SPALLATION NEUTRON SOURCE OPERATION AT 1 MW AND BEYOND*

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Abstract

Since the Spallation Neutron Source construction was completed in 2006, the performance of the accelerator complex has reached 1 MW beam power on target, ~5000 hours of accelerator operation per year, and ~90% availability during neutron production operation. In this paper the performance of the SNS is described, and some of the many challenges which had to be overcome are described. Finally, plans for further increase in beam power are presented.

INTRODUCTION

The Spallation Neutron Source (SNS) at Oak Ridge National Laboratory is the world's most powerful pulsed neutron scattering facility. 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 the design beam power of 1.4 MW the SNS will operate at beam powers a factor of 8 beyond that which had been previously achieved [1]. The SNS baseline parameters and present operating parameters are summarized in Tab. 1

Table 1: Operating Beam Parameters Compared to Design Values

	Design	Operating
Beam Power on Target	1.44 MW	1.1 MW
Beam Energy	1.0 GeV	0.93 GeV
Linac Beam Macropulse Duty Factor	6.0%	5.0%
Beam Pulse Length	1.0 ms	0.82 ms
Repetition Rate	60 Hz	60 Hz
Peak linac current	38 mA	40 mA
Average Linac H- current	1.6 mA	1.3 mA
Ring accumulation time	1060 turns	530
Ring bunch intensity	$1.5x10^{14}$	$1.1x10^{14}$
Ring Space-Charge Tune Spread	0.15	0.11
Operating SRF Cavities	81	80

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 Front-End System consists of an H- volume-production ion-source [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 current, 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 [7] where the 1 msec long pulse is compressed to less than 1 μs by multi-turn charge-exchange injection. According to design, beam is accumulated in the ring over 1060 turns reaching an intensity of $1.5x10^{14}$ 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 [8] 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 was carried out in seven discrete commissioning runs over a four year period. Beam commissioning results are summarized in [9,10].

Formal SNS operations for scheduled neutron scattering experiments began in October 2006. The initial instrument suite was commissioned, and the user program began in 2007. The SNS is now nearly four years into the operations phase. It was originally envisioned to ramp-up the beam power to 1.4 MW, the beam availability to 90%, and the accelerator operating hours to 5000 in the first three years following construction. Performance status during the initial operation phase is summarized in [11,12,13].

SNS PERFORMANCE

Table 1 shows a summary of SNS design and operating parameters. The design values refer to the baseline construction project parameters, and the operating values refer to present routine operation.

Figure 1 shows the SNS beam power history since the start of formal operation. One MW of beam power was delivered to the target in routine operation on Sept. 18, 2009, three years after the beginning of formal operation. This accomplishment satisfied the high-level requirement

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[#] Present address: Fermilab, Batavia IL, email: stuarth@fnal.gov articulated in the early planning for the SNS; namely, that the SNS Project deliver a facility capable of operating with a beam power exceeding 1 MW. Since neutron production rate in the GeV energy range scales with beam power, the integrated beam power on target is the most useful figure of merit for measuring productivity of the accelerator complex. Figure 2 shows the daily integrated beam power, which has climbed to more than 23 MW-hrs delivered per day. At this point there are only two parameters left to further increase the power toward the design value: the linac output energy, and the beam pulse width. The pulse width can be increased further in the near-term, now that a number of modulator improvements have been implemented, as will be discussed below. Increasing the output energy will require improvements in high-beta SC cavity gradient, as is described below.

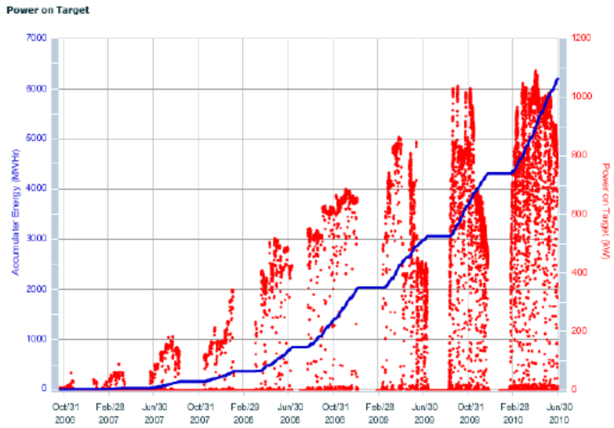

Figure 1: Beam power history of the SNS since the beginning of formal operations in October 2006.

