optical spectrometer for detecting precursors of the antenna coating damage as a temporary solution. An external antenna source is being developed as a long term solution [3].

The other major problem is electrical breakdowns in the electrostatic LEBT. The arcs damage fast MOSFET switches of the chopper high voltage power supply. This problem caused significant beam downtime and operational difficulties during the last run. It has not been fully resolved yet. Short term fixes include improving existing LEBT design, implementing additional protective circuitry in the chopper electronics, and developing operational procedures to disconnect the chopper when an excessive spark rate is observed. As a long term solution we plan to use a magnetic LEBT which is in the early stages of development [4].

Chopper Systems

The 1-ms long H^- macro-pulses has to be chopped at the revolution frequency of the accumulator ring into mini-pulses of 645 ns duration with 300 ns gaps. Beam chopping is performed by two separate chopper systems located in the LEBT and MEBT. The last lens in the LEBT is split into four quadrants to allow electrostatic chopping using the RFQ entrance flange as a chopper target. The LEBT chopper removes most of the beam charge during the mini-pulse gaps, and the traveling-wave MEBT chopper further cleans the gap to a level of 10^{-4} and reduces the rise and fall time of the mini-pulse to 10 ns. A chopper controller provides different patterns of chopped beam: "regular chopping", "single mini-pulse", "every n-th mini-pulse", "blanking-off", and current ramp up. The chopper systems demonstrated design parameters during commissioning for the nominal chopping pattern at low average beam power.

During the last run the frequency of the chopper high voltage switches failures caused by the electrical breakdowns in the electrostatic LEBT increased to the point where the LEBT chopper operation became

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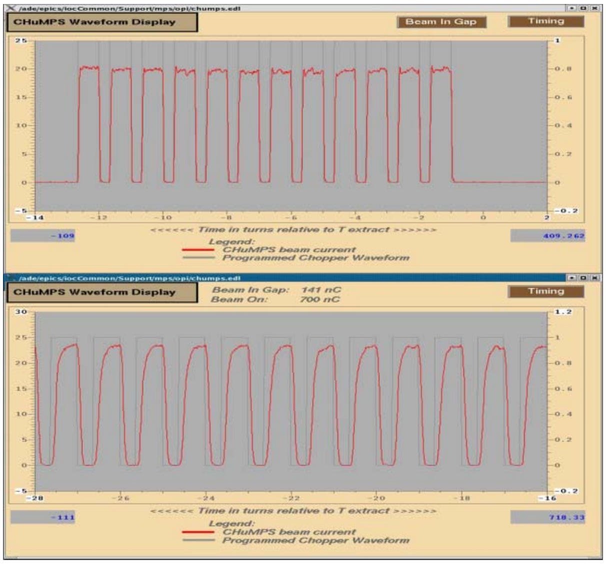
impossible. The most effective immediate fix was to install protective resistors between the power supplies and the chopper electrodes. As a result the LEBT chopper rise time increased from <40ns to >120ns as shown in Fig.1. The corresponding increase in partially deflected beam and beam in the gap could have been mitigated by use of the MEBT chopper, but the MEBT chopper deflector failed beyond repair due to inadequate cooling of its printed circuit board structure [5]. Surprisingly, we were able to continue production run with 60kW of beam power on target and acceptable losses using the LEBT chopper alone. Various improvements aimed to reduce spark rate in the LEBT have been implemented and a new MEBT chopper structure has been developed and manufactured. We expect to see significant improvement in chopping quality in the next run.



Beam In Gap: 141 nC
Beam On: 700 nC

Figure 1. Chopped beam pattern produced by the LEBT chopper without the protection circuitry (top, rise/fall time is ~50ns) and with the protection circuitry (bottom, rise/fall time is ~150ns).

