COMMISSIONING EXPERIENCE OF SNS*

M.A. Plum representing the beam commissioning team, Spallation Neutron Source,
Oak Ridge National Laboratory, Oak Ridge, TN, U.S.A.

Abstract

The Spallation Neutron Source accelerator complex consists of a 2.5 MeV H^- front-end injector system, a 186 MeV normal-conducting linear accelerator, a 1 GeV superconducting linear accelerator, an accumulator ring, and associated beam transport lines. The linac was commissioned in five discrete runs, starting in 2002 and completed in 2005. The accumulator ring and associated beam transport lines were commissioned in two runs in January-February and April 2006. With the completed commissioning of the SNS accelerator, the facility has begun initial low-power operations. In the course of beam commissioning, most beam performance parameters and beam intensity goals have been achieved at low duty factor. A number of beam dynamics measurements have been performed, including emittance evolution, transverse coupling in the ring, beam instability thresholds, and beam distributions on the target. The commissioning results, achieved beam performance and initial operating experience of the SNS linac will be presented.

INTRODUCTION

The Spallation Neutron Source (SNS) is a short pulse neutron scattering facility located on the campus of the Oak Ridge National Laboratory in Oak Ridge, TN, USA. The construction project was a partnership of six US DOE national laboratories, each of which had responsibility for designing and manufacturing a portion of the facility. At 1.4 MW of proton beam power on target, the SNS will operate at beam powers a factor of eight beyond that which has been previously achieved [1]. The SNS baseline parameters are summarized in Table 1.

Table 1: SNS Design Parameters

Beam Power on Target	1.4 MW
Beam Energy	1.0 GeV
Linac Beam Macropulse Duty Factor	6.0%
Beam Pulse Length	1.0 msec
Repetition Rate	60 Hz
Chopper Beam-On Duty Factor	68%
Peak macropulse H^- current	38 mA
Average Linac H^- current	1.6 mA
Ring accumulation time	1060 turns
Ring bunch intensity	1.5×10^{14}
Ring Space-Charge Tune Spread	0.15
Beam Pulse Length on Target	695 nsec

The SNS accelerator complex [2] consists of a 2.5 MeV H^- injector [3], a 1 GeV linear accelerator [4], an accumulator ring, and associated beam transport lines [5]. The injector (also called the Front-End Systems) consists of an H^- volume ion-source with 50 mA peak current capability [6], a Radio-Frequency Quadrupole and a Medium Energy Beam Transport line for chopping and matching the 2.5 MeV beam to the linac. The linear accelerator consists of a Drift Tube Linac (DTL) with 87 MeV output energy, a Coupled-Cavity Linac (CCL) with 186 MeV output energy, and a Superconducting RF Linac (SCL) with 1 GeV output energy [7]. At full design capability the linac will produce a 1 msec long, 38 mA peak, chopped beam pulse at 60 Hz for accumulation in the ring. The linac beam is transported via the High Energy Beam Transport (HEBT) line to the injection point in the accumulator ring where it is multi-turn charge-exchange injected over 1060 turns and compressed to less than 1 microsecond, reaching an intensity of 1.5×10^{14} protons per pulse. When accumulation is complete the extraction kicker fires during the 250 nsec gap to remove the accumulated beam in a single turn and direct it into the Ring to Target Beam Transport (RTBT) line, which takes the beam to a liquid mercury target. Staged commissioning of the accelerator complex, completed May 2006, was performed in seven discrete beam commissioning runs (shown in Figure 1) which were devoted to commissioning the i) Front-End, ii) Drift Tube Linac Tank 1, iii) Drift Tube Linac Tanks 1-3, iv) Coupled Cavity Linac, v) Superconducting Linac, vi) High-Energy Beam Transport Line and Accumulator Ring, and vii) Ring to Target Beam Transport Line and the mercury target. Table 2 summarizes the main beam commissioning results, comparing beam measurements with design goals. Ramp up to high power operation is now in progress.

LINAC COMMISSIONING

Linac commissioning results have been presented before [8], but for completeness we will provide a brief summary here.

