OPERATIONAL EXPERIENCE OF THE SNS FRONT END AND WARM LINAC

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Abstract

The Spallation Neutron Source accelerator complex uses set of pulsed linear accelerators of different types to accelerate beam to 1GeV. 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. In the process of the commissioning and beam power ramp up many technical systems, as well as tuning algorithms, have deviated significantly from the original design. Our understanding of beam behavior has been evolving continuously and resulted in a steady reduction of fractional beam losses in the linac. In the same time new unexpected problems have been discovered, which are still in the process of investigation. In this paper we summarize our experience up to date and report on the current directions of experimental study, simulations, and development of tuning methods.

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 87 MeV Drift Tube Linac (DTL), a 186 MeV Coupled Cavity Linac (CCL), and associated transport lines. 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 in 2009 [1]. Results of the initial commissioning can be found in [2], and of the initial operation experience in [3]. At the time of this writing the Front End and warm linac routinely provides beam at 40% of the design average power.

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.

Ion Source and LEBT

The ion source has been capable of satisfying peak and average beam current requirements for the power ramp up goals. At the time of this writing it produces 32mA 750us pulses at 60Hz. We do not expect significant difficulties in expanding the pulse width to the design value of 1200us. Increasing peak current to the nominal 38mA is more challenging but peak current higher than 40mA in 800us pulses has been demonstrated recently in dedicated tests [4].

The RF antenna life time and the possibility of catastrophic antenna failures still remains a concern. We implemented several interlock mechanisms to prevent a possible water leak into the LEBT chamber in case of antenna failure and have not had such events for the two last run periods. An external antenna source is being developed as a long term solution and the first experimental tests have shown promising results [4].

The long standing problem of electrical breakdowns in the electrostatic LEBT has not been fully resolved yet. An improved LEBT design, which does not have glue joints and has a better isolation between the chopper electrodes and the rest of the LEBT, was installed before the last run and demonstrated significant reduction of arc related chopper failures. As a long term solution we plan to use a magnetic LEBT which is in the early stages of development.

Chopper Systems

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 “ramp up”. The chopper systems demonstrated design parameters during commissioning for the nominal chopping pattern at low average beam power. We encountered serious problems with both the LEBT and the MEBT choppers at higher beam power.

The main problem of the LEBT chopper is frequent damage to the high voltage switches by arcs in the electrostatic LEBT. Serial resistors were installed in the chopper circuitry for protection, resulting in significant increase of the chopper rise time. We change the resistor value in the range from 750 Ohm, for the case of high arcing rate, to 175 Ohm, for the case when the LEBT electrodes are well conditioned, and the arc rate is low. Even in the latter case the chopper rise time is ~80ns, which is still significantly longer than the design requirement of <50 ns. At the time of this writing we have 450 Ohm resistor installed resulting in rise/fall time in excess of 100ns as shown in Fig.1. Quite surprisingly, we are able to deliver up to 550 kW of beam power on the target with acceptable losses everywhere in the machine even with such poor chopping quality. The redesigned high voltage switch with more robust protection from the arcs is planned to be installed in January of 2009.

The MEBT chopper high voltage switches had poor reliability in early runs, and the kicker structure had to be redesigned [5]. A number of small evolutionary improvements in the high voltage electronics design resulted in significant improvement in reliability, which, together with using a new kicker, allowed using the MEBT chopper for extraction loss reduction during neutron production runs. The kick strength provided by the prototype structure of the new design is about 15% below the original design specification. Results of the kick strength measurement are shown in Fig.1. The chopper rise time of ~16 ns is still longer than the design specification. The final version of the chopper kicker, which we plan to install in January of 2009, will have a 25% stronger kick and an 8ns rise time. Figure 2 demonstrates the effect of the MEBT chopper on the ring extraction losses in one of the experiments. Just inserting the chopper target reduces losses by factor of 2 due to scraping of the vertical halo, when the chopper is on the losses are reduced by another factor of 5. In the later experiments we discovered that ion source alignment has a significant effect on the LEBT chopper efficiency. With improved alignment procedure we are able to run with negligible extraction losses even with the MEBT chopper off. We do see effects of the slow chopper rise time, most notably in bunch position and phase variation along the pulse and effective beam size increase. We have not found evidence of additional losses in the linac associated with the slow chopping.

