COMMISSIONING OF THE SPALLATION NEUTRON SOURCE ACCELERATOR SYSTEMS *

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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 from January to 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 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 will be discussed.

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
Ring betatron tune Q_x, Q_y	6.23, 6.20

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 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 [6,7]. 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 transports 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. Ramp up to high power operation is now in progress.

The overall status of the SNS, and details of the warm and cold linac commissioning, are discussed in depth by papers in this conference by S. Henderson, A. Aleksandrov et al. and R. Campisi et al. In this paper we will focus on the Ring commissioning.

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 of little 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 2006, in anticipation of receiving permission to commission the ring, we tuned up the linac to the linac beam dump. On January 12 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

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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. By 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).

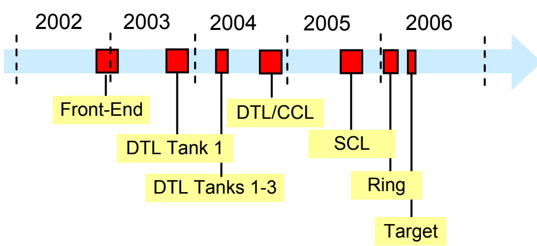

Figure 1: SNS Beam Commissioning Schedule.

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.

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 November 8. On November 30, 2006 we demonstrated accumulation and storage of 9.6×10^{13} ppp, which is the highest number of protons per bunch of any proton ring. During routine operations in November the beam parameters were 30 kW at 5 Hz, making SNS the world's highest peak neutron flux spallation neutron source. On Feb. 19, 2007 during machine development, the linac was temporarily re-tuned to accelerate H^- particles to 1.01 GeV – a world record for H^+ and H^- linacs (the highest energy beam accumulated in the ring to date is 931 MeV). On March 28, 2007 we demonstrated our highest beam power to date, 90 kW at 15 Hz. During our present run from June – September 2007 our goal is routine operations at 180 kW, 30 Hz. To date the range of beam energies accumulated in the Ring is 839 to 931 MeV.

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 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, put into place in November 2006, was to use a primary stripper foil 5 mm wider, 5 mm taller, and about 50% thicker. 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, which reduces the beam loss in the injection dump beam line. However, this is not a long-term solution because of the increased beam loss in the ring caused by increased foil scattering.

The mid term solution involves shifting the fourth chicane magnet 8 cm 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 high-sensitivity beam current monitor to the diagnostics suite. These modifications, with the exception of the increased-gap septum magnet, were put into place during the April – May 2007 outage, and we expect them to 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 modeling and beam measurements. It may 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. 2.

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 [8].

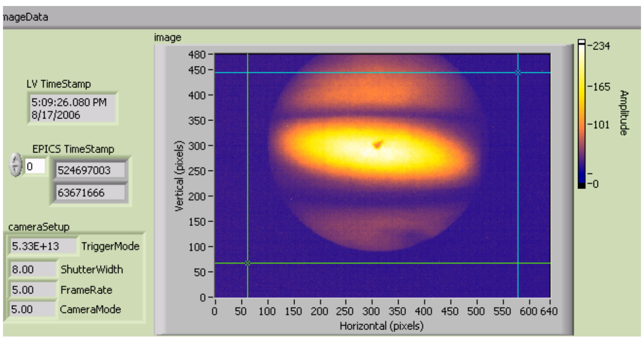

Figure 2: Image from the target view screen, for 5.3×10^{13} ppp extracted from the ring.

Transverse coupling

The usual method of measuring transverse coupling in the ring by measuring the response to a kick to the beam is not yet possible due to lack of a kicker. Instead, the coupling was measured by injecting single minipulses at a large offset relative to the closed orbit in the vertical plane, and very close to the closed orbit in the horizontal plane. Under these conditions a perfect ring with no coupling would exhibit large oscillations in the vertical plane and very small oscillations in the horizontal plane. However, our observations showed significant horizontal oscillations with an envelope that depends upon the difference between the horizontal and vertical betatron tunes, as shown in Fig. 3.

