PROGRESS WITH MW-CLASS OPERATION OF THE SPALLATION NEUTRON SOURCE*

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Abstract

The Spallation Neutron Source (SNS) [1] operates at beam powers over 850 kW. Challenges in operating a proton accelerator at these power levels include maintaining the uncontrolled beam loss to levels approaching 10^{-6}/meter, and ensuring machine protection. Experience with beam tuning and safely handling the high power will be presented. Also the progress in beam loss reduction over the course of the power ramp-up will be reviewed.

INTRODUCTION

The SNS is designed to be the world's first MW-class pulsed spallation neutron source. The accelerator consists of a linac for beam acceleration, and an accumulator ring to enable short pulse (< 1 μsec) beam delivery to a mercury target (see Ref. 1). The linac consists of Drift Tube (DTL) structures up to 87 MeV, Coupled Cavity (CCL) structures up to 186 MeV and superconducting cavities for acceleration to full energy of 1000 MeV.

Realizing the SNS design potential involves operating at unprecedented beam power levels for pulsed proton accelerators. Construction and beam commissioning were completed in the summer of 2006 and neutron production began in October of 2006. Progress in increasing the operational beam power since the start of operations is shown in Fig. 1 with operational power levels approaching 1 MW. The integrated charge delivered (blue line in Figure 1) is increasing even faster than the beam power level. The power increase is roughly consistent with the plan for power ramp-up adopted at the start of operations.

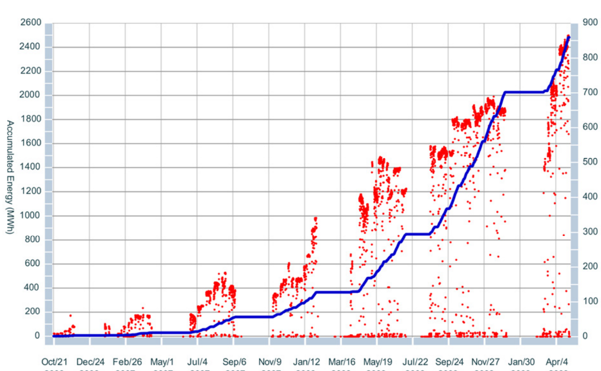

Figure 1: Progress in ramp up of the beam power since the start of operations (Beam power in red and integrated charge delivered in blue).

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Table 1: High Level Beam Parameters

	Max. Design	Best ever, not simultaneous	Highest power run, simultaneous
P_{beam} (kW)	1440	850	850
W (MeV)	1000	1010	928
τ_{linac} (μSec)	1000	990	670
$I_{peak\text{-}linac}$ (mA)	38	40	38
$\langle I \rangle_{linac}$ (mA)	26	23	23
Repetition Rate (Hz)	60	60	60
Ring turns	1060	1020	700
Ring ppp	1.5×10^{14}	1.3×10^{14}	9.3×10^{13}
Δν space-charge	0.15	0.18	0.11

Some high level parameters achieved in the SNS accelerator are shown in table 1, relative to the design goals. The third column shows individual maximally achieved parameters, and the last column shows beam parameters for the highest attained beam power. Present deficiencies relative to design values are ~ 7% in beam energy, about 50% shy in pulse length and about 12% in low in average beam current. The present SNS operational beam power is over five times higher than that of the previous world record short pulse neutron source.

Controlling beam loss is critical with beam powers approaching 1 MW. To maintain hands-on maintenance requires maintaining most of the uncontrolled beam loss levels < 1 W/m (or 10^{-6} of the beam/m at 1 MW). Loss levels of 1 W/m beam correspond to residual activation levels of ~ 100 mRem/hr at 30 cm ~ 4 hrs after shutdown (see Ref. 2 and references therein) Understanding beam loss at these levels is challenging. Directly measuring beam distributions and simulating beams to these small fractional levels is difficult. The state of beam loss and machine activation in the linac and accumulator Ring are discussed below. Also the machine availability and machine protection issues are discussed.

BEAM LOSS ISSUES

Linac Beam Loss

Beam loss in the warm linac (DTL, CCL) is largely within the expected levels. Figure 2a shows integrated beam loss accumulated over a recent 16 day run at ~860 kW as measured by the beam loss monitors along the linac. Also shown in Fig. 2 (red numbers) are the measured residual activation levels (all residual activation numbers here are at 30 cm, and taken ~24 hrs after end of production). There is minimal beam loss and residual activation detected in the DTL. The CCL section has a hot spot near the start of a lattice transition. Levels are below 100 mrem/hr everywhere, and in most areas are ~ 10 mRem/hr, within expectations [3]. Losses in the CCL are not expected to be a limiting factor in further power increases.

