STATUS OF THE SNS RING POWER RAMP UP*

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Abstract

Beam was first circulated in the Spallation Neutron Source (SNS) ring in January 2006. Since that time we have been working to raise the beam power to the design value of 1.4 MW. In general the power ramp up has been proceeding very well, but several issues have been uncovered. Examples include poor transmission of the waste beams in the injection dump beam line, and cross-plane coupling in the ring to target beam transport line. In this paper we will discuss these issues and present an overall status of the ring and the transport beam lines.

INTRODUCTION

The SNS accelerator complex comprises a 1 GeV linac, a storage ring, and a mercury spallation target. In the linac 1-ms long, 38-mA peak current, H^- beam pulses are accelerated to 1 GeV, 60 times per second, to give a final design beam power of 1.56 MW. The beam pulses are compressed down to 690 ns through multi-turn charge exchange injection in the storage ring. Immediately after accumulation the beam is extracted and transported to the mercury spallation target to create intense pulses of neutrons that are then directed through beam lines for various life-science, materials-science, and basic physics experiments.

Beam was first circulated in the SNS ring in January 2006, and since that time we have been working to raise the beam power to the design value of 1.4 MW of power on the target. We are presently about one third of the way to our goal. As shown in Fig. 1, our highest beam intensity to date is $1.3\mathrm{x}10^{14}$ protons per pulse, and our highest production-level beam power to date is 510 kW. In this paper we will discuss the status of the power ramp up and summarize some of the issues we've encountered along the way.

PRESENT STATUS

In Table 1 we compare achieved vs. design beam parameters. Not all of these parameters were achieved simultaneously – e.g. the 1.01 GeV linac beam energy was obtained at 15 Hz before we started removing cyromodules for upgrades and repairs, and the peak intensity measurements of $1.3\mathrm{x}10^{14}$ ppp (protons per pulse) were done at less than 1 Hz. For our typical neutron production runs we now operate at 60 Hz, 873 MeV, and 510 kW on target.

Beam Loss and Activation

The beam loss per Coulomb of beam delivered to the target continues to decrease as we improve the performance of the accelerator. The high loss points in the ring area are mostly in line with our expectations. Beam loss monitor signals, together with activation levels from our most recent production run, measured 24-28 hours after the end of the production run, are shown in Fig. 2 and Table 2. These levels are higher than usual due to problems with the low energy beam chopping system during this run.

Table 1: Beam Parameters Achieved to Date

Parameter	Design	Achieved
Linac transverse output emittance [π mm-mrad (rms, norm)]	0.4	0.3-0.4 (H) 0.3-0.4 (V)
Linac pulse length/rep rate/duty factor [msec/Hz/%]	1.0/60/6.0	1.0/60/5.4 (DTL1) 1.0/60/3.6 (SCL)
Beam energy [GeV]	1.0	1.01
Ring bunch intensity	$1.5\mathrm{x}10^{14}$	$1.3\mathrm{x}10^{14}$
Beam intensity on target [protons per pulse]	$1.5\mathrm{x}10^{14}$	$1.3\mathrm{x}10^{14}$
Beam power on target [MW]	1.4	0.51
Ring accumulation time	1060 turns	1010 turns
Beam Pulse Length on Target	695 nsec	695 nsec
Ring betatron tune Q_x, Q_y	6.23, 6.20	6.23, 6.20

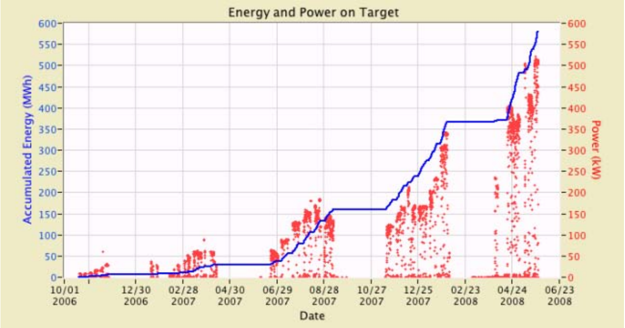

Figure 1: The beam power ramp up curve through May 28, 2008. the highest beam power to date is 510 kW.

The highest activation levels in the entire accelerator are at the primary stripper foil, due in part to our stripper foils [1] that are 42% wider and about 10% thicker than design, to alleviate a beam loss problem in the injection dump beam line (see next section). Once we transition to the nominal foil size and thickness we expect that the beam loss will be reduced by 10-20%. We expect to make further gains through improved painting schemes which will reduce the number of foil hits from the circulating protons.

