SNS OPERATIONL EXPERIENCE: EXPECTATIONS AND REALITIES*

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Abstract

The Spallation Neutron Source (SNS) accelerator [1] has operated at 1 MW for about one year, as a driver for a pulsed neutron source. This represents the highest pulsed power operational level for a proton accelerator. This paper discusses the experiences encountered in the four year operational period, compared to expectations. The superconducting linac has shown some surprises, yet is capable of delivering the required beam to the storage Ring. On the other hand the Ring is operated close to expectations.

EXPECTATIONS

During the design period, challenges were recognized associated with increasing the existing pulsed beam power capability by nearly an order of magnitude. Inherent with high-pulsed beam power is high beam intensity. Space charge effects were a concern for both the linac and the ring. Charge exchange injection in the ring was recognized as a challenge, with foil survivability a major concern. In the end, beam loss was expected to be the final limit to the attainable operational power.

THE SNS POWER RAMPUP

A quite aggressive internal power ramp-up schedule was initially proposed [2]. While the attained power level did not completely meet this initial plan, sponsor commitments were met and 1 MW achieved within three years of initial operation. Figure 1a shows the realized beam power compared to the initial expectation (more detail on the power rampup history is given in Ref [3]). From the neutron user perspective, the beam availability is at least as important as beam power (see Fig. 1b). The availability goal for the last year was 85% (which was met), and approaches 90% over the next two years. SNS has approached the availability typical for mature high power accelerators for spallation sources. A more detailed history of the power ramp-up is shown in Fig. 2, with annotations indicating some periods where operational power was limited by equipment issues. Presently the operational power is limited by availability concerns. The beam pulse length is about 15% short of the design goal, beam energy is 7% low, and the average beam current is about 5% lower than the design. Increasing these parameters to their design goal will be done slowly, to mitigate any adverse impact on the availability of beam to the neutron scattering user program.

The aggressive initial power ramp-up schedule had an unanticipated benefit. In the early ramp-up years, more time was dedicated to accelerator studies, as the neutron user program was just evolving. Making fast progress in the increase of accelerator beam power was crucial to reaching one MW within 3-4 years. Later, as more neutron user program matured, less time was available for accelerator development and importantly, fewer risks could be taken in beam operation.

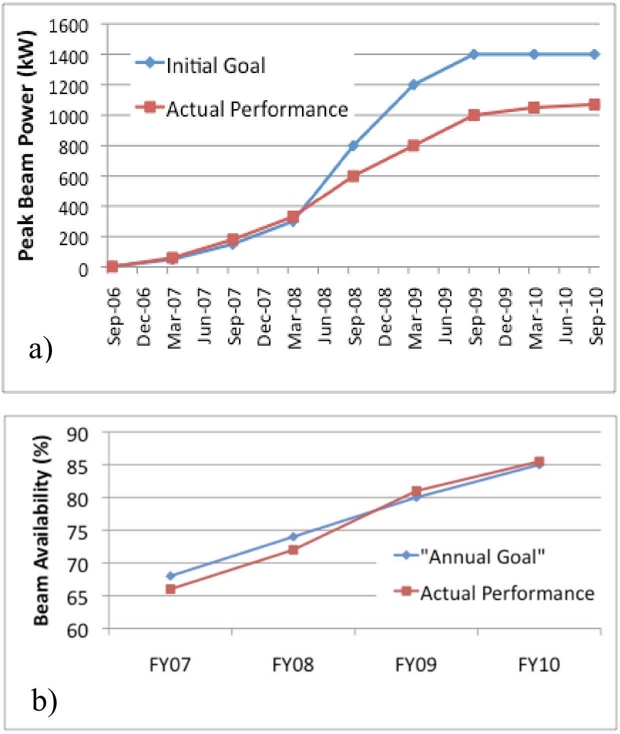

Figure 1: Expectations vs actual a) neutron production beam power, and b) neutron production availability.

THE LINAC

The SNS linac is comprised of a traditional copper accelerator structure to 186 MeV and a superconducting linac (SCL) RF structure to 1 GeV [1]. SNS is the first accelerator to employ superconducting RF for a pulsed beam, for a high-energy hadron beam, as well as for a high power hadron beam. A number of technical issues were encountered [4], but the implications on beam dynamics are emphasized here.