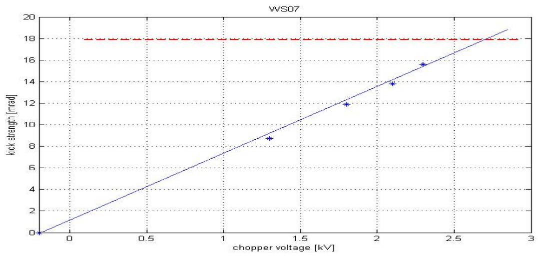

Figure 1: Chopper kicker strength vs. kicker voltage calculated from the profiles in Fig.1. Red dashed line shows the design requirements.

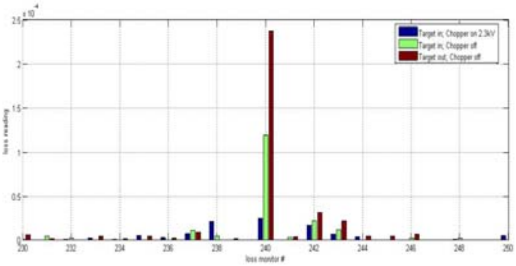

Figure 2**:** Effect of the MEBT chopper on the ring extraction losses. Bar chart is BLM readings: the brown bar– chopper is off, target is out; the green bar – chopper is off, target is in; the blue bar – chopper is on, target is in.

DTL AND CCL PERFORMANCE

The Drift Tube Linac consists of six accelerating tanks operating at 402.5 MHz with 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 Coupled Cavity Linac (CCL) consists of four 12-segment accelerating modules operating at 805 MHz with output energy of 187 MeV. The inter-segment sections contain electromagnet quadrupoles arranged in a FODO focusing lattice, BPMs, wire scanners, and Beam Shape Monitors.

The original plan for the transverse beam matching was to use profile measurements in several places along the linac. So far we have not achieved any significant progress in using wire scanner data for loss reduction. We set all quadrupole magnet strengths to the design values and manually tweak some of them within 1-2% range to minimize beam losses.

Longitudinal tuning of the linac had been routinely done using PASTA phase scan algorithm [6]. Measured longitudinal rms Twiss parameters were close to the design values and we did not observe significant beam losses in the warm linac [7]. However, with the increased average beam power we started seeing unexpectedly large losses in the Super Conducting Linac (SCL). These losses depended weakly on the transverse focusing parameters but were very sensitive to the RF phase settings of the warm linac cavities. One of the strange experimental findings was that minimum losses were achieved by shifting some of the RF phases away from the nominal set points found from the PASTA phase scans. For example, DTL6 phase had to be shifted by 6 degrees. In the process of resolving this puzzle we developed a beam based measuring technique, which allows us to measure the deviation of accelerating gradients from the design value with high accuracy. For this measurement the phase of the beam is shifted by several degrees at the entrance of a selected cavity, and the phase shift at all available BPMs downstream is recorded. The period of the resulting synchrotron oscillation inside the longitudinal separatrix depends on the accelerating field amplitude. By fitting the model to the measurements it is possible to deduce the RF amplitude errors, as illustrated by an example in Figs. 3 and 4. We found that our standard PASTA scans produced RF amplitude set points overestimated by 1-2% for each cavity. The cumulative effect of these relatively small errors led to significant deviation from the design longitudinal phase advance. After correction of the set points the minimum of the losses corresponded to the nominal set points found from the phase scans, and no DTL phase tweaking is required.

