STATUS OF THE SNS BEAM POWER UPGRADE PROJECT*

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Abstract

The baseline Spallation Neutron Source (SNS) accelerator complex, consisting of an H- injector, a 1 GeV linear accelerator, and an accumulator ring, will provide a 1 GeV, 1.44 MW proton beam to a liquid mercury target for neutron production. Even in the baseline design, many of the accelerator subsystems are capable of supporting higher beam intensities and higher beam energy. Upgrades to the SNS accelerator and target systems to increase the beam power to at least 2 MW, with a design goal of 3 MW, are in the planning stages. The upgrade beam parameters will be presented and the required hardware modifications will be described.

INTRODUCTION

The Spallation Neutron Source (SNS) accelerator complex [1] consists of an H^- injector [2], a 1 GeV linear accelerator [3], an accumulator ring and associated transport lines [4]. The baseline SNS accelerator will provide a 1.44 MW proton beam to liquid mercury target [5] for neutron production. Following successful commissioning of the accelerator complex, the SNS construction project was completed in June 2006, and the transition to operations is underway [6].

Since many neutron-scattering measurements are intensity-limited, greater neutron fluxes are desired in order to extend the capabilities of the experimental program. The need for a beam power upgrade to the SNS was envisioned early in the design effort; even in the baseline design, many of the accelerator subsystems are capable of supporting higher beam intensities and higher beam energy [7].

The SNS Beam Power Upgrade project received DOE CD-0 approval in November 2004. A Conceptual Design Report and cost range was recently completed [8]. The upgrade plan, reported previously in [9], calls for improvements to the accelerator and mercury target system. The plan calls 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 a second, long-wavelength target station (LWTS), which would require 1 MW of beam power. Table 1 lists parameters for the initial baseline SNS accelerator complex (1.44 MW) and the Beam Power Upgrade (3 MW).

As part of the conceptual design, a cost range was established: the estimated Total Project Cost is \$160 M and the cost range is \$150-173 M.

SNS UPGRADE PLAN

A straightforward increase in SNS beam power to 3MW 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 (detailed below), 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 [4,7]. Therefore, the 3MW SNS upgrade, while certainly containing challenging aspects, can nevertheless be considered an extension of the present SNS design.

Ion Source Upgrade

The peak current from the H^- injector must be increased from 38mA to 59 mA for the 3 MW upgrade. Furthermore, we maintain a MEBT output emittance requirement of 0.35 π mm-mrad (rms, normalized) which is a demanding constraint on the ion source brightness. The Power Upgrade requirement will be met by combining a low-emittance, high-current ion source with a LEBT that causes minimal emittance growth, both of which have been demonstrated.

An aggressive H- ion source development program is underway to develop a source of the required current and emittance. The Japan Atomic Energy Research Institute developed a filament-driven multicusp H- source that delivered up to 72 mA with a 5% duty cycle, and a measured emittance of 0.2 $\pi\cdot$mm$\cdot$mrad (rms, norm) [10,11]. The development program is aimed at capitalizing on source performance characteristics from this and other sources to achieve the required brightness and lifetime goals.

To achieve the 99.5% availability requirement, a two-source injector based on a magnetic “Y” LEBT is envisioned, which will allow rapid switching between sources. The two-source LEBT has two identical ion source beam lines that are merged with a double-focusing switching magnet into the RFQ injection line.

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Linac Upgrade

Nine additional high-beta cryomodules will be installed in the linac tunnel to increase the beam energy to 1.3 GeV. As is shown in Table 1, 1.3 GeV beam energy is obtained while keeping an entire cryomodule in reserve and at the same time operating the high-beta portion of the linac at 10% reduced gradient. If, instead, the high-beta linac is operated at design gradients, a beam energy of 1.4 GeV results.

Table 1: SNS baseline and upgrade parameters.