To analyze the data we adopted the formalism from Sagan et al. [9]:

$$\begin{pmatrix}x\\y\end{pmatrix}=\begin{pmatrix}A_x\sqrt{\beta_x}\cos\psi_x + A_y\sqrt{\beta_x}(C_{11}\cos\psi_y - C_{12}\sin\psi_y)\\ -A_x\sqrt{\beta_y}(C_{22}\cos\psi_x + C_{12}\sin\psi_x)+A_y\sqrt{\beta_y}\cos\psi_y\end{pmatrix}$$

where x and y are the horizontal and vertical turn-by-turn beam positions, β_x and β_y are the betatron functions at the BPM, A_x and A_y are amplitude factors to be determined, C_{ij} are the coupling coefficients to be determined, and $\psi = n\omega + \phi$, where n is the turn number, ω is the normal mode frequency, and ϕ is an arbitrary offset which varies from one BPM to the next. The C_{ij} are a measure of the coupling with $C_{ij} \sim 1$ corresponding to full coupling. C_{11} is the normalized amplitude of the horizontal component of the motion that is in phase with the vertical motion, C_{12} is the out of phase component, and C_{22} is the vertical component in phase with the horizontal motion.

An example fit to the data for one of the 44 BPMs is shown in Fig. 3, and the resulting coupling coefficients at all 44 BPMs (excluding the non-functional ones) are shown in the top of Fig. 4. After energizing skew quadrupole corrector magnets the coupling coefficients were reduced to those shown in the bottom of Fig. 4. Although skew quadrupole corrector magnets are distributed at many points around the ring they all have similar effects on the coupling correction, and there is no strong preference at this time of which ones to use. A likely source of the coupling is the ring injection section, where we have strong multipole components from the chicane magnets and also fringe fields from the injection septum magnet. For this reason we chose to energize six vertical skew quadrupole corrector magnets in the vicinity of the injection section to about half their maximum strength to empirically minimize the coupling. The residual coupling does not appear to adversely affect the performance of the ring at this time, so a more detailed analysis has been postponed for now.

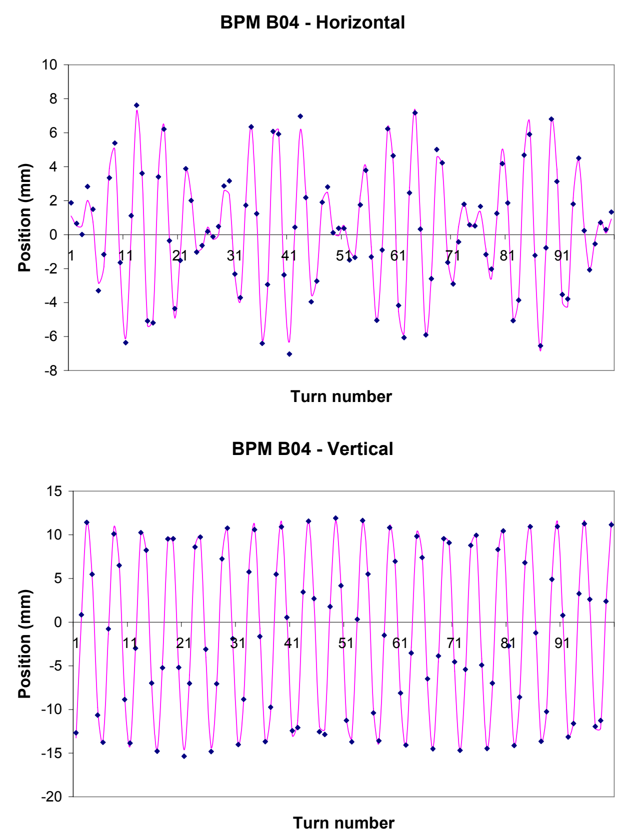

Figure 3: Turn-by-turn beam position oscillations of a single minipulses injected into the ring, measured by a BPM in the ring. Top: horizontal oscillations. Bottom: vertical oscillations. Measured positions are shown as dots and the fits are shown by the lines.