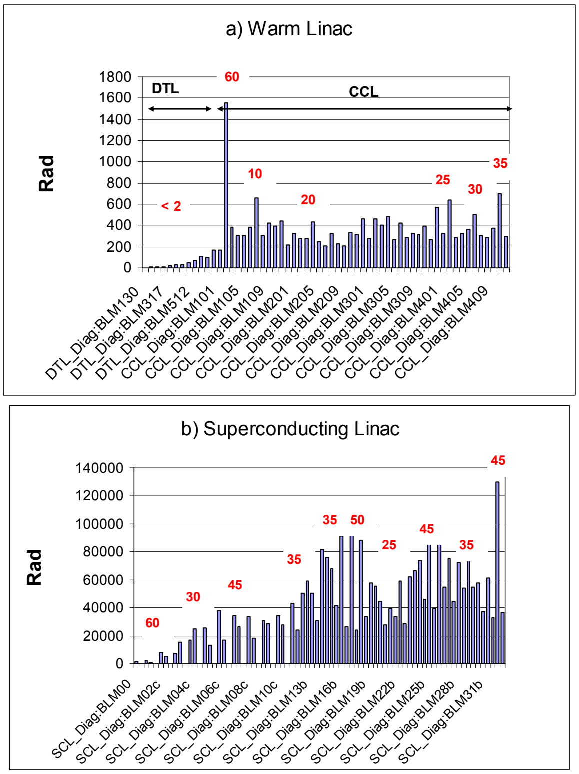

Figure 2: Beam loss throughout the a) warm linac and b) SCL. Numbers in red are residual activation levels after a 16-day production run at 730 kW.

The SCL was predicted to be a “loss free” region [3], in part due to the large aperture associated with the superconducting structures. But there is a nearly constant background level of residual activation of ~20-40 mrem/hr in the warm sections between the cryomodules (activation levels in the cryomodules are lower). The cause of the observed beam loss in the SCL region is not well understood [4], but the magnetic field quality in the focusing quadrupoles is under investigation. Recent 10-15% reductions in the focusing strength relative to design values reduced beam loss by ~ 40%.

The beam loss levels at various parts of the accelerator are not always proportional to the resultant residual activation. For example in Fig. 2b there is generally a similar level of activation throughout the SCL despite large differences in the loss monitor response. Beam energy and geometrical effects can strongly influence loss monitor sensitivity. None-the-less it is possible to extrapolate the expected activation based on historical experience. The SNS power ramp up has been done incrementally with modest power increases, and careful monitoring of the activation levels.

Recent reductions of the SCL focusing quadrupole strength has resulted in reduced beam loss. Fig. 3 shows normalized measured beam loss (loss signal / charge transported) for historical loss levels compared to the reduced focusing strength case. The reason for this reduction is not completely understood, candidate effects including poor magnet quality and better transport of off-energy beam [4].

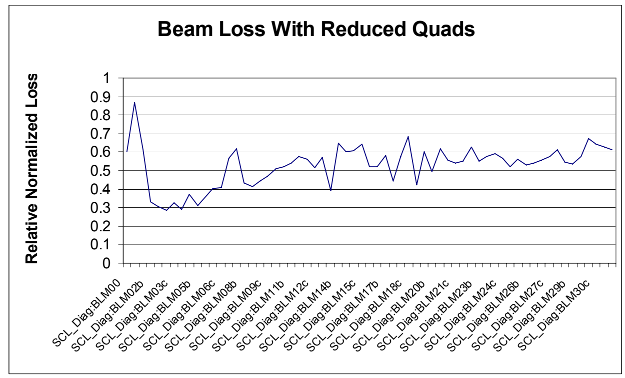

Figure 3: Ratio of beam loss with reduced focusing strength to beam loss with design quadrupole strength in the SCL.

Ring and Transport Line Beam Loss

Losses and residual activation levels in the Ring and transport lines are shown in Fig. 4 (for the same run period described in Fig. 2). Regarding the Ring [5], the injection area is most critical. H^- charge exchange stripping with a foil is used to control emittance growth during injection, but this has the inevitable drawback of scattering induced beam loss. This area was predicted to be the highest beam loss region of the SNS accelerator and it is in line with predictions typically with activation levels of ~500 mRem/hr at our present beam power. The Ring injection dump line, collimation straight, extraction region and transport lines [6] all have much lower loss and activation levels, and much of the Ring is relatively loss free.

