STATUS OF THE SNS POWER RAMP UP*

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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. Since formal operations began in 2006, the beam power has been steadily increasing toward the design goal of 1.4 MW. In September 2009 the power surpassed 1 MW for the first time, and operation at the 1 MW level is now routine. The status of the beam power ramp-up program and present operational limitations will be described.

INTRODUCTION

The SNS accelerator complex [1] comprises two main parts – the linac and the accumulator ring. The linac, with a design output beam power of 1.5 MW, comprises an H^- ion source, an RFQ, a DTL, a CCL, and finally an SCL, with design output beam energies of 0.065, 2.5, 87, 186, and 1000 MeV. Immediately following the charge-exchange injection and accumulation in the Ring of the 1-ms-long pulses from the linac, the now 700-ns-long beam pulses are single-turn-extracted and delivered to a mercury neutron spallation target 60 times per second.

On September 18, 2009, the SNS reached, for the first time, a beam power of 1 MW. Since that time our focus has been on delivering this level of power routinely and with high availability. In this paper we will discuss the overall performance of the accelerator facility, and also some of the challenges we face in continuing the power ramp up while operating with high availability and reliability.

PERFORMANCE

A comparison of high-level design vs. achieved beam parameters is shown in Table 1. Not shown in this table are some design parameters that have been met only at low repetition rates, e.g. the beam energy (1.01 GeV) and the ring bunch intensity (1.55×10^{14} protons per pulse). The beam availability to date for the present fiscal year beginning October 2009 is 86%. A plot of the beam power vs. time, starting from the beginning of formal operations in October 2006, is shown in Fig. 1.

Beam loss

At high intensity accelerator facilities, such as the SNS, beam loss is always a key issue. A large fraction of the accelerator physics group's effort is focussed on reducing and managing these losses. To date the beam loss is mostly in line with expectations and it has not been a beam-power-limiting factor.

A recent history of the beam loss per unit beam charge in the superconducting linac is shown in Fig. 2. The data show significant improvements from December 2008 to December 2009, primarily due to a new, empirically determined, set of quadrupole magnet gradients, which are now about 20% to 35% lower than the original design gradients. We believe the lower losses can be explained by a combination H^- to H^0 stripping by intrabeam scattering [2]; higher order multipole components in the quadrupole magnets, which cause an increase in the beam halo; longitudinal halo beyond the acceptance; and possibly other mechanisms [3]. The activation levels in the linac, approximately 24 to 48 hours after high power operations, are typically 0.01 to 0.8 mSv/h at 30 cm, depending on the location. The highest activation levels are found at the end of the CCL and the end of the SCL.

A history of the beam loss in the Ring is shown in Fig. 3. In this case the improvement in the loss per Coulomb has been relatively minor. Most of the beam loss occurs just downstream of the primary stripper foil, as expected. Other high loss areas are the collimator section and the extraction section. Activation levels near the stripper foil, approximately 24 to 48 hours after high power operations, are up to 8 mSv/h at 30 cm. Beam losses in the transport lines from the linac to the ring, and from the ring to the target, are low, with activation levels typically less than 0.05 mSv/h at 30 cm, with a few hot spots up to 0.5 mSv/h at 30 cm.

Table 1. Design vs. achieved parameters.

	Design	Routine Oper.
Kinetic Energy [GeV]	1.0	0.93
Beam Power [MW]	1.4	1.03
Linac Beam Duty Factor [%]	6.0	5.0
Modulator/rf Duty Factor [%]	8.0	7
Peak Linac Current [mA]	38	42
Average Linac Current [mA]	1.6	1.1
Linac pulse length [msec]	1.0	0.80
Repetition Rate [Hz]	60	60
SRF Cavities	81	80
Ring Accumulation Turns	1060	825
Peak Ring Current [A]	25	18
Ring Bunch Intensity [ppp]	1.5×10^{14}	1.1×10^{14}

Equipment upgrades

Substantial upgrades and improvements have been made to the accelerator in the last year that directly contributed to the increased beam power and improved availability.

The SNS RFQ resonance frequency in controlled by regulating the temperature of the copper structure, and

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sudden changes in the resonance frequency were significantly impacting the beam availability [4]. The cause was determined to be adsorption of hydrogen gas from the ion source, subsequent outgassing caused by beam impingement, and then RF discharge which absorbed a significant fraction of the rf power and caused the structure to heat up and thus affect the resonance. To stabilize the resonance error, an administrative control was placed on the hydrogen flow rate, and a slow feedback loop was added on the rf pulse length.

