STATUS OF THE SPALLATION NEUTRON SOURCE*: MACHINE AND SCIENCE

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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 completion of the construction project in June 2006, attention has focused on ramping up the performance of the SNS accelerator complex to the design parameters, and on neutron scattering instrument commissioning and obtaining early science results. Recent operational history will be presented.

INTRODUCTION

The Spallation Neutron Source (SNS) is a short-pulse neutron scattering facility which was recently completed at Oak Ridge National Laboratory. The SNS construction project was a partnership of six US DOE national laboratories, each of which had responsibility for designing and manufacturing a portion of the facility. At 1.44 MW of proton beam power on target, the SNS will operate at beam powers a factor of 8 beyond that which has been previously achieved [1]. The SNS baseline parameters are summarized in Table 1.

Table 1: SNS Design Parameters

Beam Power on Target	1.44 MW
Beam Energy	1.0 GeV
Linac Beam Macropulse Duty Factor	6.0%
Beam Pulse Length	1.0 msec
Repetition Rate	60 Hz
Chopper Beam-On Duty Factor	68%
Peak macropulse H- current	38 mA
Average Linac H- current	1.6 mA
Ring accumulation time	1060 turns
Ring bunch intensity	$1.6\text{x}10^{14}$
Ring Space-Charge Tune Spread	0.15
Beam Pulse Length on Target	695 nsec

The SNS accelerator complex consists of a 2.5 MeV H^- injector [2], a 1 GeV linear accelerator [3], an accumulator ring and associated beam transport lines [4]. The injector (also called the Front-End System) consists of an H- volume ion-source with 50 mA peak current capability [5], a Radio-Frequency Quadrupole and a Medium Energy Beam Transport line for chopping and matching the 2.5 MeV beam to the linac. The linear accelerator consists of a Drift Tube Linac (DTL) with 87 MeV output energy, a Coupled-Cavity Linac (CCL) with 186 MeV output energy, and a Superconducting RF Linac (SCL) with 1 GeV output energy [6]. At full design capability the linac will produce a 1 msec long, 38 mA peak, chopped beam pulse at 60 Hz for accumulation in the ring.

The linac beam is transported via the High Energy Beam Transport (HEBT) line to the injection point in the accumulator ring where the 1 msec long pulse is compressed to less than 1 microsecond by multi-turn charge-exchange injection. According to design, beam is accumulated in the ring over 1060 turns reaching an intensity of $1.5\text{x}10^{14}$ protons per pulse. When accumulation is complete the extraction kicker fires during the 250 nsec gap to remove the accumulated beam in a single turn and direct it into the Ring to Target Beam Transport (RTBT) line, which takes the beam to a liquid-mercury target.

The liquid mercury target system [7] consists of a closed-loop mercury-handling system. The target module is designed for remote-handling maintenance by retraction into a service bay outfitted with remote manipulator systems. Neutrons are moderated in four moderators, one using ambient water, and the other three utilizing supercritical hydrogen at 17-20 K.

The beam commissioning campaign of the SNS accelerator complex, initiated in 2002 and completed in May 2006, was performed in seven discrete runs which were devoted to commissioning the i) Front-End, ii) Drift Tube Linac Tank 1, iii) Drift Tube Linac Tanks 1-3, iv) Coupled Cavity Linac, v) Superconducting Linac, vi) High-Energy Beam Transport Line and Accumulator Ring, and vii) Ring to Target Beam Transport Line and the mercury target. In the course of beam commissioning, most beam performance parameters and beam intensity goals have been achieved at low duty factor [8,9]. The commissioning of the SNS project was formally completed at the end of this phase in June 2006.

With the construction project complete, the SNS is now eight months into a three-year ramp-up phase in which the performance will be increased to the design capability.

FRONT-END SYSTEM PERFORMANCE

The SNS front end has a number of challenging design and operational aspects. The design calls for a high-current, low-emittance H- source operating at high-duty factor with adequate source lifetime and fast risetime, chopping with an extinction ratio of 10^{-4}. A front end test stand is used for ion source development [10] aimed at proving long source lifetime at full duty factor, and development of different source technologies to deliver higher-brightness beams for a future upgrade.

Table 2 shows baseline comparison design values for a number of important front end parameters: those that have been achieved on the test-stand, achieved on the front end

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system and achieved in routine operation. Achieved parameters meet or exceed those in routine operation. The main challenge in early operation of the front end has been in reliability of the various components, in particular the chopper systems and the LEBT. Recent operation showed that arcs in the electrostatic LEBT assembly can destroy chopper driver circuits. A number of improvements to the LEBT assembly have been implemented as a result. In addition, improvements to the protection of the LEBT chopper driver circuits have been implemented.