The observed levels of Ring beam loss are close to the predicted levels [3]. Significant reductions in the normalized beam loss per charge delivered to the Target have been made in the Ring injection dump line by equipment modifications. Reductions in the Ring Injection area have been facilitated by using thinner foils made possible by better dump line transport and also by improved linac beam quality. Reductions in the extraction region beam loss are due to improvements to the linac beam chopping quality and improved Ring RF setup.

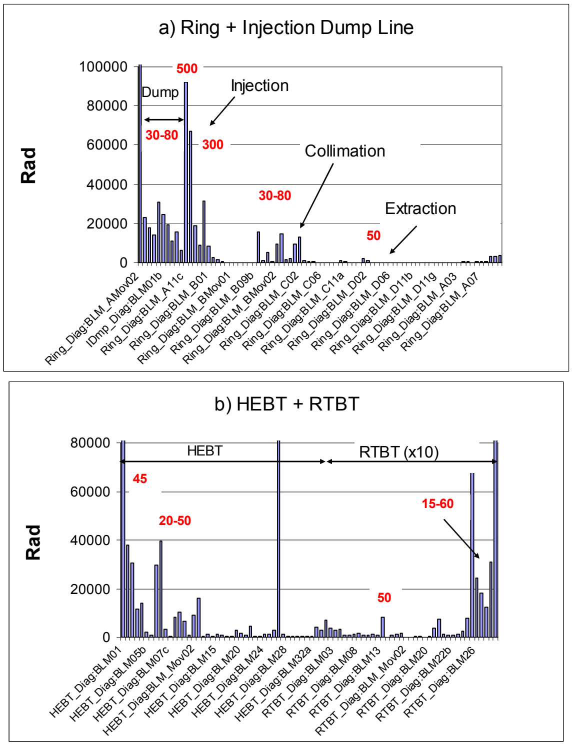

Figure 4: Beam loss and residual activation a) in the Ring and Ring injection dump line and b) in the transport lines for the same case as Figure 2.

Importantly, the residual activation levels in the SNS at present are not limiting the operational beam power.

Activation Build-up

Figure 5 shows residual activation build-up over the power ramp-up period for some areas of concern. Data are taken at the end of major run cycles. Also indicated is the integrated charge delivered to the Target over these cycles. The green curve is an average of all the warm section activation levels in the SCL. The pink curve is the activation level just downstream from the Ring Injection foil (the hottest point in the SNS accelerator). Also indicated in blue is the Ring Injection Dump activation level, which is not increasing over time (this area of the Accelerator is particularly challenging with multiple waste beams and has also been an area of significant equipment upgrades). The increases in the activation levels over the power ramp-up are less than proportional to the increase in the charge delivered to the Target, reflecting improvements in beam tuning throughout this period.

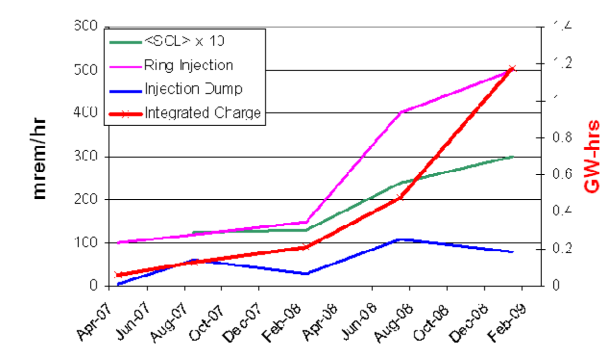

Figure 5: Build-up of residual activation levels following major run cycles, and the increase in the integrated power delivered to the Target. Green is the average SCL warm section activation, pink is the Ring injection area and the blue line is the Injection dump-line activation

Fractional Beam Loss

Quantifying the level of beam loss is challenging, with overall loss levels in various accelerator sections being $< 10^{-4}$. While the activation levels do indicate uncontrolled beam loss is $< 10^{-6}$/m in most areas, it is nonetheless interesting to verify this by calibration of the loss monitor signal with an absolute beam loss. However, given the wide range of loss monitor response (e.g. see difference in ranges of Figs. 2-4) this calibration is location specific. One example case used to calibrate SCL loss monitors involves using a short pulse laser (used for profile measurements) to strip the outer electron from the H^- linac beam. Figure 6 shows the beam loss in the SCL region with and without the laser on. Knowing the laser pulse duration and size of the laser beam we calculate the maximum possible H^- beam that is intercepted by the laser, and assume all of this is responsible for the increased beam loss observed downstream from the laser interaction region. This provides us with a calibration indicating $< 10^{-5}$ of the beam is lost per SCL warm section (~ 7 m separation per warm section).