SCL Experience

A major unforeseen SCL linac experience was the high degree of variability in cavity-to-cavity performance. Figure 3 shows the present cavity performance relative to the expected design values (initial operational experience had even larger variations). Not only is the cavity gradient capability spread higher than the expected ~ ±10% level; there are systematic differences in the average cavity family performance relative to expectations (the medium

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beta cavities are over-performing expectations and the high beta cavities are under-performing expectations). Despite this variation, the SCL has proved to be quite flexible and we are easily able to adapt to varying SCL performance [5]. Providing acceleration with many independent SCL cavities is the basis for this flexibility. A model based difference scheme has been developed to quickly recover from cavity gradient performance changes. Also, use of this scaling method has been employed to perform "slices" of the longitudinal acceptance using the beam to measure the beam/RF relationship in un-anticipated ways. The reduced level of smooth RF focusing arising from the un-equal cavity gradient distribution does not appear to be a significant beam loss driver.

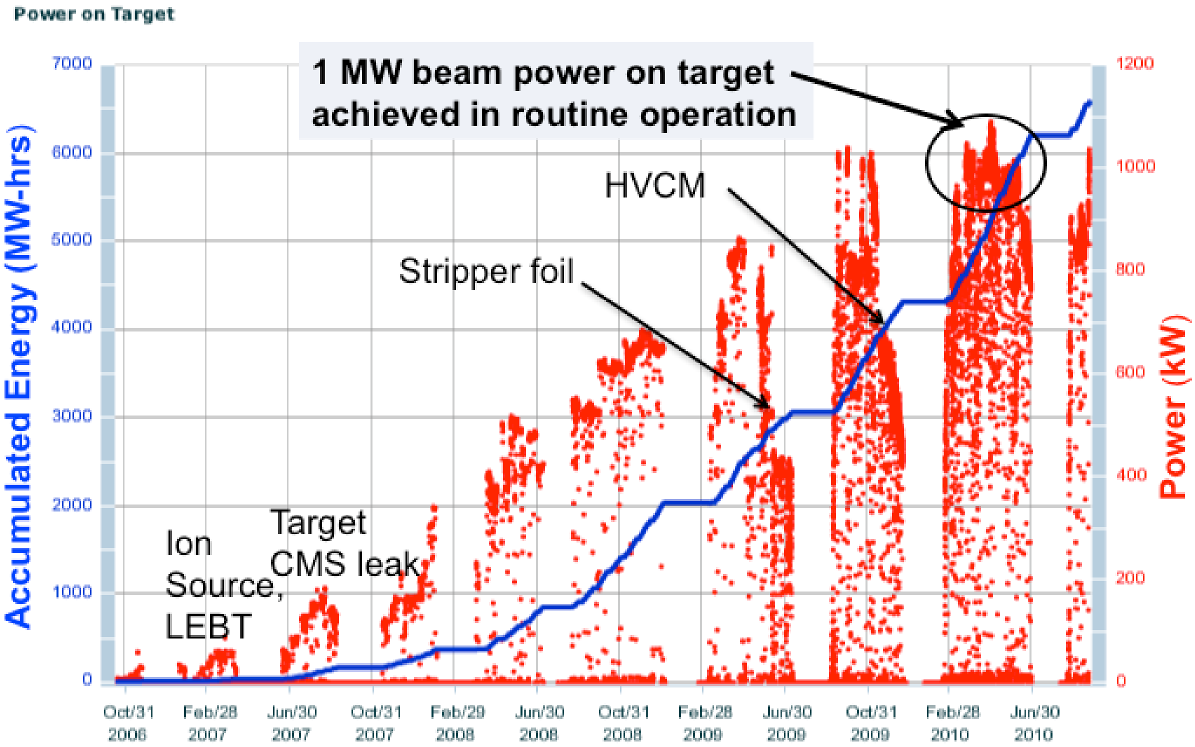

Figure 2: History of the SNS power ramp-up to 1 MW operation, with annotations for some equipment set-back periods.