The next two highest beam loss points are just downstream of the secondary stripper foil, and at an

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aperture reduction in the ring injection straight downstream of the stripper foils. The activation near the secondary stripper foil is easily explained by foil scattering. For the next production run we plan to reduce the secondary stripper foil thickness by a factor of nine, which should make significant improvements to the nearby beam loss. We do not yet fully understand the beam loss at the aperture reduction, but we believe that beam scattering in the primary foil is a strong component. As we improve our understanding of this loss point we expect to make further improvements.

Other high beam loss points are in the collimation region, as expected, and in the vicinity of the extraction septum magnet. These latter losses are due to beam in the gap, which we are making steady progress on improving as we improve our low and medium energy chopper systems on line.

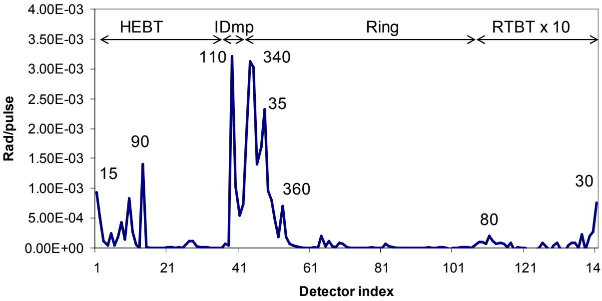

Figure 2: Beam loss monitor signals in the Ring area. The beam parameters were 475 kW beam power, 60 Hz, 873 MeV.

Table 2: Activation Measurements at High-loss Locations

Location	**Activation (mrem/h at 30 cm)**
Linac to Ring transport line (HEBT)	15-90
HEBT collimation section	300
Ring injection section	140 - 340
Injection dump beam line	60 - 110
Ring collimation section	30 - 260
Ring extraction section	30 - 50
Ring to Target transport line (RTBT)	30 - 80

INJECTION DUMP BEAM LINE

The ring injection chicane comprises four magnets to create a closed orbit bump and merge the injected and circulating beams at the primary stripper foil. Some of the injected H^- beam misses the stripper foil (2% by design) and some is partially stripped (3% by design). After passing through a secondary stripper foil, these "waste" beams are transported to a water-cooled beam dump via the injection dump beam line, and the trajectory of these beams depends on the chicane magnet set points. We refer to these two beams as the H^- and H^0 waste beams, but once downstream of the secondary stripper foil they are of course actually both H^+.

During commissioning we discovered an error in the design set points of the chicane magnets. We were able to change the set points to achieve good injection into the ring, but this resulted in poor waste beam transmission. We also discovered that the H^- waste beam trajectory was passing outside of the good field region of the fourth chicane magnet, which caused an undesirable vertical deflection of this beam into the injection dump beam line.

The larger and thicker primary stripper foils mentioned above help by 1) intercepting a greater fraction of the H^- beam, thus reducing the intensity of the H^- beam in the injection dump beam line, and 2) reducing the H^0 component. Today we still use 17-mm wide foils, although the thickness is now only about 10% greater than the design thickness of 0.260 mg/cm^2.

In April-May 2007 we moved the offending chicane magnet 8-cm beam left to place the H^- waste beam trajectory within the good field region of the magnet. This solved the vertical deflection problem and has had no measurable impact on the circulating beam. We also installed a C-magnet immediately downstream of the injection dump chicane magnet to provide independent control over the H^- and H^0 waste beam trajectories. After these modifications we were able to simultaneously deliver both H^- and H^0 waste beams to the center of the dump.

The most recent modification to the injection dump beam line occurred in March 2008, when we replaced the septum magnet with a spare, modified to increase the gap by 2 cm. Unfortunately, rather than achieving a reduction in the measured beam loss, we observed a slight increase, probably due to just moving the aperture limitation down stream where the losses are more easily measured. Beam losses in this beam line are primarily due to a combination of tails in the beam distribution and scattering in the secondary stripper foil. To alleviate the beam loss component due to scattering we are working to replace the existing 18-mg/cm^2 carbon-carbon foil with a 2-mg/cm^2 polycrystalline carbon foil, which should reduce the scattering losses by a factor of nine. We also plan to improve the losses due to beam tails by improving beam matching throughout the linac and by more fully utilizing the halo scraping system in the High Energy Beam Transport line.

TILTED BEAM DISTRIBUTION IN EXTRACTION LINE

A temporary view screen was mounted to the face of the neutron spallation target during the first phases of target commissioning. Unfortunately it had to be removed in order to increase the beam power above 10 kW, but until that time it proved to be a very valuable beam diagnostic. Among many of the measurements made, the view screen showed that the beam distribution on the target had a tilt of about 3 to 7 degrees, as shown in Fig. 3.