The linac was successfully commissioned in five discrete runs from December 2002 to August 2005. The warm linac commissioning progressed smoothly and measured beam parameters are in good agreement with expectations [3]. RF phase and amplitude set points were determined using two methods (energy degrader / Faraday Cup acceptance scan and phase scan signature matching) that gave consistent results. We now use the phase scan signature matching method exclusively.

The superconducting linac commissioning proceeded much faster than expected. Before commissioning began there was some uncertainty in the algorithms to set the phases of the rf cavities due to concerns with beam loading, but the simple procedure of fitting the time of flight vs. cavity phase with a sinusoidal curve, for 10 mA

* ORNL/SNS is managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract DE-AC05-00OR22725

peak current, 20 μs-long beam pulses, worked very well and the initial tune up was completed in just nine days [8]. For higher peak currents, in addition to feedback control of the cavity amplitude and phase, feed forward has proven essential for achieving the required amplitude and phase regulation in the presence of heavy beam loading. Typical amplitude and phase regulation errors are better than 1% and 1 degree respectively.

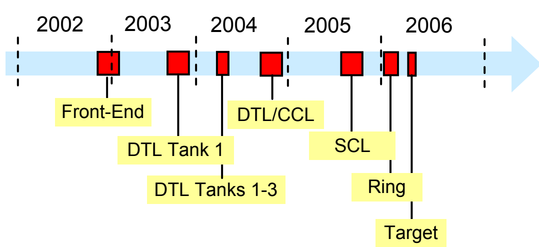

Figure 1: SNS Beam Commissioning Schedule.

Table 2: Beam parameters achieved to date

Parameter	Design	Measured
Linac Transverse Output Emittance [π mm-mrad (rms, norm)]	0.4	0.3 (H) 0.3 (V)
CCL1 Bunch Length [deg]	3	4
Linac Peak Current [mA]	38	>38
Linac Output Energy [MeV]	1000	952
Linac Average Current [mA]	1.6	1.05 (DTL1) 0.007 (SCL)
Linac H^-/ions/pulse	1.6×10^{14}	1.0×10^{14}
Linac pulse length/rep rate/duty factor [msec/Hz/%]	1.0/60/6.0	1.0/60/5.4 (DTL1) .85/15/.54 (SCL)
Ring intensity	1.5×10^{14}	9.6×10^{13}
Extracted beam intensity	1.5×10^{14}	9.6×10^{13}
Beam intensity on target	1.5×10^{14}	5.3×10^{13}

The linac output energy has ranged between 860 and 950 MeV, depending on the cavity amplitude set points and the number of off-line cavities. At the end of the last running period (Oct – Nov/06) ten of the 81 cavities were off line. One was off line because the tuner range was not set properly to bring the cavity on resonance at the present operating temperature of 4.4 °K. This tuner will be reset during a future maintenance period. The remaining nine cavities were off line due to unexpected signals observed from the higher order mode couplers due to a combination of fundamental power coupling and electron-related or vacuum activity. To be conservative we decided to turn off these cavities until the phenomena are better understood. The SCL has proved to be remarkably robust to changes in cavity amplitudes and the number of off-line cavities, even for up to three consecutive cavities off line.

In December 2006, 60 Hz rf operation was demonstrated for the first time for a full set of four cavities in a cryomodules at 4.4 °K. This was made possible by a recent upgrade to one of the High Voltage Converter Modulators (HVCMs) that provide the high voltage for the klystrons. The other cryomodules will be tested at 60 Hz as the remaining HVCMs are upgraded (expected completion date for the upgrades is May 2007). The maximum repetition rate for beam delivery achieved to date is 15 Hz (the beam power at this time was 60 kW).

Except for the MEBT, where we can use a slit and collector to measure emittance, we use multiple wire scanners to measure the rms emittance and Twiss parameters. In Table 3 we show a comparison between the measured and design transverse emittance for the different parts of the linac.

Table 3: Comparison of measured and expected rms transverse beam emittances. The estimated measurement error is about 20%.

