HIGH INTENSITY CHALLENGES AT THE SPALLATION NEUTRON SOURCE*

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Abstract

The Spallation Neutron Source (SNS) has ramped up the operational power level from a few kW to over 500 kW since initial operations nearly two years ago. As SNS approaches the design operating level of 1.44 MW, high intensity effects are encountered. Beam loss is the primary concern at the present time. Other high intensity issues of concern include foil survival, collective effects and machine protection.

INTRODUCTION

The SNS is a short pulse (µsec) accelerator driven Spallation Neutron Source. It is designed to provide short pulses of 1 GeV protons (1.5x1014 ppp) at 60 Hz. Acceleration is provided entirely by a linac, composed of copper structures up to 186 MeV and superconducting cavities beyond. The beam is compressed from a 1 msec linac pulse to the 1 µsec pulse on the Target with an accumulator ring. Initial beam commissioning was completed in April of 2006 and initial neutron production began in October 2006. Since the initial beam operations, the beam power has been increased from a few kW to over 500 kW, as indicated in Figure 1. Table 1 shows high level beam parameters achieved throughout this period.

Apart from equipment issues, the primary challenge throughout the power ramp-up has been reducing beam loss. Many of the issues faced to date are described in references [1-5], and here we concentrate on high intensity issues presently of concern. For the linac there is an unexplained beam loss in the Superconducting linac section. In the Ring foil survivability is a concern as well as the potential for e-p driven beam instabilities. In all areas of the accelerator a concern is measuring beam loss and being able to model local beam effects at the level of 1 part in 10^5 to 10^6 of the beam.

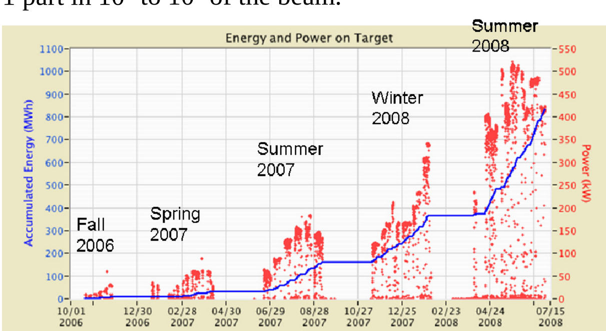

Fig. 1. The SNS power ramp-up history through July 2008.

Table 1: SNS High level beam parameters to date

	Design	Best ever, not simultaneous	Highest power run, simultaneous
Pulse Length (µSec)	1000	1000	600
Beam Energy (MeV)	1000	1010	890
Peak Accelerated Current (mA)	38	40	32
<Accelerated Current> (mA)	26	22	17
Repetition Rate (Hz)	60	60	60
Beam Power (kW)	1440	520	540

HIGH INTENSITY CHALLENGES

Linac Beam Loss

During initial operation of the linac at powers below about 50 kW, no indication of measureable beam loss was evident. As the power increased, residual activation levels began to increase, and subsequent movement of loss monitors to be quite close to the beam pipe revealed beam loss. Figure 2 shows some characteristic residual activation levels in the beginning of the Superconducting Linac (SCL), 1 day after shutdown. The source of this beam loss is not well understood at present. Based on the measured residual activation levels and rule-of-thumb scaling for 304 stainless steel, the loss appears to be less than 1 W/m, or about 2 parts in 10^6 loss per SCL warm section. This is in close agreement with estimates based on Beam Loss Monitor (BLM) calibrations from controlled spills of small amounts of beam [6]. Given that there are 32 warm sections in the SCL, this represents < 10^{-4} total beam loss in the SCL. These losses are sensitive to the warm linac RF setup, so the longitudinal plane is a suspect, and has been an area of focus. Figure 3 shows an example of measuring the SCL longitudinal acceptance near its entrance, using a newly developed technique [7]. The measured acceptance is similar to that predicted by models, indicating that the SCL RF setup is as expected. The source of the SCL beam loss is at present unexplained: improved transverse matching does not reduce the beam loss, and increasing the longitudinal acceptance in the SCL does not reduce the beam loss.

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This example of beam loss at a small fractional level highlights the need to a) to have the ability to model beam loss to the level of 10^{-4} to10^{-6} in order to understand the beam loss mechanisms, and b) devise ways to measure fractional beam at these small levels to verify the models. At present accurate resolution at this level is a challenge for both simulation and measurement.