Beam loss

As expected, beam loss is a primary constraint on our ramp up to higher beam power. The high-loss points during 2007 operations are shown in Fig. 5 and in Table 2 along with the highest activation levels measured at 30 cm one day after the conclusion of 10 days of 60 kW operations.

One contribution to the beam loss in the coupled cavity linac (CCL) was 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 December 2006 – January 2007 outage.

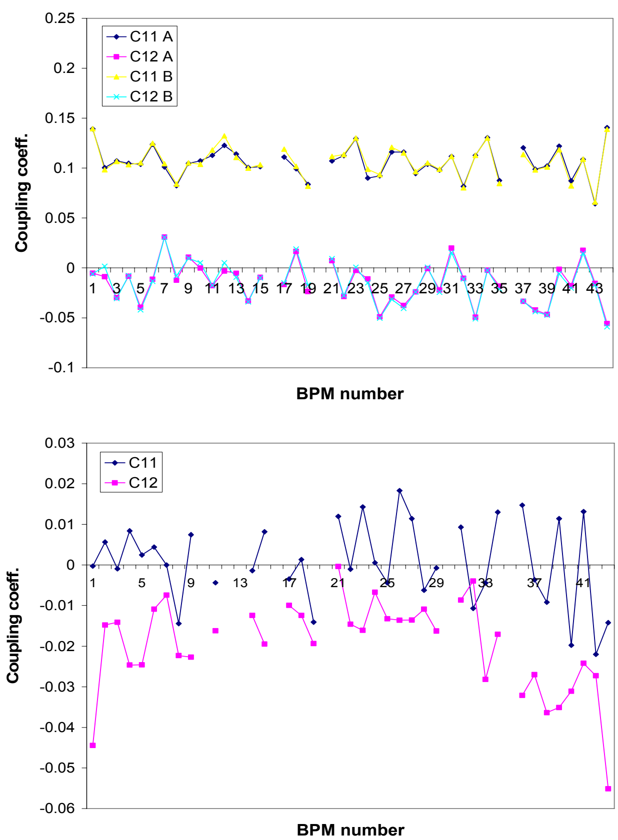

Figure 4: The coupling coefficients C_{11} and C_{12}, before (top) and after (bottom) correction. The top plot shows two different measurements to demonstrate the reproducibility.

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. In June 2007 we replaced the 23 mg/cm^2 self-supporting carbon-carbon foils with 15 mg/cm^2 carbon-carbon foils, which are the thinnest carbon-carbon foils that we could purchase. We ultimately prefer ~1 mg/cm^2 foils and we are now exploring our options.

Some 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 by the LEBT chopper and the absence of a functional medium energy beam transport chopper. 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. We have improved this loss point by modifying the RTBT quadrupole magnet set points to reduce the vertical betatron function in the vicinity of the aperture reduction, but we still expect further improvements once we have a better understanding of this loss point.

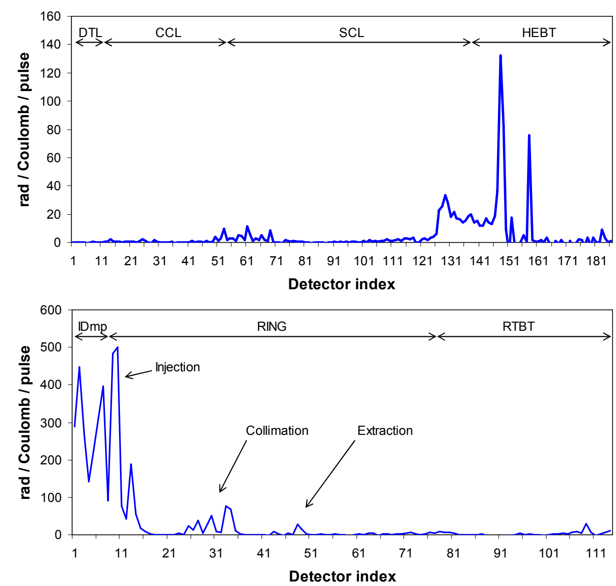

Figure 5: Beam loss monitors in the linac and ring. The beam parameters were 60 kW beam power, 15 Hz, 888 MeV.