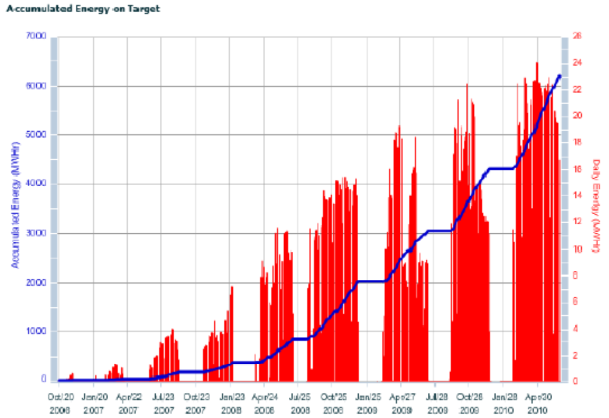

Figure 2: Daily integrated beam power history of the SNS since the beginning of formal operations in October 2006.

The ascent in beam power over the last four years has required overcoming numerous challenges, such as ion source and LEBT failures and component redesign, target mercury pump and cryogenic moderator failures, high beamloss in the ring injection region due to a design shortcoming, the necessary removal and repair of two cryomodules, the failure of the momentum dump in the HEBT, anomalous detuning of the RFQ structure, stripper foil failures and mounting redesign, a series of modulator failures, and many others, some of which are described below.

The present operational focus is on improving the beam availability for neutron production, and in increasing the user-mode operating hours. Figure 3 shows the beam availability, defined as the neutron production hours delivered divided by scheduled neutron production hours, for individual run cycles. The red bars show the run cycle length in days, and the blue bars show the beam availability over that period. A steady improvement in beam availability has been achieved through an aggressive campaign of hardware improvements on nearly all the operating systems. As a result, beam availability has climbed to ~90%. In the last four years, the beam power, the availability and the operating hours have increased substantially, as is shown in Fig. 4.

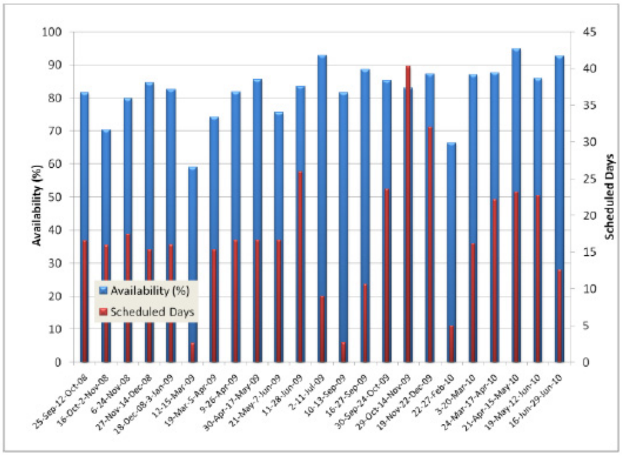

Figure 3: Beam availability (blue bars) for individual neutron production run cycles. The length of each cycle is shown by the red bars.

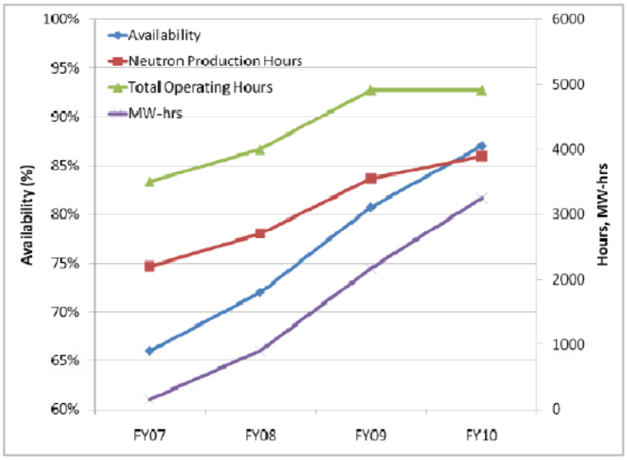

Figure 4: Improvement in beam power, integrated beam power, beam availability and delivered neutron production hours since the start of operation, displayed by fiscal year. The FY10 numbers are year-to-date values, as of August 1, 2010.

OPERATIONAL ISSUES

Details of many of the operational performance limitations have been documented in various conferences proceedings, referenced in this paper and elsewhere. A few of the most significant limitations are described in this paper.

Front-End Systems

The ion source routinely delivers the design peak current at the RFQ output. Improvements in the beam current performance have been realized through a series of incremental improvements over time [14]. A focus of effort has been on improving the reliability of the ion source and associated systems. In initial operations, excessive arcing of the electrostatic LEBT lenses led to periods of poor availability. After redesigning the LEBT, improving operational procedures and quality control, the LEBT arc rate is now routinely less than one per day. This, coupled with improved chopper protection circuitry, has largely eliminated this failure mode.

Poor performance of the ion source 2 MHz RF source has motivated a program to deploy an RF drive system at ground potential powering the source through a high-voltage isolation transformer [15] which removes the RF power source from the high voltage enclosure, and allows for better thermal stability and improved access. In addition, a reliable solid-state RF system has been purchased and is being readied for installation.