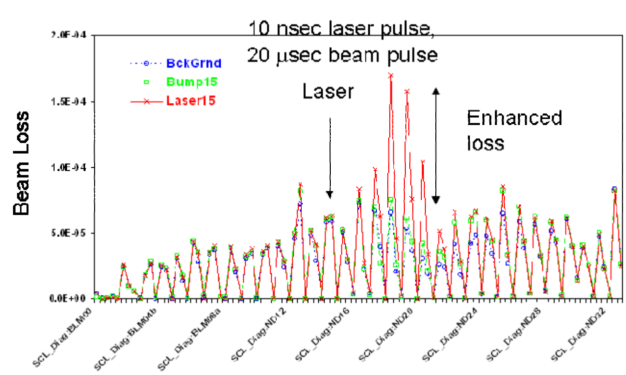

Figure 6: Beam Loss in the SCL with (red) and without (green) a diagnostic laser on, used as a method to calibrate the loss signal to a know amount of beam.

Wide dynamic range diagnostics are needed to understand the beam distributions to this level and are a focus of attention. At present the loss monitors are the primary diagnostic used in measuring beam loss at these small fractional levels.

Worker Dose

The main motivation for reducing beam loss is to minimize worker dose rates accumulated during maintenance. Figure 7 shows the annual worker dose for the major maintenance periods following SNS run-cycles. Also indicated is the integrated beam power delivered over each of the run-cycles. The integrated beam power delivered in the run-cycles has increased a factor of 20, whereas the collective dose has only increased by about a factor of six. Part of the collective dose increase is due to an increase in the amount of work done during the maintenance cycles. Also shown is the total dose received per hour worked, which has only increased a factor of two over the entire power ramp-up period. This is in part due to the less than linear increase in beam loss with beam power and also because most of the accelerator facility is relatively loss free. The collective worker dose in Fig. 7 is still less than other high power proton facilities [7].

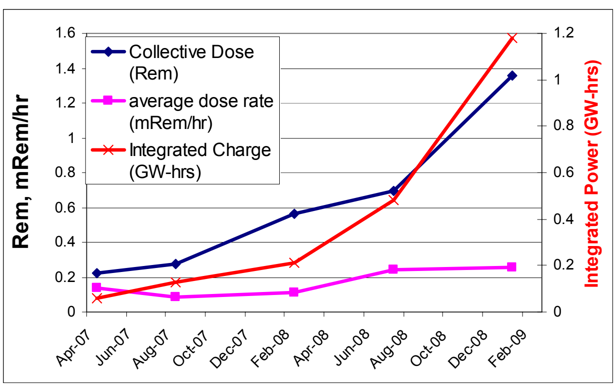

Figure 7: Worker dose accumulation during maintenance periods following major run cycles, along with the integrated power delivered during the run-cycle.

AVAILABILITY

Beam availability (= beam on time / promised beam on time) is one of the most important metrics for neutron scattering users. Many experiments last only a few days, and poor availability can be catastrophic for the users present during major down times. Fig. 8 shows the SNS beam availability since the start of operations. The availability goals were 75% and 80% for FY 2007 and FY 2008 respectively. This metric has proved more difficult to attain than the beam power level, as seen in Fig. 7. A 90% availability goal is aimed for.

Attaining high availability is a common issue when starting up a new facility using new technologies. For example in SNS the High Voltage Convertor Modulators (HVCM) are first-of-a-kind applications of solid state technology for powering high power RF. Starting in the summer of 2008, the planned power ramp was scaled back in an effort to increase beam availability. At the present time the beam power is equipment limited (not beam loss limited), primarily driven by concerns over availability. The rapid power ramp-up over the first two years helped illuminate weak components relatively soon, thus allowing mitigation efforts to start early.

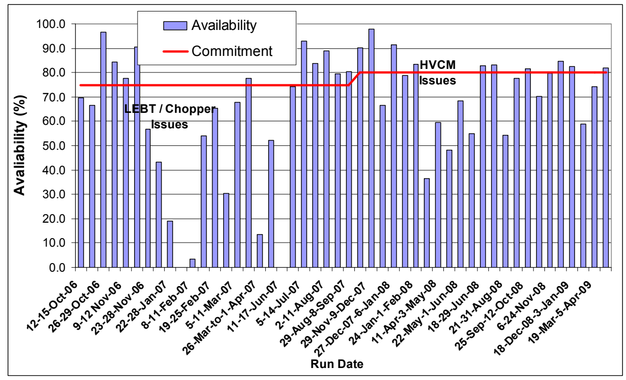

Figure 8: Beam availability (= actual on time / promised on time) since the start of beam operations at SNS.