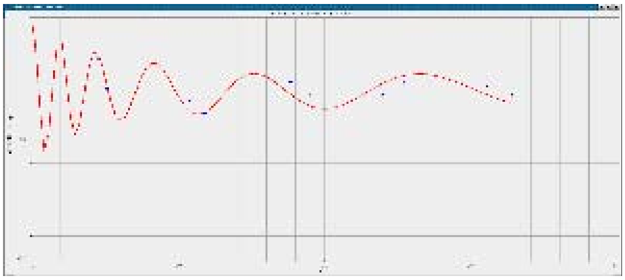

Figure 3: Synchrotron bunch oscillation in the DTL. Solid line is simulation result for the nominal cavity amplitudes; points are measured values for the case of 2.7% error of the DTL2 amplitude.

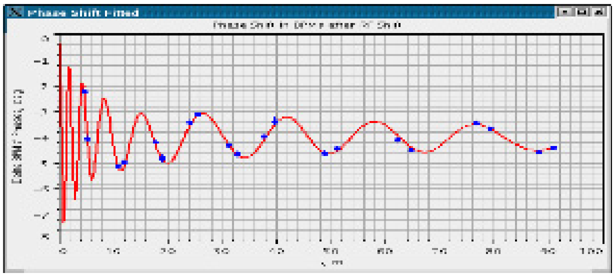

Figure 4: Synchrotron bunch oscillation in the DTL and CCL. Solid line is simulation result for the nominal cavity amplitudes; points are measured values for the case of good linac tuning.

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 prompt radiation due to beam losses.

The integrated radiation dose recorded by the BLMs during a typical 10 day run with 400 kW beam on target is shown in Fig. 5. The result of the activation survey after 2 days of cool down period is shown in Fig. 6. There is a good correlation between the activation levels and prompt radiation doses; therefore we can use BLM data reliably in machine tuning. We associate the main hot spot in the beginning of the CCL with particles falling out of the longitudinal DTL separatrix due to large energy and/or phase deviation at the entrance. In order to fix this problem we will have to improve longitudinal beam quality in the Front End. The first step will be to increase the available RF power for the MEBT rebunchers, which is currently limited at about 75% of the nominal design level.

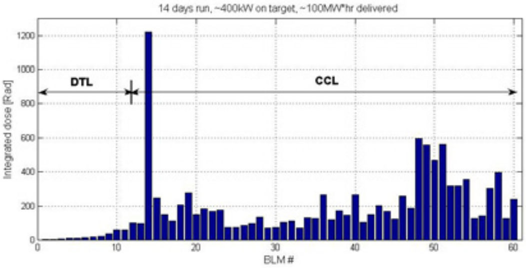

Figure 5: Measured distribution of prompt radiation due to beam loss in the warm linac.

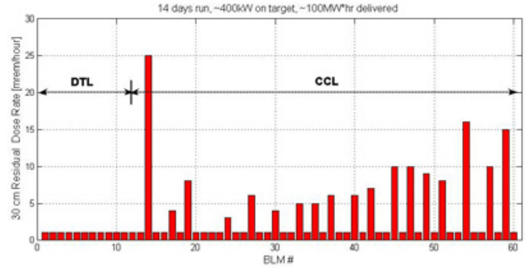

Figure 6: Measured distribution of the residual radiation in the warm linac after 36 hours of cool down period.

CONCLUSIONS

The SNS Front End and warm linac has been successfully keeping up with the requirements of the beam power ramp up plan. We continue to refine the tuning algorithms. The most significant technical problem at the moment is inadequate chopping quality due to the electrical breakdowns in the electrostatic LEBT. Transition to a magnetic type LEBT is seen as the long term solution and various design improvements are being implemented on the existing LEBT as a temporary fix. The new MEBT chopper deflector has been successfully tested and is in use. In general, losses in the warm linac itself are well under control and should not present any limitations to increasing the average beam power to the design level. A bigger concern is losses in the downstream parts of the machine, possibly caused by the halo generated in the Front End and warm linac. This is a subject of an ongoing research.

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