Location	**Measured ε_x, ε_y π-mm-mrad (rms, norm)**	**Design ε_x, ε_y π-mm-mrad (rms, norm)**
MEBT Entrance	0.22, 0.25	0.21
CCL Entrance	0.22, 0.25	0.33
SCL Entrance	0.27, 0.35	0.41
Linac Dump	0.26, 0.27	0.41
HEBT	0.50, 0.37	0.45

RING COMMISSIONING

Much of the ring commissioning was performed using single minipulse injection, where the beam from the ion source is chopped to allow just a single turn (~690 ns bunch length) of beam to be accelerated. For such a beam pulse the power (~12 W) is low enough that beam loss is not a concern, and because beam is injected into the ring with an offset relative to the closed orbit we are able to measure the betatron tune, closed orbit, injection position and angle, magnet polarities and strengths, etc.

The initial stage of the ring commissioning progressed very quickly. In early January, in anticipation of receiving permission to commission the ring, we tuned up the linac to the linac beam dump. On January 12, 2006 we received the final approval from the US Department of Energy to deliver beam from the linac to the ring extraction beam dump. On January 13 we tuned up the 162-m long beam transport line from the linac to the ring injection beam dump. On January 14 we injected single minipulses into the ring, and by January 15 we achieved more than 1000 turns of beam storage. On January 16 we extracted the beam from the ring and directed it to the ring extraction dump 75 m downstream of the ring, and also demonstrated accumulation of seven minipulses. On January 26 we increased the beam intensity to 1.3×10^{13} protons per pulse (ppp) to meet our commissioning goal of $>1 \times 10^{13}$ ppp. By the end of the commissioning period on February 13 we demonstrated accumulation of 1×10^{14} ppp of unbunched beam and also made some preliminary measurements of beam instability thresholds (more on this later).

The second ring commissioning period ran from April 8 to May 31. On April 28 we delivered 1.6×10^{13} ppp to the spallation target to meet the CD-4 goal needed to successfully mark the end of the construction and initial commissioning of the SNS facility. The entire project was thus completed ahead of schedule and under budget.

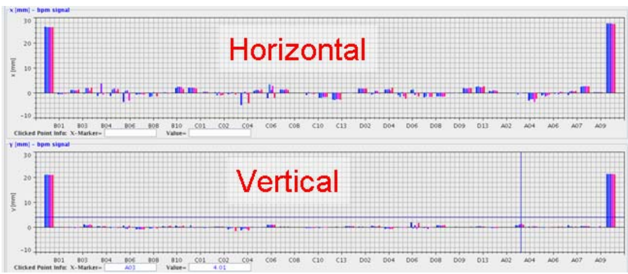

Figure 2: Example of closed orbit in the ring. The large position excursions at the left and right edges of the plot are due to the injection kickers upstream and downstream of these BPMs. For both plots the vertical axis runs from -10 to +30 mm.

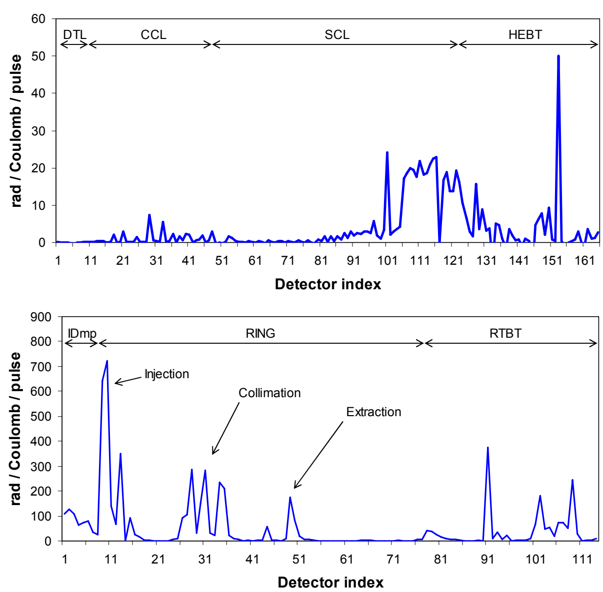

Figure 3: Beam loss monitors in the linac and ring. The beam parameters were 30 kW beam power, 5 Hz, 888 MeV.