MACHINE PROTECTION

Machine protection is a critical concern with high power operation. The beam loss monitoring system is a major component of this system [8]. There are two components to the SNS beam loss management: 1) a fast hardware trip (within 10 μsec) on input from a single elevated loss pulse, and 2) a slower trip due to elevated loss over a 10 sec software average. The first type of trip protects equipment from direct damage from the beam, and the second type trip protects equipment from undue longer term activation.

Also care is taken to qualify the position of the beam on the Target center, as well as the waste beam components associated with un-stripped beam at the Ring injection dump. Initial positioning setup is done using upstream position measurements and model extrapolations to the Target, but final steering is done using thermocouples near the Target and near the beam dump. Likewise during setup profile measurements are made to ensure the peak power density is within acceptable limits, and a Harp is constantly in the beam ~10 m upstream of the Target to monitor the power density. Once the beam is qualified in the tune-up stage, errant beam control mechanisms apply small tolerances on the steering and focusing elements leading to the Target to prevent over-focusing the beam or mis-steering. The qualification of the beam densities and positions on the Targets and dump constitute a large part of the final beam tune-up for beam operations.

FUTURE CONCERNS

Although the power ramp-up to date has been remarkably smooth, there are a number of areas of concern as we push beyond the 1 MW power level. One critical area is the stripper foil lifetime. Fig. 9 shows an image of the primary stripper foil under 850 kW conditions. All the light is from the glowing foil, and the bottom left hand corner of the foil has curled (corner not visible in the image). The physical changes to the foil are happening faster as the power level increases, and one recent foil was observed to “flutter” at 6 Hz. There is uncertainty in the foil lifetimes and R&D programs are ongoing for foil development [9], and laser stripping development [10,11] as a possible alternative to foil stripping.

Other concerns are collective effects and stability at the record beam intensities being stored in the SNS Ring (present beam operations use ~0.97×10^{14} ppp). Figure 10 shows the growth in the vertical difference signal observed in the SNS Ring during recent beam operations. There is an exponential growth near the last ~80 µsec (out of a total 670 µsec accumulation). Although this particular case does not appear to cause beam loss, it could be the onset of the e-p instability. Efforts are ongoing to prepare a broad-band damper system to mitigate instabilities [12]

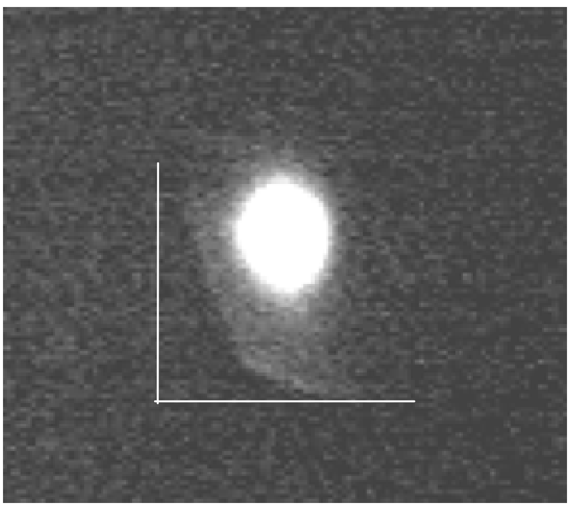

Figure 9: Image of the SNS Stripper foil under 860 kW beam operations with an outline inserted indicating the original corner position.

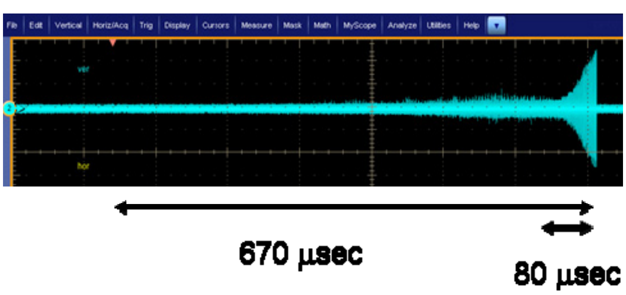

Figure 10: Vertical difference signal in the Ring indicating possible e-p activity near the last 80 µsec of a 670 µsec beam accumulation during neutron production.

SUMMARY

The SNS has experienced a rapid increase in the operational beam power since the start of neutron production operations 2.5 years ago. Production powers are approaching 1 MW, with 865 kW attained to date. Beam loss, while always a concern at these power levels, is largely within the expected range and is not limiting beam power. Beam availability is more problematic and is a focus of attention. Despite the rapid ramp-up in beam power, there are concerns regarding further power increases. Collective beam effects in the stored beam are becoming important and equipment survivability may become a limitation at some point.

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