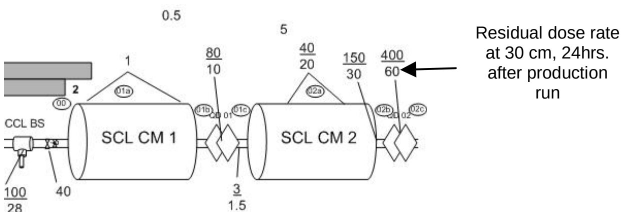


Fig. 2. Residual activation levels after a 520 kW run, at contact (numerator) and at 30 cm (denominator) near the beginning of the SNS SCL.

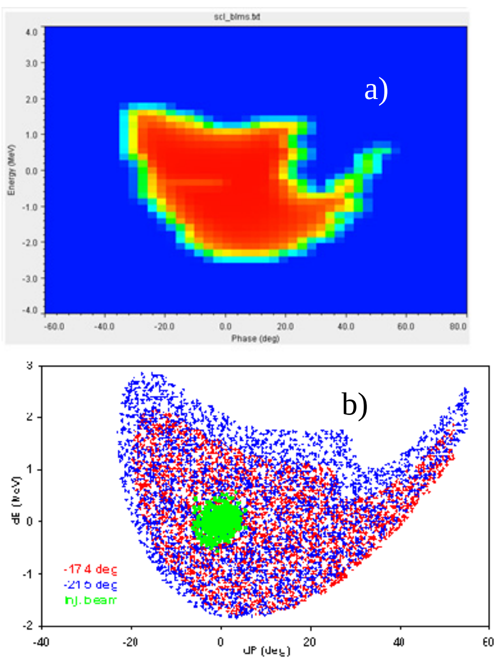


Fig. 3. SCL entrance longitudinal acceptance from (a) measurement and (b) model predictions for two RF configurations. The green spot in (b) is an artificially enhanced representation of the expected SCL input beam emittance.

Ring Foil Heating

The stripping foil at Ring injection is a crucial component for maintaining a controlled injection painting scheme. As we increase the charge injected per pulse at 60 Hz, the foil heating increases and while uncertain sublimation temperatures may be reached as 2 MW is approached [8]. Detrimental changes in the material properties are possible even before the sublimation temperature is reached. Given the importance of the foil integrity and the uncertainty in the foil lifetimes at high power operation, an R&D effort is underway at SNS for nano-crystalline diamond foil development [9]. To date foil lifetime and degradation has not been an issue. Figure 4 shows an SNS foil which is supported from only the top. Also shown is an enlargement of the characteristic corrugations around the perimeter which provide support against curling. Figure 5 shows an image of the foil during production, with the light source being entirely from the glowing foil itself. The injected linac beam spot and the area heated by additional traversals from ring circulating beam are both visible.

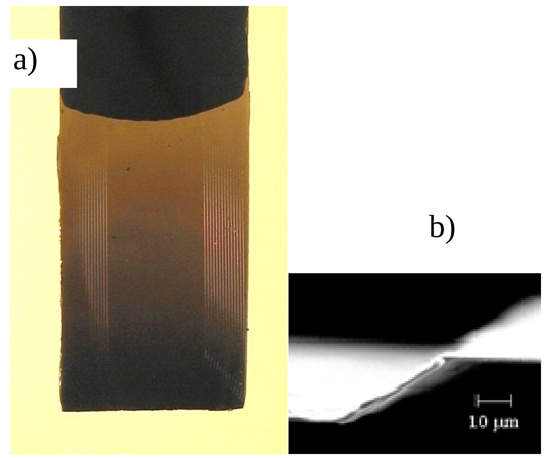


Fig. 4. a) An SNS nano crystalline foil and b) an enlargement of the corrugated section around the periphery.

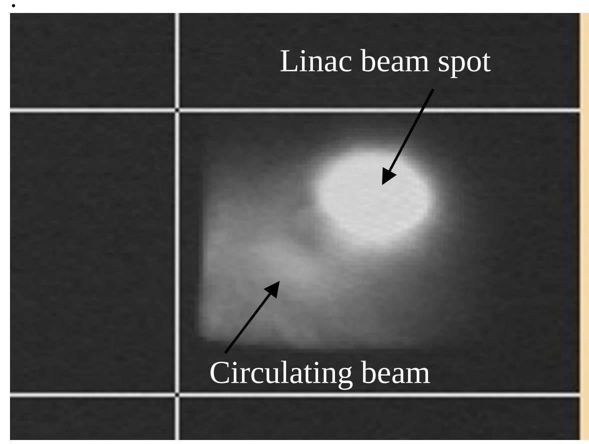


Fig. 5. Image of the SNS foil during production indicating areas of heating from the linac beam spot and additional heating from the circulating injected beam.