Since the Ion Source is a single-point failure for the neutron production program, an effort is underway to design and deploy a magnetic LEBT system [16] with the capability of switching to a hot-spare source (which is not possible with the present compact LEBT design), thereby improving overall system availability. This system will also have the benefit of a simpler chopper configuration which can operate at ground potential.

The RFQ experienced two sudden shifts in the resonant frequency of the structure [17]. After each case the structure was retuned by appropriate re-machining of slug tuners. In each case, operation resumed with no noticeable impact on beam quality, but the cause remains unknown. A spare RFQ will be fabricated by an industrial vendor.

At longer beam pulse lengths, greater than ~700 µs, we encountered difficulty achieving stable RF resonance control [18]. At constant field amplitude, resonance error change in response to changing beam conditions and ion source hydrogen flow. The model described in [18] is the following. Hydrogen gas (from source operation) is adsorbed on the vanes. Beam enhances hydrogen desorption and a local discharge ensues which heats the vanes and changes the resonant frequency, due to the extreme frequency sensitivity to intervane spacing. Changes in resonant frequency occurred at time scales much shorter than the cooling water circuit transit time. A resonance control loop was implemented to adjust the pulse width to provide response time much faster than the cooling water circuit transit time. After implementation, the pulse width has been successfully tested to 1 ms.

Linac Systems

The normal-conducting linac structures are operating reliably for neutron production. Improvement have been made to the resonance control systems.

At project completion, 74 of 81 superconducting cavities were in operation. The output beam energy was 850 MeV and the pulse repetition rate was 5 Hz. Now, 80 cavities are operational at 60 Hz, delivering an output energy of 930 MeV. In the last four years, two cryomodules were removed from the tunnel to make repairs related to higher-order-mode filter difficulties [19]. Thirteen cryomodules in total have been thermally cycled to make repairs in the insulating vacuum space, including repairs to mechanical tuners, harmonic drives, piezo-electric stacks and HOM filter feedthroughs [19].

The output beam energy is lower than the design value of 1000 MeV due to the inability to operate the high-beta cavities at their design gradients. Operational cavity gradients are shown in Fig. 5. The operational gradient of a given cavity is lower than its maximum gradient obtained by individually testing the cavity, due to "collective effects," in which field emitted electrons in a cavity are transported to adjacent cavities, where their energy is deposited [20]. The transmission of these field emitted electrons depends on the phases of intervening cavities, therefore the operating gradient for one cavity depends on the surrounding cavities and their phases in a complicated way. For this reason, operating gradients in practice are below those measured for a single cavity. Operating gradients are ~20% lower than the average individual gradients, and ~15% lower than design.

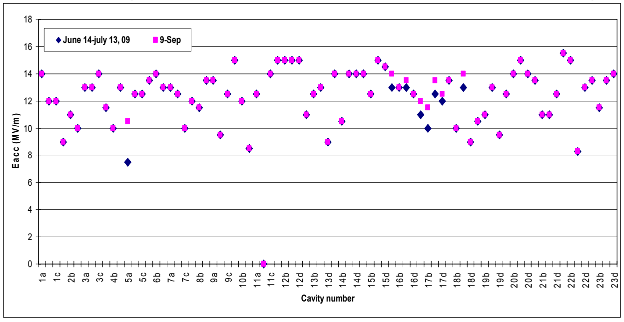

Figure 5. Operational superconducting cavity gradients before and after the 2009 summer shutdown, in which several improvements were implemented.

Recently, we observed degradation in gradient performance of two SC cavities, following beam trips caused by excessive beamloss. The degradation was not immediately recoverable, so these cavities were turned off and the downstream cavity phases adjusted accordingly. The cause of the degradation was traced to a situation in which substantial beam could be lost in the SCL in some conditions, due to very slow beam truncation by the Machine Protection System (MPS). It was discovered that the beam turn-off time in several MPS channels was much longer than the design value (~100-200 µs vs. 30 µs design). The cause was traced to field modifications implemented in early operations to combat spurious trips. The gradient performance of these two cavities was recovered following extensive conditioning during the next maintenance period.

The cavity RF control performs better than the specifications of ± 1% and ± 1º in phase and amplitude respectively [21] in the presence of beam, which is made possible with the implementation of both feedback and feedforward methods.