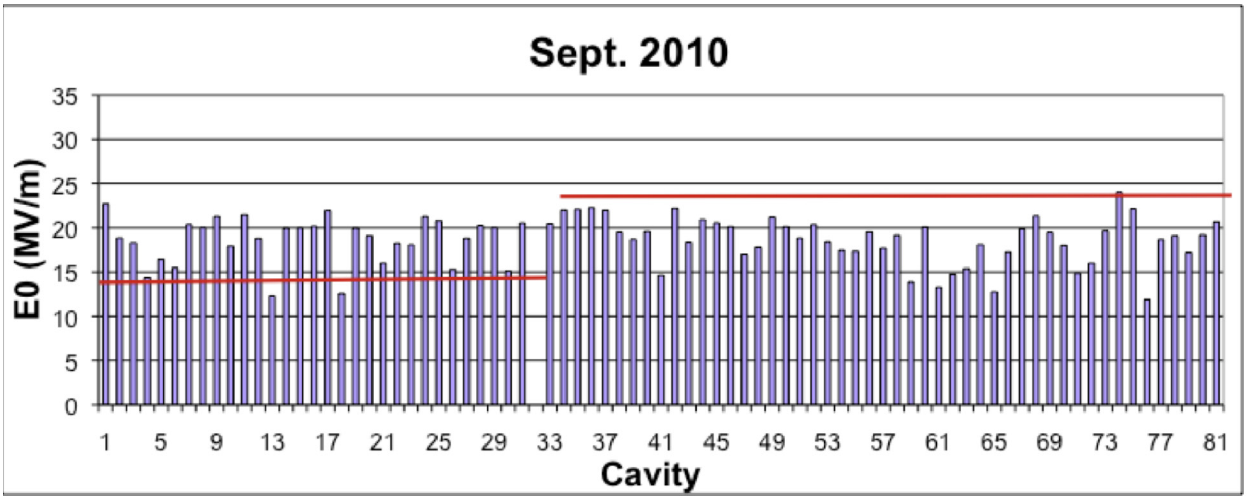

Figure 3: SCL cavity gradient for the medium beta family cavities (1-33) and high beta cavities (34-81). The red lines indicate the expected family performance level.

Linac Transverse Lattice

The copper linac quadrupoles are operated close to design values. However the SCL quadrupole strength has been reduced in an effort to reduce beam loss, as indicated in Fig. 4. Figure 4 shows the present operational quadrupole strength compared to the design values. Beam loss is reduced by almost 50% with the lower focusing strength mode. The drastic reduction in focusing strength results in much reduced phase advance (a 20-30 degree reduction) and increased RMS beam size (by almost 50%). This is one of the largest deviations from the design expectations for the SNS accelerator. The reduced field operation was largely an empirically motivated effort to reduce losses. Some possible explanations are discussed below.

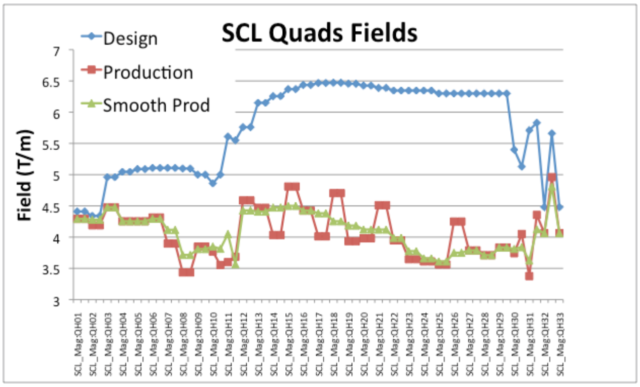

Figure 4: SCL transverse focusing strengths for the design (blue) and minimum loss (red) setups. The green curve is smoothed version of the minimum loss case, with slightly higher losses.

Linac Beam Loss Experience

Beam dynamics simulations in the SNS design indicated no beam loss in the SCL. However, this has not been the experience. Figure 5 shows levels of measured residual activation in the warm sections between the SCL cryomodules. Activation data shown here is at 30 cm, typically 1-2 days after a neutron production run of 3-4 weeks. Beam loss monitor calibration experiments indicate a few x 10^{-5} of the beam are lost in the SCL. Since late 2008, the linac activation levels have not increased noticeably (see Fig. 5), despite large increases in power and operational hours. This "breakpoint" corresponds to the time when reduced focusing strength operation was adopted in the SNS (see above). The copper linac activation has not proved to be problematic.

While not completely understood, there are theories on the source of beam loss. One recent explanation is the possibility of "Intra-Beam-Stripping" [6], in which the Coulomb interactions within the bunch strip the outermost H^- electron. Increasing the beam size (with reduced focusing strength) deceases the stripping probability. Another possible beam loss mechanism is loss of beam from the longitudinal acceptance, resulting in a low energy beam transported down the linac. Reduced field strength throughout the linac reduces the level of transverse miss-match for this low-energy beam and may reduce beam loss from this effect

The linac beam loss, while not expected, has not limited the power ramp-up, as the resultant activation levels are tolerable. However, measuring and understanding the extremely small beam fractions associated with this beam loss are more difficult than expected, and much progress has been made with empirical tuning.