Ideally one would prefer to not use a stripping foil. In addition to foil survivability concerns there is an inherent beam loss associated with scatting during the beam foil interactions. Earlier studies at SNS demonstrated proof-of-principle verification of a laser stripping concept [10], Demonstration of this concept is presently being pursued at an intermediate step of ~ 1 μsec time scale [11].

Ring Collective Effects

At high power operation it is important to understand fractional beam loss at levels below 10^{-3}. For high intensity beams this means collective effects such as space charge are important. Figure 6 shows an example of multi-particle beam tracking in the SNS Ring with the ORBIT code [12]. This particular case involves transport in the injection region in a chicane, in which the beam centroid is off axis by design, and close to the aperture. We experimentally observe a local beam loss on the order of < 1 W based on residual activation (which represents < 2×10^{-6} of the beam). The figure indicates the importance of space charge effects when modeling beam transport, especially when trying to understand quite small fractional beam loss levels such as in this case.

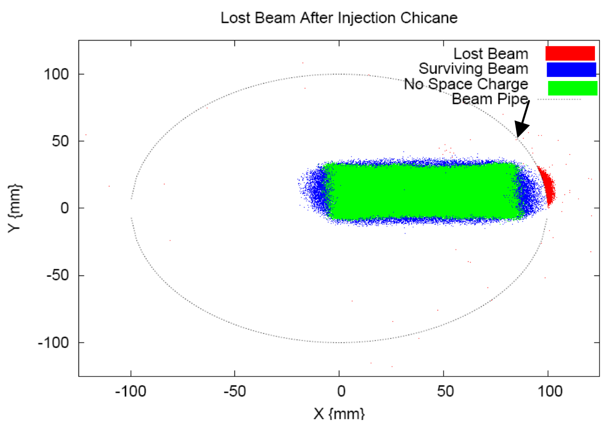


Fig. 6. Beam transport simulations in the SNS Ring Injection region indicating a situation where beam loss is possible if space charge is included (otherwise no beam is lost in the simulation).

Another concern with high intensity operation is avoiding the e-p instability. To date we have no indication that e-p activity leads to beam loss for production conditions. However during beam study periods we have explored higher intensity levels at reduced RF levels and do see high frequency (50-100 MHz) transverse oscillations characteristic of e-p activity [13]. Figure 7 shows evidence of such a case for a beam charge similar to the present production level (10 μC) , but stored for an additional 500 turns after accumulation and with reduced RF in the Ring. Sometimes this "instability" signature is observed, for small amplitude oscillations, although it does not grow without bound for the limited storage times available at SNS, and does not contribute to beam loss.

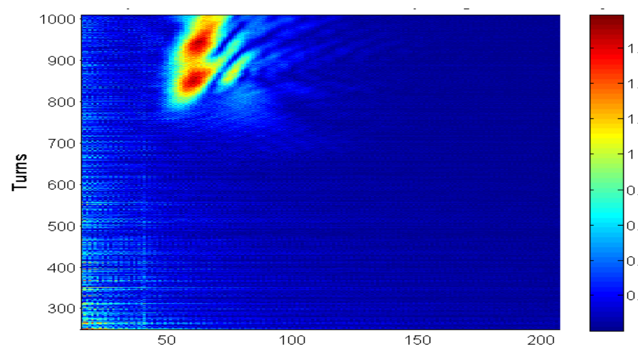
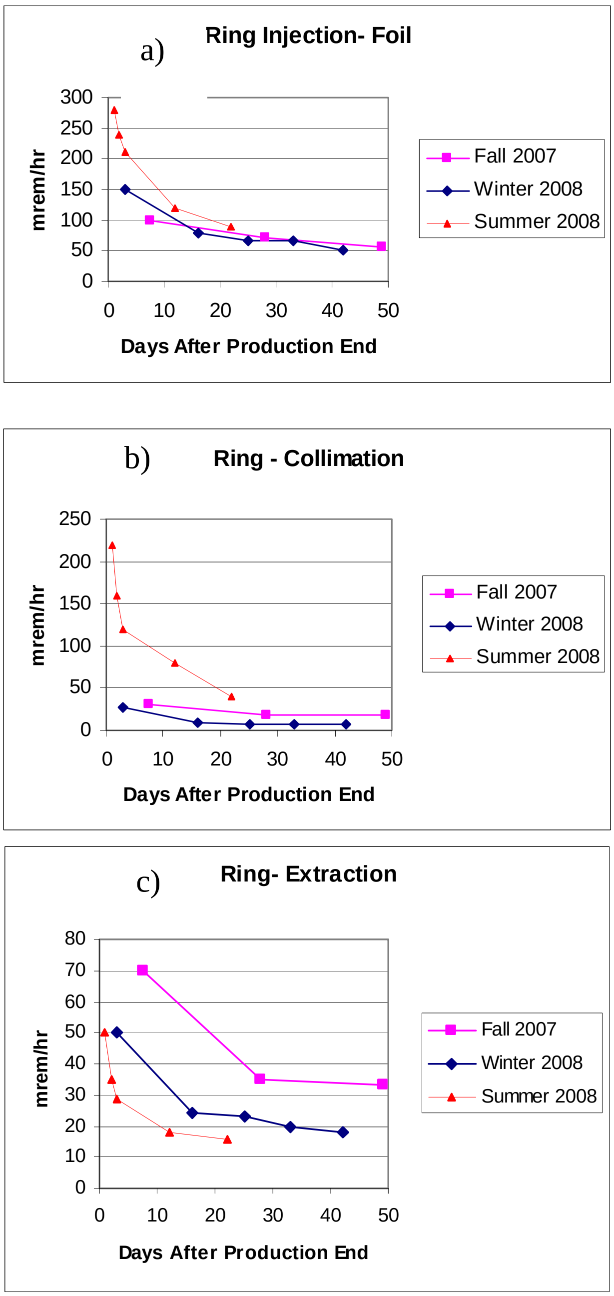