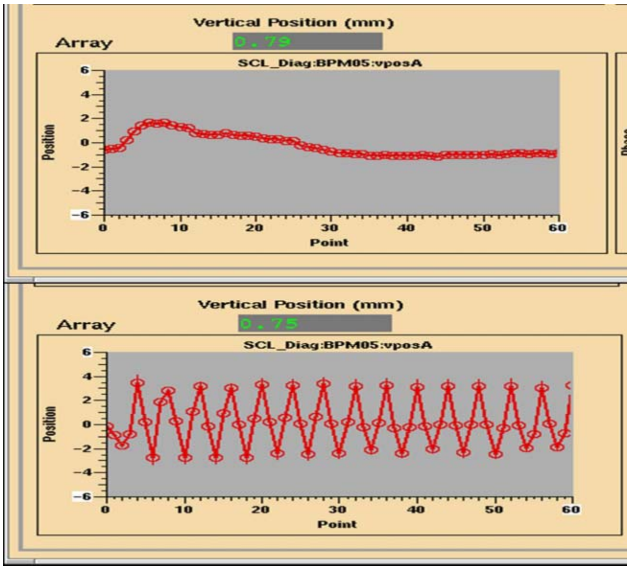
DTL AND CCL PERFORMANCE

The Drift Tube Linac consists of six accelerating tanks operating at 402.5 MHz with final output energy of 87 MeV. The transverse focusing is arranged in a FFODDO lattice utilizing permanent-magnet quadrupoles. Some empty drift tubes contain BPMs and dipole correctors. The inter-tank sections contain BCMs, wire scanners and energy degrader/faraday cups.

The Coupled Cavity Linac (CCL) consists of four 12-segment accelerating modules operating at 805 MHz with final output energy of 186 MeV. The inter-segment sections contain electromagnet quadrupoles arranged in a FODO focusing lattice, BPMs, wire scanners, and Beam Shape Monitors.

Longitudinal tuning of the linac is routinely done using "phase-scan signature matching" algorithm implemented in XAL [6]. Measured longitudinal Twiss parameters at the end of the first CCL module are close to the design values and we do not observe any significant losses at the RF frequency jump in the DTL-CCL transition area.

We intended to use profile measurements at several locations along the linac for transverse beam matching. Unfortunately, the poor chopper performance mentioned above made interpretation of the wire scanners data very difficult. The relatively low time resolution of the wire scanner doesn't allow to distinguish between partially deflected bunches in the mini-pulse edges and non-deflected bunches in the middle of the mini-pulse. The resulting effective beam size is increased as seen in Figs.2 and 3. It is hard to use this data for quantitative beam dynamics study. As a result, we started from the nominal settings for all focusing magnets and manually tweaked them to minimize beam loss.



0.79

0.75

Figure 2. Effect of slow chopping on the measured beam position. Top – vertical beam position along the pulse with chopper off, bottom – vertical beam position along the pulse with chopper on.

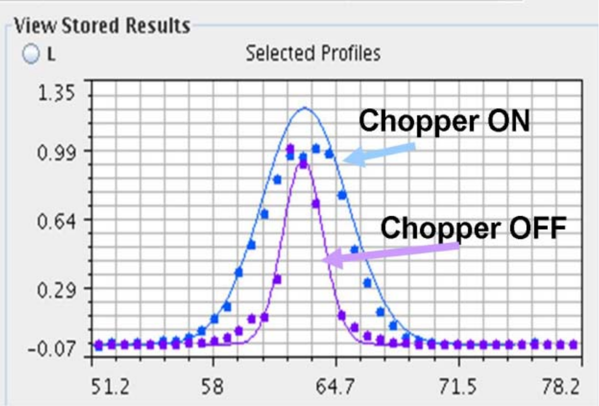
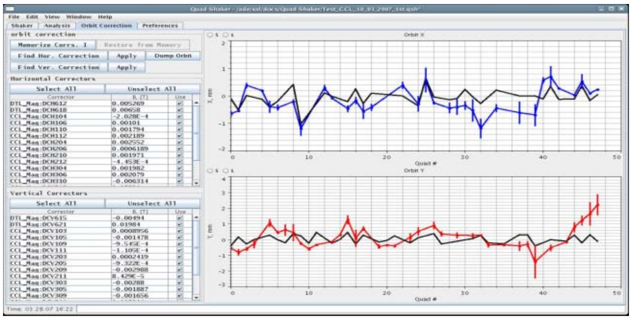


Figure 3. Effect of slow chopping on the measured beam size.



Horizontal Correctors

Corrector	B, [T]	Use
DTL_Mag:DCH612	0.005269	☑
DTL_Mag:DCH618	0.00658	☑
CCL_Mag:DCH104	-2.028E-4	☑
CCL_Mag:DCH106	0.00101	☑
CCL_Mag:DCH110	0.001794	☑
CCL_Mag:DCH112	0.002189	☑
CCL_Mag:DCH204	0.002552	☑
CCL_Mag:DCH206	0.0006189	☑
CCL_Mag:DCH210	0.001971	☑
CCL_Mag:DCH212	-4.453E-4	☑
CCL_Mag:DCH304	0.001982	☑
CCL_Mag:DCH306	0.002079	☑
CCL_Mag:DCH310	-0.006314	☑