The rf high voltage converter modulators [5] were (and still are) a significant contributor to down time. Problems with capacitor lifetimes have dominated, but insufficient engineering margins have also led to upgrades or replacements of transformers, filter chokes, resistors, insulators, IGBT circuitry, cabling, and oil pump systems. These upgrades have allowed the modulator to operate at near full duty cycle parameters (825 us beam pulse at 60 Hz) at ever increasing reliability. Additional modifications this summer will allow higher duty cycle operation. However, some issues remain (see later discussion).

Improvements to the ion source [6] have also contributed to the availability improvement. Most importantly the second electrostatic lens was redesigned to be a glue-free assembly with fully shielded insulators. Also the shape and position of the ion converter near the outlet of the H^- source was optimized, and improvements to the high voltage standoffs of the electron dump led to a 15% increase in the RFQ transmission. Since fall of 2009, the 38-mA design requirement can be usually met when the 2 MHz amplifier can deliver the required 50-60 kW without tripping (see later discussion). The 3-week source lifetime design requirement has been extended to 4 weeks without any negative impact so far.

The rf bunching system in the medium energy beam transport was the second-highest contributor to down time in FY09, mostly due to the charging power supplies blowing fuses. The long-term plan is to replace these tube-based amplifiers with solid-state amplifiers, and the expected completion date for this is August 2010. In the mean time, the charging power supplies have been replaced with more reliable units, and the downtime due to the MEBT rf systems has been greatly reduced.

High intensity

No obvious collective beam dynamics effects are seen during operations at 1 MW beam power (1.1×10^{14} protons per pulse). The beam loss per Coulomb is essentially the same as for low power operations.

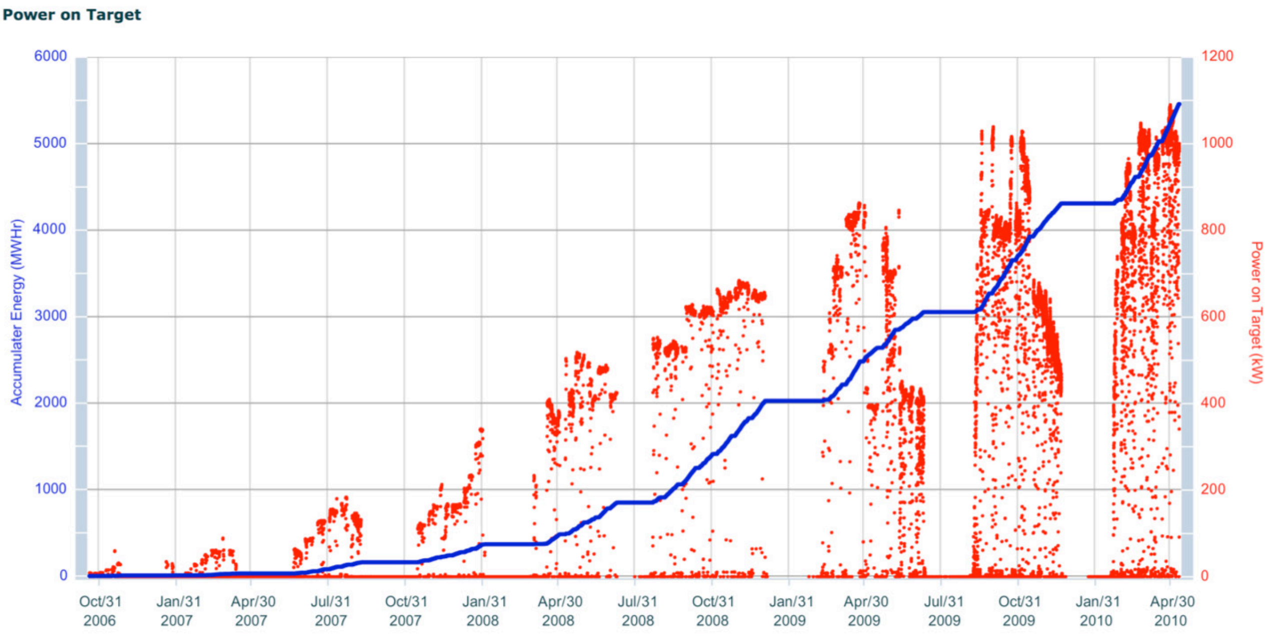

Figure 1: Beam power plot from the beginning of formal operations in October 2006 to the present.

During a high intensity beam study period in July 2009, when the 1.55×10^{14} ppp record was achieved, we were able to achieve a tune with modest beam losses, but this involved running the second harmonic Ring rf system at the maximum value of 20 kV. It is likely that with more time a lower loss tune could have been obtained, close to the loss per Coulomb shown in Fig. 3. More studies are planned to optimize the machine set up for the design intensity of 1.5×10^{14} ppp, and to determine how to best achieve reliable operations at this intensity.