	Baseline	Upgrade
Kinetic energy [MeV]	1000	1300
Beam power [MW]	1.4	3.0
Chopper beam-on duty factor [%]	68	70
Linac beam macro pulse duty factor [%]	6.0	6.0
Average macropulse H- current [mA]	26	42
Peak macropulse H- current [mA]	38	59
Linac average beam current [mA]	1.6	2.5
SRF cryo-module number (med-beta)	11	11
SRF cryo-module number (high-beta)	12	21
SRF cavity number	33+48	33+84
Peak surface gradient (β=0.61 cavity) [MV/m]	27.5 (+/- 2.5)	27.5 (+/- 2.5)
Peak surface gradient (β=0.81 cavity) [MV/m]	35 (+2.5/-7.5)	31
Ring injection time [ms] / turns	1.0/1060	1.0/1100
Ring rf frequency [MHz]	1.058	1.098
Ring bunch intensity [10^{14}]	1.6	2.5
Ring space-charge tune spread, ΔQ_{SC}	0.15	0.15
Pulse length on target [ns]	695	691

Thirty-six additional SCL klystrons and associated systems would be procured, as well as three additional High-Voltage Converter Modulators (HVCM) and associated subsystems. The existing cryogenic plant has sufficient capacity for the additional cryomodules.

The increased beam current in the 3 MW upgrade requires a 50% increase in RF power delivered to the beam. Fortunately, substantial RF overhead has been built into the SNS baseline design, and can be exploited in the upgrade. Figure 1 shows the beam power requirements in the superconducting linac, including 12% RF control margin and 3% waveguide losses. The design specification for the existing SCL klystron is 550 kW. We expect to reliably exceed the design specification by at least 20% based on recent test results. Upgrades to some of the HVCMs are required to handle the increased average power and higher voltage, as shown in Figure 1.

The linac output emittance is the most important beam quality measure; as such an output emittance goal of < 0.5 π mm-mrad is required to minimize losses. The linac emittance growth, shown in Figure 2, has been estimated using the PARMILA code. The Figure shows emittance growth for an input particle distribution which was based on SNS ion source emittance measurements, and including all RF setpoint and quadrupole strength and alignment errors.

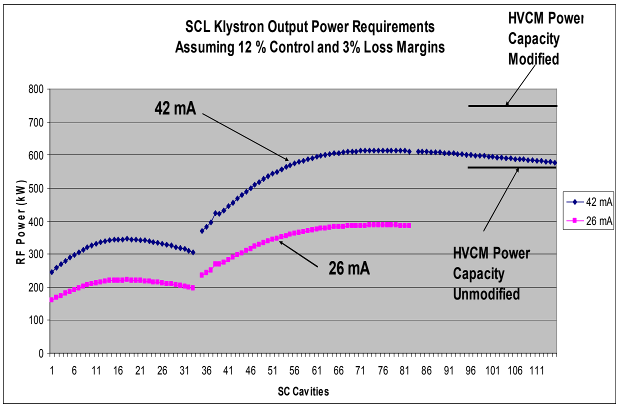

Figure 1: Superconducting linac klystron power requirements in the SNS baseline (26 mA) and in the upgrade (42 mA).

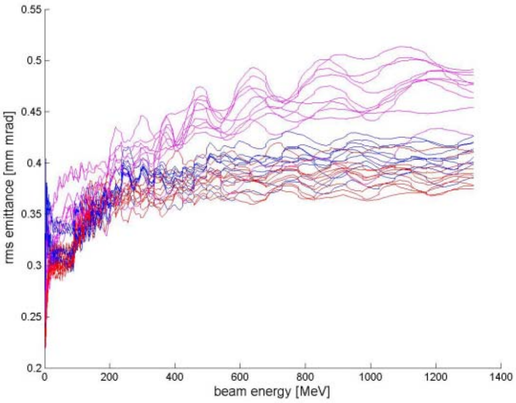

Figure 2: Normalized rms beam emittance evolution in the linac for ten different random seeds, including anticipated construction tolerances and quadrupole and rf setpoint errors. The traces show horizontal (red), vertical (blue), and longitudinal (magenta) emittances.

Accumulator Ring Upgrade

Most magnets and associated power supplies can accommodate 1.3 GeV beam parameters [7,9]. Required ring hardware modifications for 3 MW at 1.3 GeV are the following: i) installation of two additional extraction kicker magnets and associated power supplies, ii) replacement of two injection chicane magnets near the stripping foil to reduce partial stripping losses, iii) upgrade of pulsed injection kicker magnets for higher energy.