Table 2: Activation measurements at high-beam-loss locations.

Location	Activation (mrem/h)
Coupled-cavity linac	10
Ring injection section	90
Injection dump beam line	8
Ring collimation section	30
Ring extraction section	50
Ring-to-target transport line (RTBT)	8

Another contribution to beam loss in the linac, HEBT, and Ring is due to slow LEBT chopper rise and fall times caused by the increased resistor values installed to protect the chopper from arcs in the ion source lenses. These

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resistors have been in place since January 2007. We are now working on new lens designs that will allow us to return to the nominal resistor values.

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. Initial instability measurements in February and November 2006 did not reveal any instabilities at normal operating conditions up to a bunched beam intensity of 9.6x10^{13} ppp stored for 1100 turns (the nominal full-power intensity is 1.5x10^{14} ppp and the nominal storage time is 10 turns). Figure 6 shows the Ring beam current monitor for one of the 9.6x10^{13} ppp accumulation cycles.

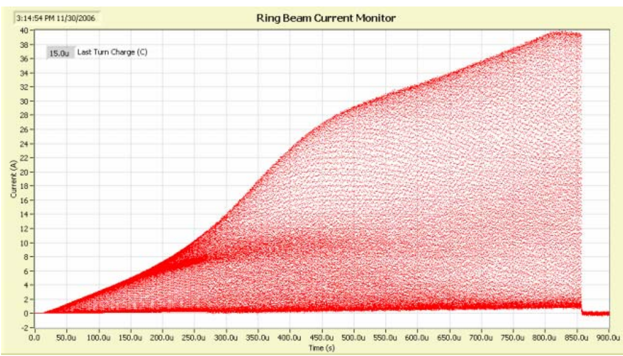

Figure 6: Ring beam current monitor showing accumulation of 9.6x10^{13} ppp.

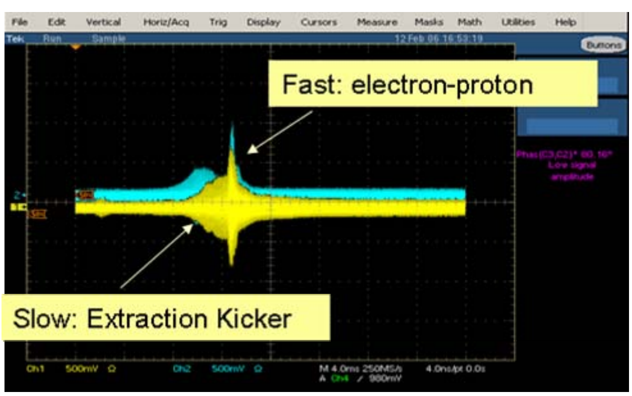

Figure 7: Horizontal (yellow) and vertical (blue) oscillations observed after storing the beam for several milliseconds. Two different instabilities are simultaneously present for this shot.

However, three different instabilities were observed [10,11] after turning off the rf bunchers in the ring. The first instability, with characteristics consistent with e-p instability, was observed after storing 4, 8, and 16 μC of beam charge for several milliseconds. The second instability, an impedance-driven instability due to the extraction kickers, was observed after storing 3, 6, and 12 μC of beam charge for several milliseconds. These two instabilities are sometimes present at the same time, as shown in Fig. 7. The third instability was observed after lowering the betatron tune to slightly below the integer ($Q_y \approx Q_y \approx 5.8$) to create conditions favorable 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. We do not expect any of these instabilities to be present at full-power beam intensity under normal operating conditions.

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 [12] calls for reaching 3 kW operations in fiscal year (FY) 2006, 180 kW in FY2007, 820 kW in FY2008, and the final power of 1440 kW in FY2009.

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