The source of this tilt has now been identified as cross plane coupling caused by a large skew quad component in the extraction septum magnet. In addition to the tilted profile on the target view screen, this coupling is also manifest in strangely peaked wire scanner profiles, and horizontal oscillations in the extraction beam line induced by the vertical extraction kickers. The most direct evidence came from a newly developed technique [2] to reconstruct beam profiles by injecting a single turn into the ring and storing it for different numbers of turns. To the extent that a beam profile in the extraction line is just a superposition of individual injected turns, any beam position monitor (BPM) in the extraction line can be used to reconstruct a beam profile. One such reconstruction, for BPM25, is shown in Fig. 4.

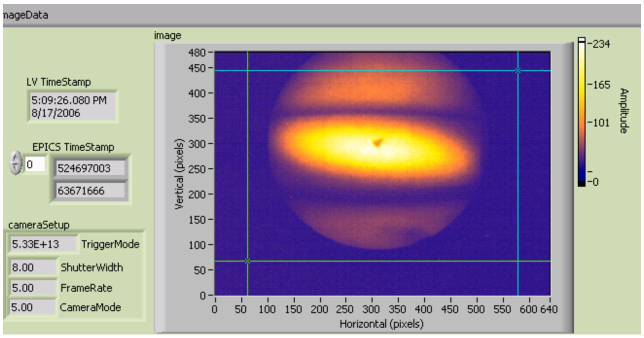
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Figure 3: Image from the target view screen, for $5.3x10^{13}$ ppp extracted from the ring [3].

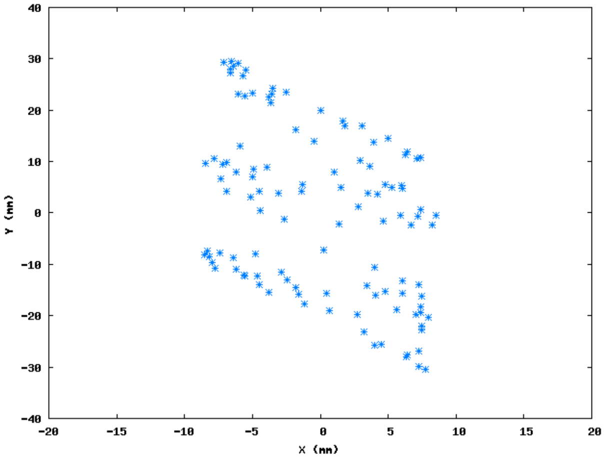

Figure 4: A reconstructed beam distribution at BPM25 in the extraction line.

The skew quad component of the septum magnet was never measured, but a detailed 3-D model [4] has subsequently been developed, and it shows a strong skew quad component. Particle tracking simulations [2] that include this component are in good agreement with the measured profiles and reconstructed distributions. We have added corrector skew quads to the model to determine how to best cancel the effect of the septum magnet. The model shows that two skew quads added to the first few meters of the extraction beam line could correct the cross-plane coupling. Another option we are exploring is modifying the septum magnet with pole-tip shims. A final decision on correcting the tilt is now in progress.

HIGH INTENSITY RESULTS

The highest beam intensity to date in the ring is $1.3x10^{14}$ protons per pulse. Beam was injected for 1010 turns (close to the design value of 1060). We were not able to achieve the full design value of $1.5x10^{14}$ ppp due to ion source limitations on that day.

Beam losses at these conditions, per Coulomb of stored charge, were as much as 3.2 times higher than our typical production tune, and were located primarily in the collimation section. All the pulsed power systems, including the buncher system, worked well under these conditions. Since our limited time was focused on beam instability measurements [5] we did not attempt to address the cause of the beam loss (other than that due to the instability).

Several of the high intensity beam pulses, up to $1.3x10^{13}$ ppp, were delivered to the spallation target. At the same time we measured the beam profile as a function of beam intensity using a harp ~10 m upstream of the target. To check for space charge effects on the beam distribution we measured the beam profile as a function of beam charge. Other than a slight filling in of the centers of the flat-topped profiles we did not observe significant changes, indicating only a weak dependence on space charge.

Earlier instability measurements [6] showed three different instabilities – e-p, extraction kicker impedance, and injection-kicker resistive-wall impedance. More recent measurements [6] show that the character of the e-p instability is changing from one set of measurements to the next. Sometimes the instability first occurs in the horizontal plane, at other times in the vertical plane. The onset of the instability also varies, starting with beam intensities as low as $3.4x10^{13}$ ppp (with the ring bunchers turned on). The initial transverse oscillations also sometimes appear at the head of the bunch and other times at the tail.

The instabilities caused by the injection kicker and extraction kicker should not interfere with full power operations. Due to the changing nature of the e-p instability it is not yet clear if this will significantly impact operations. As a precautionary measure a wide-band dual-plane transverse-feedback system is in the process of being fabricated and installed [7].

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