During the July and August 2006 running period we began routine beam delivery for neutron production. After the September outage beam delivery resumed for the October – November running period, and the 10 kW administrative limit imposed by the Accelerator Readiness Review process was lifted on 8/Nov/06 (the limit now in place is 100 kW). By the end of November we had separately demonstrated accumulation of 9.6×10^{13} ppp and 60 kW of beam power (at 15 Hz) on target, and for routine operations we achieved 30 kW at 5 Hz on target. A typical closed orbit measurement for the ring is shown in Fig. 2, and a typical beam loss profile is shown in Fig. 3.

ISSUES ENCOUNTERED

Ring injection and injection dump beam line

The ring injection section includes four chicane magnets that merge the incoming H^- beam with the circulating proton beam at the charge-exchange stripper foil. These same magnets also direct the H^- beam that misses the foil, and the H^0 beam partially stripped by the foil, to the injection dump beam line. Early in the ring commissioning period we discovered that the nominal chicane magnet set points caused a large (~14 mm) closed orbit distortion and poor beam injection into the ring. This was traced to a design change made in 2000 that had the unintended consequences of the closed orbit offset and also caused large beam losses in the ring injection dump beam line. We were able to adjust the magnet settings to give good injection into the ring and a good closed orbit, but we were not able to simultaneously obtain good transmission of the H^0 and H^- waste beams in the injection dump beam line. A short term solution is now in place where we are using a primary stripper foil that is 5 mm wider and 5 mm taller. This foil fully intercepts the incoming H^- beam so there is little to no H^- beam entering the injection dump beam line. This allows the beam line to be optimized for just a single beam, and reduces the beam loss to levels that should allow us to increase the beam power on target to more than 100 kW.

The mid term solution involves shifting the fourth chicane magnet beam left to place the H^0 and H^- beams in the good field region of the magnet; enlarging the gap of the injection dump septum magnet; adding a C-magnet just downstream of the septum magnet to allow individual control over the H^0 and H^- beam trajectories; and adding a wire scanner profile monitor, a beam position monitor, and a beam current monitor to the diagnostics suite. These modifications should allow the beam power on target to be increased to several hundred kW.

The final solution, needed to raise the beam power to the full 1.4 MW, will depend on the outcome of further modelling and beam measurements. It will likely involve adding a second quadrupole magnet to the injection dump beam line.

Tilted beam on target

A late addition to the target commissioning plan involved mounting a temporary view screen to the face of the neutron spallation target to measure the beam position and distribution on the target. The last permanent beam diagnostic (a harp with three signal wire planes) is 9.5 m upstream of the target, so without the view screen the beam distribution and position would have to be extrapolated based on upstream beam position monitors, wire scanners, the harp, and knowledge of the beam transport. The view screen turned out to be an invaluable tool during commissioning and operation that survived far longer than expected, and we removed it only when necessary to increase the beam power above 10 kW. An example image is shown in Fig. 4.

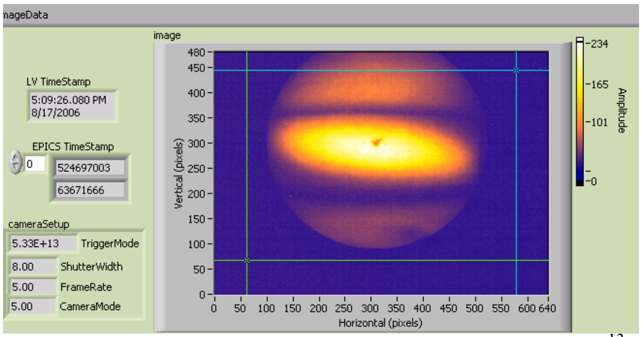

Figure 4: Image from the target view screen, for 5.3×10^{13} ppp extracted from the ring.

The beam distribution on the target shows a slight tilt of ~3 deg. We initially suspected this was due to transverse coupling in the ring, but after further beam measurements and after correcting the coupling we concluded this is not the source of the tilt. We now believe the most likely source is transverse coupling in the ring to target (RTBT) transport beam line, probably due to slight misalignments in the quadrupole magnets. Work is now in progress to develop a beam diagnostic that can be permanently mounted to the target face to provide beam position and distribution information for full power beams. It will be based on light emission, for example from red-hot tungsten wires similar to the SINQ profile monitor [9].