Vertical Correctors

Corrector	B, [T]	Use
DTL_Mag:DCV615	-0.00494	☑
DTL_Mag:DCV621	0.01984	☑
CCL_Mag:DCV103	0.0008956	☑
CCL_Mag:DCV105	-0.001478	☑
CCL_Mag:DCV109	-9.545E-4	☑
CCL_Mag:DCV111	-1.105E-4	☑
CCL_Mag:DCV203	0.0002419	☑
CCL_Mag:DCV205	-9.322E-4	☑
CCL_Mag:DCV209	-0.002988	☑
CCL_Mag:DCV211	8.429E-5	☑
CCL_Mag:DCV303	-0.00288	☑
CCL_Mag:DCV305	-0.001887	☑
CCL_Mag:DCV309	-0.001656	☑

Figure 4. Screenshot of the beam based alignment application. The top blue graph – measured horizontal beam position in the CCL quads before correction, the top black graph – after correction. The bottom red graph – measured vertical beam position in the CCL quads before correction, the bottom black graph – after correction.

Beam Loss in the Warm Linac

There is no reduction in beam current along the linac detectable by the beam current monitors. Beam loss monitors (BLMs) based on ionization chambers are used to detect radiation due to beam losses [7]. The same BLMs are used to interrupt beam for machine protection in case of higher than acceptable losses. The BLMs are calibrated using a radiation source before installation but it is still difficult to calculate absolute levels of the residual activation based on prompt radiation levels measured by the BLMs. Therefore we use activation measurements from the radiological surveys conducted periodically during the run to set trip thresholds on the machine protection systems.

Several activation locations found in the warm linac after the first production run came as a surprise because none of the BLMs indicated elevated beam losses. Because we had BLM chambers installed at every second quadrupole, and at the CCL energies the radiation pattern is localized within a single quadrupole, BLM sensitivity was insufficient to detect losses at a nearby quadrupoles. The number of ion chambers was doubled to provide full coverage and they were moved closer to the beam line to increase sensitivity. Since then we have seen a good correlation between the BLM data and the activation measurements since then as demonstrated in Fig.5.

Another observation, puzzling at first, was that after correcting the trajectory in the CCL using our standard response matrix inversion algorithm, the beam was centered in the BPMs but losses were high. By manually adjusting dipole correctors the losses could be made significantly lower, but the trajectory was then not necessarily centered in the BPMs. The problem turned out to be that we have less then two BPMs per betatron oscillation period in the CCL. In this case the correction algorithm can produce a trajectory with zero displacement in the BPMs but a significant deviation in between. To solve this problem we developed a beam based alignment technique. This technique is robust but takes about 30min to measure and correct the trajectory in the CCL compared to several seconds for the old algorithm. An example of the measurement is shown in Fig.4.

After the above mentioned improvements the activation levels did not exceed ~10 mrem/hour at 30cm at several hot spots after 10 days of 60kW beam on target as shown in Fig.5. In order to achieve that loss level some manual adjustments of several quadrupole magnets strengths within ~5% range were required.

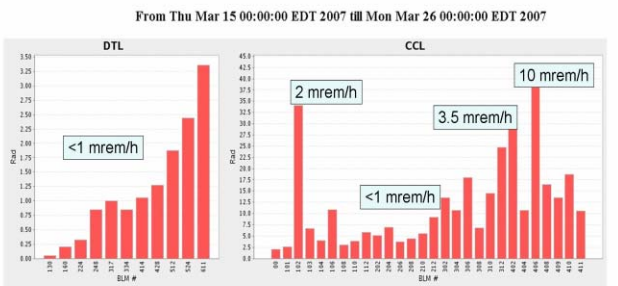


Figure 5. The measured prompt radiation due to beam loss in the DTL (left) and CCL (right). Activation levels measured after 30 hours at 30cm are shown in squares.

CONCLUSIONS

The SNS Front End and warm linac has been successfully commissioned and is in the process of power ramp up to the nominal design parameters. Tuning algorithms are well established and provide stable set points. In general, there is good agreement between the measured beam parameters and the design values. First operational experience revealed reliability problems in several systems. The most significant at the moment is inadequate chopping quality due to electrical breakdowns in the electrostatic LEBT and failure of the MEBT chopper. Transition to a magnetic type LEBT is seen as the long term solution and various design improvements are done on the existing LEBT as a temporary fix. New MEBT chopper deflector has been designed and will be ready for testing during the next run. Average beam losses in the warm linac are low and are expected to satisfy requirements at nominal beam power. There are several localized hot spots, which will require additional study and mitigation measures.

ACKNOWLEDGEMENT

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