Table 2: Front-end Beam Parameters achieved in Commissioning and Early Operations

Parameter	Baseline Design (Front-End)	Achieved (Ion Source)	Achieved (Front-End)	Routine Operation
Peak Current	38	60	50	17
Pulse length	1.0	1.25	1.0	0.3-0.5
Repetition rate	60	60	60	30
Average Current [mA]	1.6	2.5	1.05	0.070
Emittance [π mm-mrad (rms, norm)]	0.3	0.22	0.29 (H) 0.26 (V)	N/A
Chopping extinction ratio	10^{-4}	10^{-2}	10^{-4}	10^{-2}

LINAC OPERATION AND PERFORMANCE

The SNS linac design and operation must address a number of challenges. Foremost, the stringent beam loss constraints of 1 Watt/m must be met by the beam dynamics design [11] as well as achieving in actual operation a linac lattice that maintains the useful features inherent in the design. Accurate RF phase and amplitude setpoints must be determined and particular attention must be paid to proper phase-space matching. Output beam quality must be maintained to achieve required beamloss constraints in the beamline downstream of the linac, and in particular, in the Ring injection region. Likewise, careful matching is required to avoid mismatch-driven halo generation and emittance growth. Stability of RF phase and amplitude in the 96 RF cavities, particularly in the presence of heavy beam loading, is essential. Finally, for operational reasons, superconducting cavity gradient setpoints periodically require reassessment, which results in changes in operating gradients. To avoid a lengthy SCL tuneup procedure, rapid methods – on a time scale of minutes -- for adjusting downstream RF phase setpoints have been developed [12].

The SNS linac was commissioned over two years in four commissioning runs. Results from the commissioning phase have been reported in [9,13]. Results from recent operation are reported in [14].

A powerful method for RF phase and amplitude setpoint determination, the Phase Scan Signature Matching technique [15], was developed and is now routinely used for this purpose. In this technique the difference in beam arrival phase at two BPMs downstream of the DTL tank, CCL module or SC cavity in question is recorded as a function of tank or module phase for a few different RF field amplitudes. While the small amplitude motion is linear, phase scans are performed over a wide range in cavity phase to take advantage of the non-linearity of large amplitude motion. The input beam energy, tank or module RF amplitude and relative beam/RF input phase are determined with a model base fit to data obtained at two or more RF amplitudes. Figure 1 shows an example for DTL tank 4, where the curves show measured data and the points show the model results after fitting for two RF amplitudes differing by 1%. As is evident, this method can be quite sensitive to the RF amplitude, and provides setpoint accuracy to within 1% and 1 degree.

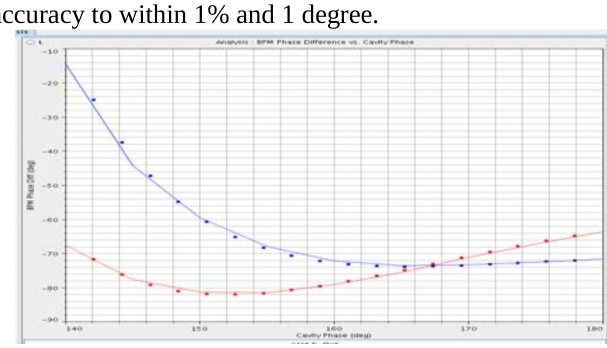

Figure 1: Results of phase-scan signature matching to determine RF setpoints. BPM phase difference is plotted vs. DTL tank 4 phase. The curves show data for two RF amplitudes. The points show the results of model-based fitting.

Table 3 shows a comparison between the baseline design parameters and those that have been achieved and are obtained in routine operation. The linac has operated thus far with output beam energies in the range 550-1010 MeV. In early low-power operations the linac output energy was about 850 MeV. Since October 2006, the output energy has remained constant at 890 MeV. A demonstration run was performed in which 1010 MeV was achieved. The highest intensity beam pulse yet produced in the SNS linac has parameters as follows: 880 μs pulse length, 930 MeV, 20 mA peak current, unchopped, and 1.0×10^{14} H^- ions/pulse. This single-pulse intensity corresponds to that required for 1 MW operation, with a linac repetition rate of 60 Hz. Typical operation today is at 30 Hz repetition-rate, 300 μs pulse length delivering 70 μA, or 60 kW of beam power. The

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maximum achieved average current is 100 μA in a four-hour demonstration run.