Beam loss

Beam loss is a primary constraint on our ramp up to higher beam power. The high-loss points during 2006 operations are shown in Fig. 3 and in Table 4 along with the highest activation levels (measured at 30 cm five days after the conclusion of 30 kW operations but less than one day after high-intensity beam experiments).

Table 4: Activation measurements at high-beam-loss locations.

Location	Activation (mrem/h)
Coupled-cavity linac	8
Ring injection section	20
Injection dump beam line	5
Ring collimation section	32
Ring extraction section	20
Ring-to-target transport line (RTBT)	25

We believe the beam loss in the couple cavity linac (CCL) is due to too few beam position monitors (BPMs) and beam loss monitors (BLMs). The lack of diagnostics made it possible to center the beam at the BPMs and minimize the beam loss at the BLMs, yet still allow substantial beam loss that could not be detected. To alleviate this problem 21 BLMs were added to the CCL in the Dec/06 – Jan/07 outage.

Most of the beam loss in the ring injection section can be explained by beam scattering in the primary and secondary stripper foils. There is also poorly-understood beam loss that occurs 10 m downstream of the primary stripper foil, where there is an aperture reduction. This latter beam loss will be investigated in the near future. The beam loss due to the primary stripper foil is close to nominal but we still expect some additional modest reductions after further beam experiments. We plan to reduce the losses due to the secondary stripper foil by installing a thinner foil. The present secondary foil is 25 mg/cm^2 carbon-carbon, but it is much thicker than necessary. It must only be thick enough to be self supporting.

The beam loss in the ring collimation section is expected since that is intentionally the limiting aperture in the ring. We believe that the majority of the beam loss in the extraction section is due to beam in the gap, caused by poor beam chopping due to the medium energy beam transport chopper that is not yet functional. The beam loss in the RTBT occurs just upstream of the dipole magnet that directs the beam away from the extraction dump and toward the target. We believe this loss is due to a combination of large vertical tails on the beam and a large vertical betatron function at the same place as an aperture reduction. To address this issue we will alter the RTBT quadrupole magnet set points to reduce the betatron function in the vicinity of the aperture reduction and also work to identify the cause of the vertical tails.

HIGH INTENSITY STUDIES

One of the biggest uncertainties in high power operation of the SNS ring is the threshold of the e-p instability, since it is difficult to confidently predict. Early in the ring commissioning period we set up the ring to create conditions most favourable for the onset of instabilities – an unbunched, un-extracted coasting beam with near-zero chromaticity that filled the ring circumference (although the bunchers were turned off, the rf buncher cavities were not shorted, and there may have been some longitudinal structure imposed on the beam due to beam excitation of the cavities). Under these conditions, at the nominal betatron tunes $Q_x = 6.23$, $Q_y = 6.20$, we observed [10] two instabilities. Under certain conditions both instabilities can occur in the same shot, as shown in Fig. 5.

The first instability, observed at 3, 6, and 12 µC beam charge and after storing the beam for several milliseconds, is consistent with an impedance-driven instability due to the extraction kickers. The measured growth rate and frequency spectrum is consistent with our expectations and the threshold is high enough that it should not interfere with full power 1.4 MW operations under nominal conditions.

The second instability, observed at 4, 8, and 16 μC beam charge, and again after storing the beam for several milliseconds, is consistent with an e-p instability. Although the threshold for nominal operating conditions cannot be directly extrapolated from these measurements, based on similar measurements at PSR [11] we believe that it is unlikely that this instability will interfere with full power operations.

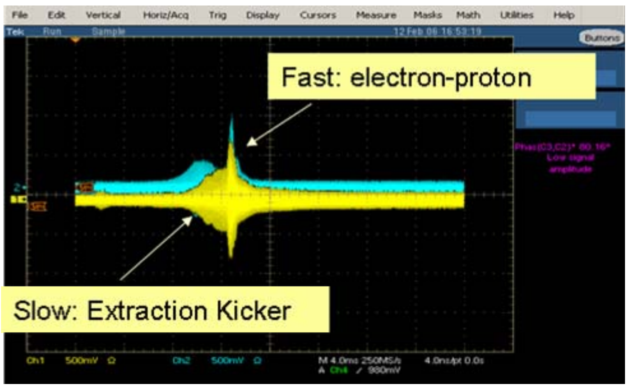

Figure 5: Horizontal (yellow) and vertical (blue) oscillations observed after storing the beam for several milliseconds. Two different instabilities are simultaneously present for this shot.