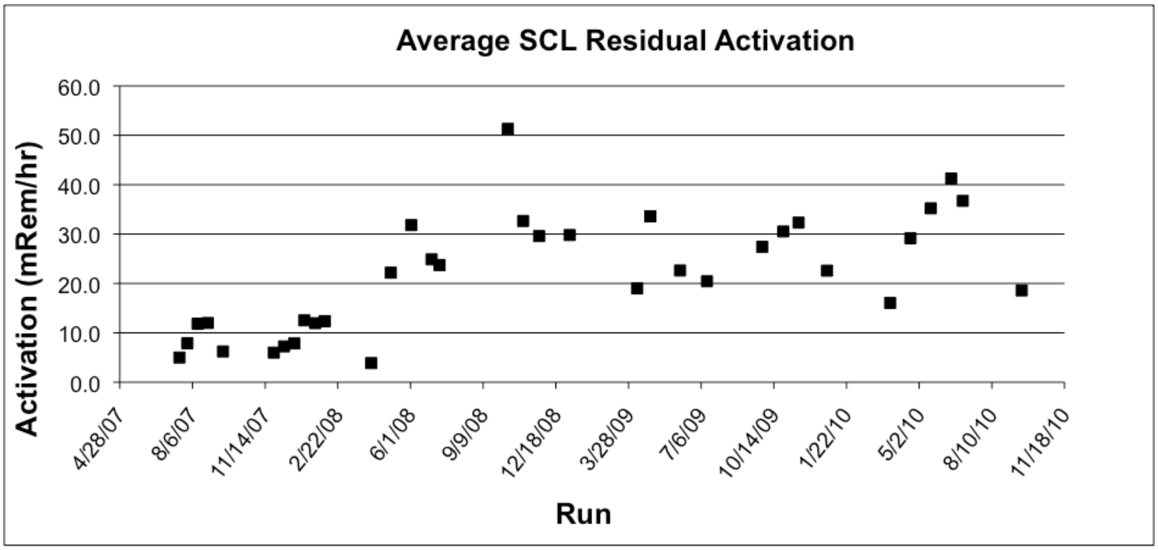

Figure 5: Residual activation history in the SCL warm sections between cryomodules. Values are at 30 cm 1-2 days after production and a few hours after beam studies.

Scraping

In the design, beam collimation was provided in the HEBT (transport line between the linac ad the Ring), as a means for cleaning halo that may have developed during acceleration, before injection into the Ring. No provision was made to scrape the low energy beam exiting the source or RFQ. We have added scrapers in the MEBT transport section between the RFQ and copper linac structure. This has proved effective at reducing loss in the linac and at the Ring Injection area, but the effectiveness varies from source to source.

THE SNS RING

The SNS utilizes a storage ring to accumulate about 1000 injection turns over ~ 1 ms, and provide a short 1 μs pulse to the target via fast extraction (single turn). Present operation of the SNS ring involves storage of $1.1\text{x}10^{14}$ ppp, a world record. Concerns with attaining this intensity in the design stage included the injection through a stripper foil, space charge effects leading to beam loss, and beam stability (primarily from electron cloud effects), and contamination of a chopped “extraction gap”. Clean extraction of the beam from the ring has not been a problem.

Ring Activation

Figure 6 shows the history of Ring injection residual activation. The measurements are in the area directly downstream of the injection foil, the highest activation of any point in the accelerator chain. Activation is increasing roughly proportional to the beam power, and is in rough agreement with predictions during the design stage. Other parts of the Ring and transport line have much lower activation and are not a major concern.

Ring Beam Dynamics

As opposed to the linac operation, the Ring is operated close to the design lattice. The design tune is used, with no observable resonance driven beam loss. Nominal correlated injection painting schemes are also used and measured profiles are close to expectations. Correlated injection refers to the simultaneously painting the horizontal and vertical closed orbit away from the foil together, throughout injection.

Foil Concerns

Foil lifetime was a major concern in the design of the SNS Ring. Consideration was given to the transport of the convoy H^- electrons, and an effort undertaken to develop foil materials to withstand the high temperatures expected with MW operation [7]. Foil evaporation was a primary concern in the design period. Foil conditioning is important, and at present operational powers, neither evaporation nor excessive foil shape deformation are limitations. However, damage to the mounting brackets and beam induced foil motion have been more serious issues in the charge exchange process to date [8].

Beam Stability

Many preventive measures were taken in the design period to address the possibility of the electron-proton instability in the SNS Ring. These included TiN coating of vacuum chambers, solenoid windings on the collimation straight chambers, and provision to bias the BPM electrodes to enable electron collection. While we have seen evidence of this instability under certain conditions (e.g. reduced applied RF field), it is not an impediment to operation [9]. Stable beam has been demonstrated up to $1.5\text{x}10^{14}$ ppp. However, a damper system is under development as a precautionary measure [10].