Table 3: Linac Beam Parameters achieved in Commissioning and Early Operations

Parameter	Baseline Design	Achieved	Routine Operation
Energy [GeV]	1.0	1.01	0.89
Output Emit. [π mm-mrad (rms, norm)]	0.4	0.3 (H) 0.3 (V)	
Pulse-to-pulse jitter [MeV]	±1.5	±1.3	
Linac Average Current [μA]	1600	100	70
Linac H^- ions/pulse	$1.6x10^{14}$	$1.0x10^{14}$	$3x10^{13}$
RF phase/amplitude stability	1 deg/1%	0.5 deg/0.5%	1 deg/1%

The linac emittance evolution has been measured using wire scanner arrays. Output emittance measured at somewhat reduced beam current – 25 mA instead of the 38 mA baseline current – shows that the rms emittance growth can be controlled and kept in line with output beam quality specifications. This is a crucial observation since emittance growth is often accompanied by halo generation which can lead to beam loss.

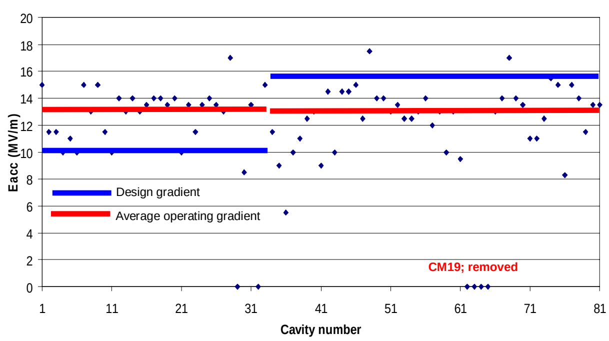

Figure 2: Accelerating gradient vs. cavity number for the SCL.

The superconducting linac is presently operating at 2.1K with 75 of 77 installed SC cavities in operation [16, 17]. One high-beta cryomodule has been removed from the tunnel for repair work, and two installed cavities are offline, one due to excessive fundamental power transmitted through an HOM feedthrough, and another due to unstable operation at high repetition rate. The operating gradients are shown in figure 2, compared with the design operating gradient. One observes that the medium-beta cavities are operated significantly higher than the baseline specification of 10.2 MeV/m, whereas the high-beta cavities are operated below the baseline design of 15.6 MeV/m. In other words, the medium-beta and high-beta cavities are operated at nearly the same accelerating gradients. It is important to point out that individually powered high-beta cavities do reach limiting fields on average near the specification. However, simultaneous operation of all cavities in a cryomodule results in reduced gradients due to collective cavity effects [16,17]. Several cavities with unusual HOM signals suggest electron activity in and around the HOM filter assembly. After thorough testing we have begun operating these cavities routinely, albeit at somewhat reduced gradients.

One of the main benefits of a superconducting linac in a proton accelerator application is the operational flexibility that it affords. With individually powered cavities, downstream cavities can be adjusted in phase and amplitude to recover from a change in operating gradient of an upstream cavity. Thus, cavities which are offline may be readily "tuned around." This is in contrast to the situation in a normal conducting linac with long CCL modules, in which the design velocity profile is expressed in the module geometry itself; the loss of a module interrupts beam operation until a repair can be completed. Thus far in commissioning and initial operations we have taken advantage of that flexibility by operating with as many as 20 cavities unpowered in the initial tuneup, and now by operating routinely with two unpowered cavities and a missing high-beta cryomodule. To capitalize on that flexibility requires rapid fault recovery algorithms. A method for adjusting downstream cavity phases in response to an upstream cavity fault or setpoint change has been developed and successfully tested; preliminary results are described in [12]. We anticipate that this flexibility will be important for achieving the high availability goals required by the user community. It is important to note that the linac beam dynamics can in fact accommodate a number of unpowered SC cavities with little or no impact on output beam quality or beamloss.

ACCUMULATOR RING PERFORMANCE

The SNS accumulator ring design and operation must confront several challenges. First, the ring must handle very high beam intensities, which motivated a number of detailed studies of collective effects [18]. The beamloss constraint of 1 Watt/m required transverse phase-space painting in both planes, use of dual-harmonic RF systems to flatten the beam profile thereby reducing the peak space-charge tuneshift, and use of a two-stage betatron collimation system [19]. Finally, since the H- stripping process cannot be made 100% efficient without adversely affecting beamlosses from circulating beam, the "waste beams" must be carefully controlled and handled. The SNS design includes an injection dump with 150 kW beam power capability.