The space-charge tuneshift at 1.3 GeV for 3MW is the same as the baseline configuration at 1.0 GeV. ORBIT simulations for the upgrade parameters have been carried out for the SNS ring at the 3.0- MW Power Upgrade parameters. In these simulations, the full ring accumulation is modeled, including interactions of the beam in the stripping foil, full three-dimensional space-charge effects, full treatment of the ring RF and beam collimation systems, as well as transverse and longitudinal impedance effects. Figure 3 shows the tune footprint at the end of accumulation for both the natural chromaticity and zero chromaticity cases. Although the incoherent tune distributions cross slightly the integer resonance, the coherent tunes remain above the integer stopband. Figure 4 shows the final painted beam emittance distributions at large amplitude to assess ring losses near the collimator acceptance. Collimation is accomplished in a two-stage collimation system consisting of an adjustable scraper and a pair of fixed collimators. The adjustable scraper operates in the range 200-300 π mm-mrad, while the fixed collimators have acceptances of approximately 300 π mm-mrad in both planes. The design goal for uncontrolled fractional beam loss in the ring is 1×10^{-4}. From Figure 4.7, we see that the beam loss goal of is reached at approximately 220 π mm-mrad, which is well within the collimator acceptance, and in the range of operation of the adjustable scrapers.

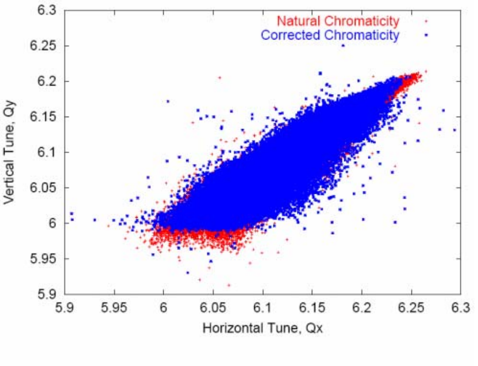

Figure 3: Tune footprints at the end of accumulation for SNS Power Upgrade parameters given in Table 1. Distributions for both natural and zero chromaticity are shown.

Beam dynamics simulations have been performed with the ORBIT code with the Power Upgrade parameters to explore collective instabilities. The ring impedance is dominated by the extraction kickers. We have taken the measured extraction kicker impedance, scaled appropriately to account for the additional kicker modules and performed ORBIT simulations to explore the instability thresholds. We find an instability threshold at twice the extraction kicker impedance for zero chromaticity. At the natural chromaticity, the threshold is about three times the extraction kicker impedance.

The electron-proton (e-p) instability (e-p) threshold is predicted to lie above the 3.0- MW SNS Power Upgrade design goal intensity [7]. Nevertheless, we plan to install a wideband feedback system for damping a potential SNS e-p instability. This feedback damper will have a bandwidth and beam power in the order of 400 MHz and 1 kW. Recent successful experimental tests at the LANL Proton Storage Ring [12] show that such instabilities in a long-bunch proton machine can be damped.

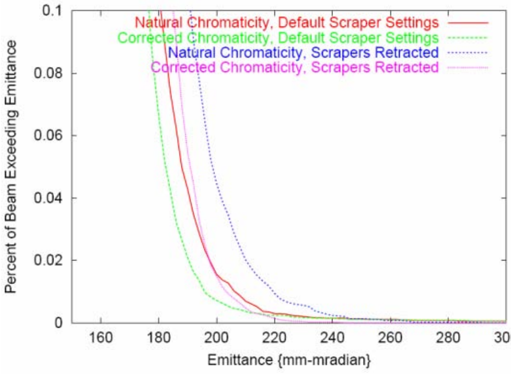

Figure 4: Emittance distributions near the edge of the beam. Full scale is 0.1%. The fixed collimator acceptance is approximately 300 π mm-mrad.

Target Systems Upgrade

With the exception of the stainless steel target container itself—containing the Hg and the inner neutron reflector plug—the remainder of the SNS target systems, including the mercury pump, mercury-to-water heat exchanger, moderator, supercritical hydrogen refrigerator for the moderators, shielding, and utility systems, is designed to operate at the upgrade power level of 2 MW or greater. The mechanism that may limit beam power to the mercury target container is cavitation damage caused by the intense pressure pulse induced in the mercury during each beam pulse. Two primary pathways are being pursued to overcome this potential limitation: mitigating the pressure pulse by injection of a fine dispersion of small gas bubbles in the mercury, thereby reducing the driving force for initiating cavitation, and establishing gas layers between the mercury and target vessel to protect it against the damaging effects of cavitation collapse. Alternate materials and surface treatments to the target vessel are believed to have limited potential to further extend its power capacity and lifetime; therefore they are not major elements of the target R&D effort.

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