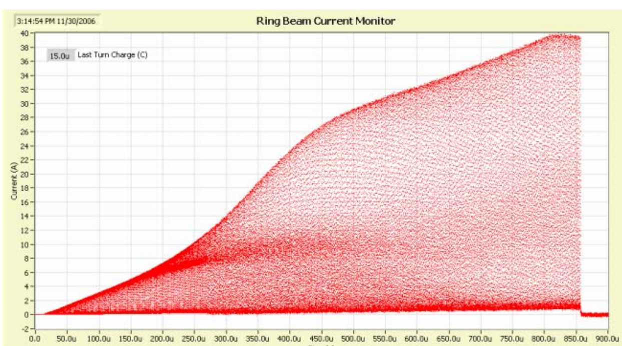

Figure 6: Ring beam current monitor showing accumulation of 9.6×10^{13} ppp.

We observed a third instability after lowering the betatron tune to slightly below the integer ($Q_y \approx Q_y \approx 5.8$) to create conditions favourable for the resistive wall instability. The frequency of this instability is about 191 kHz, as expected, with a growth rate (1.2 msec for 6 μC beam charge) consistent with previous estimates of the impedance of the injection kickers together with the vacuum pipes. As with the other two instabilities, we do not expect this one to interfere with normal operations.

No instabilities have been observed thus far under the normal condition of bunched beam in the ring, and initial indications are that any instabilities under normal conditions will have thresholds high enough that they will not interfere with full-power 1.4 MW operations. In November 2006 we accumulated 9.6×10^{13} ppp (830 turns) of bunched beam and stored it for 1.06 ms (1100 turns) and we did not observe any evidence of a beam instability.

BEAM POWER RAMP UP

So far the SNS has remained on track for the beam power ramp up plan that was set forth in 2002. That plan calls for reaching 3 kW operations in fiscal year (FY) 2006, 50 kW and 150 kW in the first and second halves of FY2007, 800 kW in FY2008, and the final power of 1400 kW in FY2009. The maximum beam power achieved to date is 60 kW at 15 Hz. In this next running period, from mid-January through March 2007, we plan to demonstrate (not necessarily concurrently) 90 kW and 30 Hz.

REFERENCES

[1] C. Prior et al., "ISIS Megawatt Upgrade Plans," PAC 2003, Portland, OR, May 2003, p. 1527.

[2] N. Holtkamp, "Commissioning Highlights of the Spallation Neutron Source," EPAC 2006, Edinburgh, p. 29.

[3] A. Aleksandrov, "Performance of SNS Front End and Warm Linac" LINAC 2006, Knoxville, TN, Aug. 2006.

[4] D. Jeon, "Beam Dynamics in the Spallation Neutron Source Linac," PAC 2003, Portland, OR, May 2003, p. 107.

[5] J. Wei, "Spallation Neutron Source Ring -- Status, Challenges, Issues, and Perspectives," PAC 2003, Portland, OR, May 2003, p. 571.

[6] R.F. Welton et al., PAC 2005, Knoxville, TN, May 2005, p. 472.

[7] I.E. Campisi, "Testing of the SNS Superconducting Cavities and Cryomodules," PAC 2005, Knoxville, TN, May 2005, p. 34.

[8] S. Henderson, "Commissioning and Initial Operating Experience with the SNS 1 GeV Linac" LINAC 2006, Knoxville, TN, Aug. 2006.

[9] R. Dölling et al., "Beam Diagnostics at High Power Proton Beam Lines and Targets at PSI," DIPAC 2005, June 2005, Lyon, p. 228.

[10] V.V. Danilov et al., "Accumulation of High Intensity Beam and First Observations of Instabilities in the SNS Accumulator Ring," ICFA-HB2006, Tsukuba, Japan, May-June 2006.

[11] R. Macek, "Status of the Experimental Studies of the Electron Cloud at the Los Alamos Proton Storage Ring," PAC 2003, Portland, OR, May 2003, p. 3089.