Accumulator ring commissioning has been described previously in [8]. Further operational experience is described in another paper in these proceedings [20]. Table 4 shows a comparison of achieved and routine performance measures relative to the baseline design. In single-pulse high-intensity studies, a beam intensity of nearly 10^{14} was achieved, which is a world record for bunched proton beam intensity in a synchrotron or accumulator ring. In these studies the beam was stored for 1000 turns with no observed instabilities.

Limitations to ring performance have arisen from higher than expected beamloss in the ring injection region arising from improper transport of both waste beams to the injection dump [21,22]. Subsequent modifications to the injection dump line have improved performance.

Table 4: Comparison of Performance Parameters for the Accumulator Ring

Parameter	Baseline Design	Achieved	Routine Operation
Extracted p/pulse	1.5×10^{14}	0.96×10^{14}	0.3×10^{14}
p/pulse on target	1.5×10^{14}	0.53×10^{14}	0.3×10^{14}
Beam Current [A]	26	17	5
Accumulated turns	1060	830	500
Space-charge tuneshift	0.15	0.1	0.03

BEAM POWER RAMP-UP

SNS operational plans include a three-year post-construction ramp-up phase in which the SNS performance is increased to 1.44 MW beam power on target, and 5000 hours of accelerator operation per year at greater than 90% neutron production availability. The anticipated ramp-up profile in these three parameters is shown in figure 3. The ramp-up phase started October 1, 2006, which marks the beginning of formal SNS operations. This ramp-up phase was anticipated early in the construction project and was communicated to the neutron scattering community to establish performance expectations for early SNS operation.

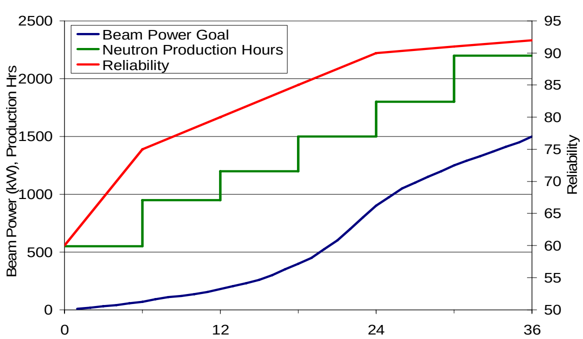

Figure 3: Beam power ramp-up goals.

Figure 4 shows the beam power history since the start of formal operation on October 1, 2006. In the first running cycle the SNS reached 30 kW beam power on target for routine neutron production. At this time the SNS became the world's brightest pulsed spallation neutron source, routinely delivering 6 kJ/pulse to the mercury target. During this cycle, a half-shift demonstration at twice the beam power (60 kW) was achieved. Following a maintenance period, the beam power was increased to 60 kW of beam delivered to the target for routine neutron production. During this cycle, a half-shift demonstration at 90 kW was performed. The beam power has been limited administratively to 10 kW prior to November 2006, and subsequently to 100 kW to the present. This limitation has arisen from the Accelerator Readiness Review process as required by the DOE. A recent review endorsed raising the administrative beam power limit to 2 MW. Operation in the present running cycle has started at 60 kW.

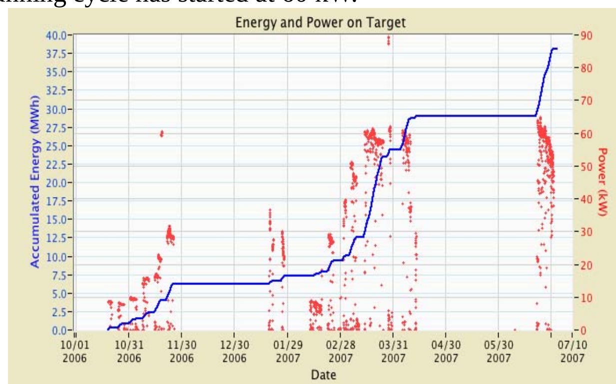

Figure 4: History of beam power delivered to the target since the beginning of formal SNS operations.

Typical final parameters in the October/November 2006 run cycle were 30 kW, 5 Hz, 890 MeV, 6.7μC/pulse. Typical final parameters in the January through April run cycle were 60 kW, 15 Hz, 890 MeV, 4.5μC/pulse. Recent operating parameters are 60 kW, 30 Hz, 890 MeV, 2.2μC/pulse. We anticipate increasing the beam power to 180 kW during the present operations cycle. The intensity required at the present repetition rate has been achieved previously in routine operation.