Fig. 7. Frequency of the beam vertical oscillation (horizontal axis in MHz) vs. time (vertical axis) in Ring turns (~ 1 μsec/turn), for a 10 μC beam accumulation and additional storage of 500 turns

High Power Concerns

As SNS has increased the operational power to many 100's of kW, protection of the machine hardware becomes more of a concern. These concerns include ensuring that the beam is centered on the Target, ensuring that the beam size does not exceed the Target size, ensuring that the peak power density on the Target is within an acceptable level, and ensuring the waste beams from both partially stripped and un-stripped beam at the Ring injection are centered on the injection dump. Fulfilling these constraints becomes more important and more of a challenge as the beam power increases, and multiple systems have been employed to verify these conditions are met. In addition to monitoring beam positions on target derived from Beam Position Monitor readings and beam transport analysis, thermocouples are used to ensure symmetric distribution of power at the target and dump periphery (hence centered beam). Interlocks are employed on loss monitor levels and on magnet setpoints after beam centering and power density limits checks are completed. We measure the peak beam intensity upstream of the Target with a wire scanners and a Harp and use an envelope model to propagate the beam size to the Target to ensure peak power density limits are met.

Another high intensity operational concern is the residual activation buildup of the machine. The SNS accelerator is designed to be a hands-on maintenance machine and the worker dose is a major concern for a high power proton machine. Generally the SNS has maintained a modest residual activation of the machine for the power levels we operate at [6]. Figure 8 shows the residual activation levels in selected locations in the Ring vs. time after shutdown for the last 3 major runs shown in Figure 1. The peak power for these runs are: 180 kW for Fall 2007, 300 kW for Winter 2008 and 500 kW for Summer 2008. The highest activation area in the accelerator is at the Ring Injection (Fig. 8a). There is some increase in this activation level immediately after the end of production for the more recent high power run cycle but not commensurate with the power level increases over this period. Also, after about one month the levels have decayed to similar levels despite the power ramp-up. Improved beam tuning accounts for some of the less than linear increase in residual activation with beam power. Figure 8b indicates a sharp increase in collimator activation recently as we began using the Ring collimation system, and Figure 8c indicates a decrease in extraction activation as linac chopping quality has improved.



Fig, 8. Decay of the residual activation (measured at 30 cm) after the end of the last three major neutron production runs for a) the Ring injection area, b) the Ring collimation area, and c) the Ring extraction area.

SUMMARY

Over the past two years the SNS has experienced a period of rapid increase in beam power. Today operation at 0.5 MW is routine. At these high power levels beam loss is a primary consideration. To meet the design requirements of less than 1 W/m of uncontrolled beam loss, this requires understanding beam effects on the level of 10^{-4} to 10^{-6}. This is challenging both from modeling and measurement perspectives. Other high intensity concerns are stripping foil survivability, potential collective instabilities, machine protection and maintaining the hands on maintenance capability. While of concern, to date none of these issues have limited the operational beam power.

ACKNOWLEDGEMENTS

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