The dominant source is downtime is due to the high-voltage converter modulator (HVCM) systems. Many failure modes have been identified, although the dominant are IGBT and capacitor failures [22]. In some cases, IGBT switchplate capacitor failure resulted in fires contained within the modulator enclosure. An aggressive campaign to stabilize modulator operation has been underway for the last six years. A variety of improvements have been implemented, including i) the replacement of chokes, transformers and resistors in the high-voltage tank with new designs incorporating higher engineering margin, ii) the replacement of flammable liquid filled dielectric capacitors with solid, self-fusing capacitors, iii) improved IGBT turn-off to limit overvoltage, iv) the installation of an additional modulator to allow SCL klystron operation at design voltage, and v) the construction of a dedicated modulator test stand to qualify modifications and prove new concepts.

BEAM LOSS AND ACTIVATION

Beamloss in the superconducting linac has been reduced by more than a factor of two in the last year, and now achieves $\sim 10^{-5}$ fractional beam loss level, or ~0.2 W/m. In the design phase, state-of-the-art simulations predicted no lost particles in the SCL even for inflated errors and halo generation, whereas readily measurable losses are observed, although at levels that are sufficiently low that there is little impact on operations. The loss mechanism is not well understood. There are at least three potential sources: i) mis-matched off-energy particles, ii) weak resonance with higher order multipoles [13], and iii) H- intrabeam scattering [23]. The latter loss mechanism, in which intrabeam scattering leads to H- stripping and subsequent loss of neutral hydrogen atoms in the SCL, is consistent with many of the observable loss features. It is worth emphasizing that while the situation is acceptable for SNS operation and future plans, these various loss mechanisms may become important for certain ranges of parameters in future high power proton/H- linear accelerators.

Uncontrolled beamloss in nearly all regions of the accelerator is in line with expectations, that is, less than 1 W/m at 1 MW operation. SNS operation has not been limited by beam loss for more than two years. Average residual activation values measured in practical accelerator operating conditions are ~15, ~20 and ~5 mRem/hr measured at 30 cm in the CCL, SCL, and transport lines/accumulator ring respectively. However, there are several local regions of higher losses and therefore higher residual activation, some of which were anticipated (such as near the injection foil, collimation systems and ring extraction kicker) and others which were not. Figure 6 displays the locations and measured residual activation for the highest local "hotspots." The highest measured activation, as anticipated, is the injection region including the foil and downstream vacuum chambers in which foil-scattered particles are lost. In the linac, the region of highest beam loss is ~60 mRem/hr at 30 cm in the SCL, and ~80 mRem/hr at 30 cm at the location of minimum linac aperture in the CCL.

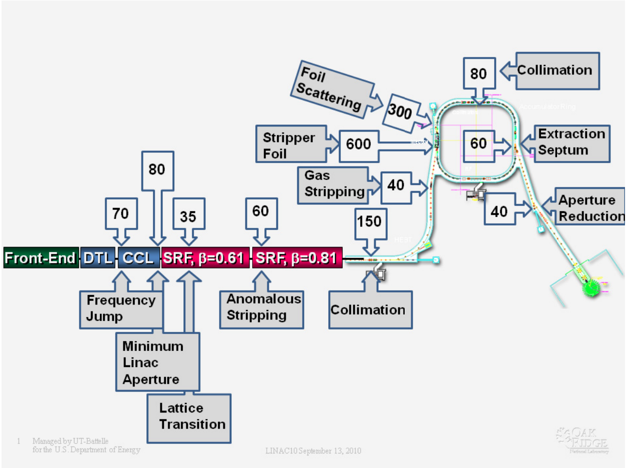

Figure 6: Highest local measured residual activation "hotspots" and their sources. All units are in mRem/hr at 30 cm, after approximately one day "cooldown."

UPGRADE PLANS

The SNS upgrade plans call for a doubling of the beam power capability of the accelerator, increasing the proton beam power to at least 2 MW with a design goal of 3 MW. The power upgrade will enable operation of a second, long- wavelength target station (LWTS), thereby doubling the scientific capability of the facility.

A straightforward increase in SNS beam power to 3 MW can be realized by i) increasing the linac beam energy from 1.0 to 1.3 GeV by installing nine additional high-beta superconducting cryomodules, and ii) increasing the H^- ion source pulsed current (measured at RFQ output) from 38 mA to 59 mA. We have chosen to maintain the present 6% linac beam duty factor. With only a few exceptions, the ring and transport line hardware have been designed and built for 2 MW of beam power at 1.0 GeV, and with the capability of 1.3 GeV operation. Therefore, the 3MW SNS upgrade, while certainly containing challenging aspects, can nevertheless be considered an extension of the present SNS design. The Power Upgrade Project is described in more detail in [24]. The Project has CD-1 approval.

In the reference concept for the second target station [25], the accelerator will deliver 20 long-pulses per second to the second target station and 40 short pulses per second to the first target station. In this mode, 1 MW beam power is delivered to the second target station and 2 MW to the first.

An additional transfer line, is required to transport beam to the second target station.

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