Figure 5 shows the integrated beam power delivered per day and the cumulative beam power since the beginning of the fiscal year. The peak integrated beam power delivered in a day is 1.38 MW-hrs. The cumulative beam power delivered to date is on track with plans established at the start of the year.

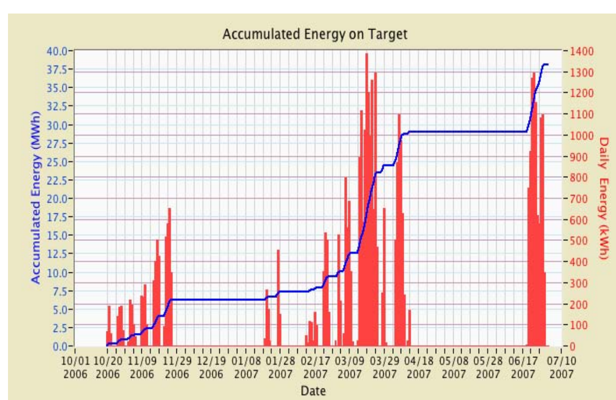

Figure 5: Integrated beam power (kW-hrs) delivered per day. The blue curve shows the cumulative quantity (MW-hrs) since the beginning of the fiscal year.

Figure 6 shows the distribution of beamloss and resulting activation in the SNS accelerator. The beam loss monitor readings in routine 60 kW operation are shown along the accelerator beamline. Overlayed are residual activation levels in mrem/hr at 1 ft after 30 hours cooldown. Beamloss and activation in most of the accelerator complex is in line with expectations. Several regions with higher than desired beamloss are observed. Peak activation levels in the linac of about 10 mrem/hr are measured in the latter portion of the coupled-cavity linac where the beam size increases to match the FODO to doublet structure of the SCL. Peak activation levels in the Ring are observed in the injection region of the ring and injection dump transport line as discussed above and in these proceedings [21,22]. Other areas of non-negligible beamloss are observed in the ring collimation region, as expected, and the extraction region. It should be noted that only the LEBT chopper is in routine operation at present; the MEBT chopper system, which is designed to reduce beam in the gap by an additional two orders of magnitude, is not yet operational [23].

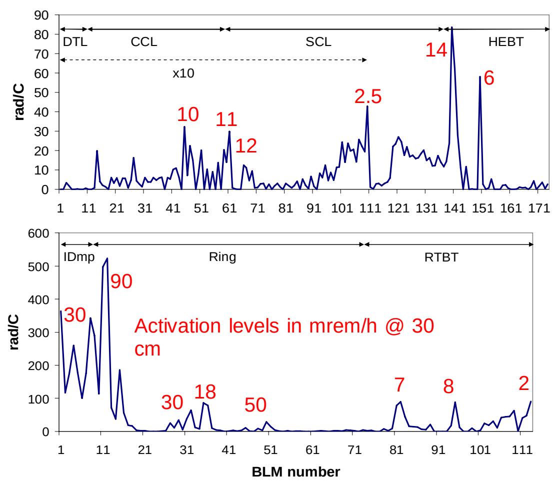

Figure 6: Beamloss (rad/C) plotted vs. beam loss monitor number in the linac (top) and ring (bottom). The activation levels in mrem/hr at 1 ft after 30 hour cooldown are shown in red.

SCIENCE PROGRAM

Ultimately, the SNS will house 24 neutron-scattering instruments. Five instruments were included in the baseline SNS construction project. Three instruments (the Backscattering Spectrometer, the Liquids Reflectometer and the Magnetism Reflectometer) were commissioned in early operation and are now fully operational and producing first scientific results. The remaining two instruments from baseline construction and three additional instruments will be operational this year. Eighteen beamline instruments have already been assigned and are in the conceptual, design or construction stage. The SNS instrument buildout continues through 2015. The initial user program begins in the summer of 2007, with the full user program beginning in 2008.

CONCLUSION

The SNS construction project was completed in June 2006. The SNS began formal operations in October 2006, which also marks the beginning of an anticipated three-year ramp-up period in which the full design performance is achieved. The SNS is making rapid progress, having achieved 90 kW delivered to the neutron production target. Plans are underway for increasing the beam power beyond the design specification to 3 MW through the SNS Beam Power Upgrade Project [24], which is presently seeking DOE CD-1 approval. This upgrade will enable a second-target station to be constructed – via a future DOE upgrade project – which will double the scientific capabilities of the SNS.

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