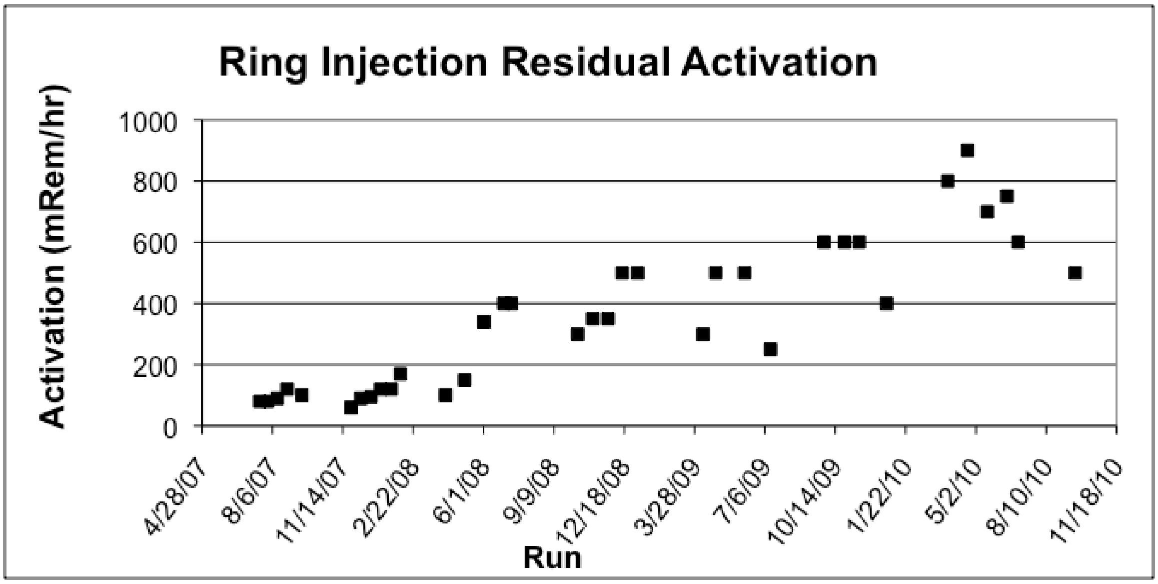

Figure 6: Residual activation history in the ring injection area directly downstream of the stripper foil. Values are at 30 cm, 1-2 days after production and a few hours after beam studies.

Target Protection

Safely handling a MW beam requires significant attention. Due to the short pulse nature of the beam power delivery, cavitation induced damage concerns exacerbated the concerns for target protection. Beam instrumentation was provided upstream of the target to provide information for beam position and size, which is extrapolated to the target by a beam model. After the beam is set up to satisfy target constraints, protection systems monitor components that could affect the beam size and or position on the target. These protective measures have required more effort to implement and to ensure proper setup than originally expected. Direct measurement of beam properties on the target can reduce uncertainty and setup time. A Target Imaging System (TIS) that monitors the response of a phosphor coating directly on the target is being implemented towards this goal [11]. Figure 7 shows an image of the SNS beam on the target from this system. Also, direct imaging of the ring injection waste beams at the injection dump is under consideration for similar reasons.

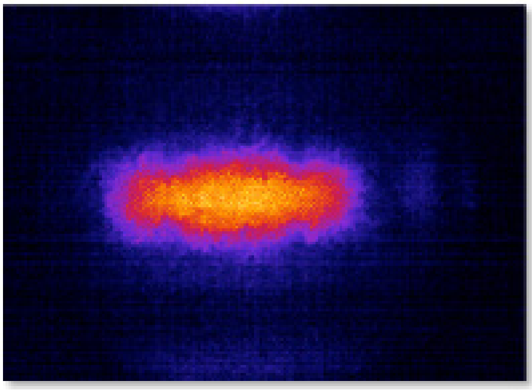

Figure 7. Image of the beam on the SNS target from the new target imaging system.

SUMMARY

Operating a pulsed MW beam has long been a goal of the accelerator community. The power rampup period of SNS towards 1 MW represents the entry into a new regime of high power proton accelerators, and is a tribute to the lessons learned from many predecessor devices. In general, the SNS accelerator has worked well and met or exceeded expectations. One MW operation at high availability and approaching 5000 hours a year is now achieved. In the linac a low level of unexpected beam loss occurs, but the operational flexibility of a superconducting linac has exceeded expectations. The Ring operates in large measure similar to expectations.

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