CHALLENGES

Stripper foils

The plot in Fig. 1 shows steady progress in the beam power ramp up until May 3, 2009, when we experienced a rash of failures of the charge-exchange stripper foil system in the ring injection area, after about three weeks at ~840 kW beam power. More failures followed later that day, and the beam power was reduced to 430 kW and then to 400 kW two days later after another failure. A mid-cycle foil change on May 19, using a modified foil bracket, did not cure the problem, and the run cycle was completed at ~400 kW.

The stripper foil failures have been attributed [7] to a combination of convoy electrons stripped from the incoming H^- beam striking the foil bracket; convoy electrons reflected from the electron catcher back up into the beam; and cathode-spot in-vacuum breakdown. Modified foils and mounting brackets were installed prior to the September to December 2009 run cycle, and a single foil lasted for that entire run cycle. We started the present February to June 2010 run cycle with a new foil, and it is still in use as of May 17, 2010.

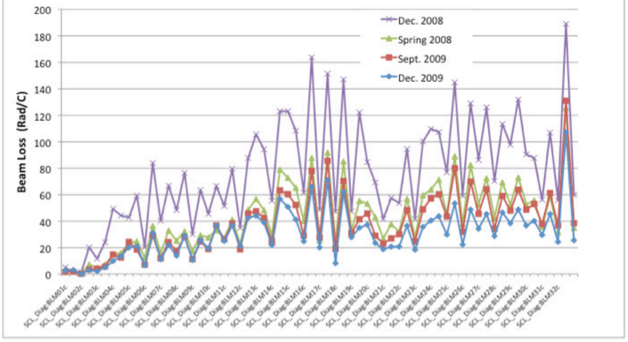

Fig. 2. Beam loss in the SCL, normalized to the beam charge.

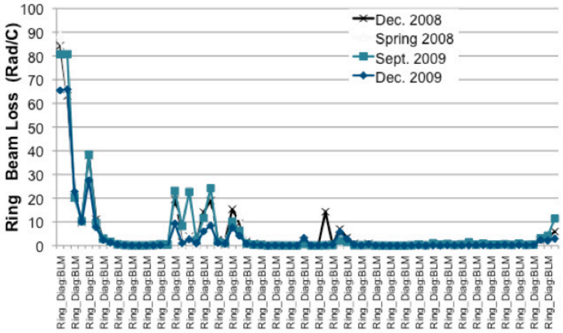

Fig. 3. Beam loss in the Ring, normalized to the beam charge.

Modulators

The plot in Fig. 1 shows a fast ramp to 1 MW beam power at the start of the September to December 2009 run cycle, but then a reduction down to ~670 kW in mid-November, followed by a gradual decrease to ~430 kW at the completion of the run cycle in late December. The first decrease to ~670 kW was due to a reduction in the beam pulse length from 825 to 575 us due to a series of premature failures of 160 kV resonance capacitors inside the warm linac HVCM oil tanks. These capacitors were all replaced with new spares during the scheduled January 2010 outage, which allowed the beam pulse length to be returned to 825 us in February 2010. New, longer-lifetime capacitors will be installed in the summer 2010 scheduled maintenance outage. This and other HVCM upgrades will allow higher beam pulse lengths in September 2010.

Ion source

The gradual decrease to ~430 kW from 670 kW during the last month of the fall 2009 run was caused by lowering the 2 MHz power to the ion source in order to avoid frequent trips of the amplifier at higher powers. Work is now underway to move the 2 MHz rf source to ground potential and to change to a more versatile low level rf control system that will allow the rf power to be varied over the length of the beam pulse. An external antenna ion source is also being developed.

SCL

The design linac output energy is 1.0 GeV, however the typical output energy is about 925 MeV. The lower beam energy is primarily due to high beta cavity gradients that are lower than design values, primarily due to field emission. During the September to December 2009 run cycle we were forced to lower the gradients on two of the SCL cavities due to degradation caused by excessive beam loss. The Machine Protection System has since been improved to lower the beam shut off time, and the gradients were largely restored for these two cavities by conditioning during the January – February 2010 outage.

An in-situ plasma-processing system is envisaged to increase the high-beta cavity gradients, and a spare high-beta cryomodule is now being assembled, with the goal of replacing the worst-performing in-tunnel cryomodule with this spare. These changes should allow the linac to reach the 1.0 GeV design energy.

Ramp to design power

To reach the design beam power of 1.4 MW on target the plan is to increase the beam pulse length to 0.95 ms by increasing the linac rf duty factor (following the modulator upgrades), increasing the beam energy to ~960 MeV by installing the spare cryomodule discussed above, and decreasing the chopped beam fraction by upgrading the low energy beam transport chopper system.

For the long term, upgrades are now in progress to increase the beam energy to 1.3 GeV and to increase the beam current to 42 mA averaged over the macropulse, for a total beam power of 3 MW.

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