THE SNS BEAM POWER UPGRADE*

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Abstract

The Spallation Neutron Source accelerator complex, presently under construction at Oak Ridge National Laboratory, will provide a 1 GeV, 1.44 MW proton beam to a mercury target for neutron production. We report on upgrade scenarios for the SNS accelerator complex which increase the beam power capability to at least 3 MW, and perhaps as high as 5 MW. The upgrade plan and beam parameters will be presented.

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 mercury target for neutron production. The SNS is presently under construction at Oak Ridge National Laboratory and will begin operations in 2006.

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. An upgrade plan has been formulated to extend the SNS beam power to 3 MW, with an ultimate capability perhaps as high as 5 MW. Table 1 lists three sets of parameters for the SNS accelerator complex: those for the baseline machine, the 3 MW upgrade, and the ultimate performance limit of the machine, which we believe is 5 MW.

SNS BASELINE DESIGN

The injector (also called the Front-End Systems) consists of an H^- ion-source with 48 mA peak current capability, a 2.5 MeV Radio-Frequency Quadrupole (RFQ) and a Medium Energy Beam Transport (MEBT) line for chopping and matching the 38mA, 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 187 MeV output energy, and a Superconducting RF Linac (SCL) with 1 GeV output energy. The linac produces 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 ring, where the 1 msec long pulse is compressed to less than 1 microsecond by charge-exchange multi-turn injection. In baseline operation, beam intensity reaches 1.5×10^{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 the mercury target.

SNS UPGRADE PLAN

A straightforward increase in SNS beam power to 3MW can be realized by increasing the H^- ion source pulsed current and increasing the final linac beam energy from 1.0 GeV to 1.3-1.4 GeV. The existing linac tunnel has reserved space for nine additional high-beta superconducting cryomodules, so that the linac energy can be easily increased above 1.3 GeV. With only a few exceptions (detailed below), the ring and transport line hardware have been designed and built to accommodate a beam energy of 1.3 GeV and a beam power of 2 MW [4]. Therefore, the 3MW SNS upgrade, while certainly containing challenging aspects, can nevertheless be considered an extension of the present SNS design.

It should be pointed out that the intensity can be increased either by increasing the source current, or the source and linac duty factor. While the latter is possible, we focus primarily on the former approach in this paper.

Ion Source Upgrade

The peak current from the H^- injector, which in the baseline is 38 mA, must be increased to 59 mA for the 3 MW upgrade. In a recent commissioning run [5], peak MEBT output currents of 51 mA were achieved, already 80% of that required for the upgrade. An aggressive H^- ion-source program is underway at ORNL. It is anticipated that this program will yield ion source performance that meets the demanding SNS baseline requirements of 38 mA MEBT peak current at 6% duty, with 99.5% availability over a source lifetime of 3 weeks. The 20% increase in source current can be realized by coupling more RF power into the plasma and by enhancing the H- surface production by separating the Cs collar from a temperature-controlled outlet aperture. To maintain the 99.5% availability with the upgraded requirements, we initiated the design of a two-source injector that allows for switching the LEBT to the alternate source within a few minutes.

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Table 1: Parameters for the SNS Baseline and Beam Power Upgrade

	Baseline	Upgrade	Ultimate
Kinetic energy, Ek [MeV]	1000	1300	1400
Beam power on target, Pmax [MW]	1.4	3.0	5.0
Chopper beam-on duty factor [%]	68	70	70
Linac beam macro pulse duty factor [%]	6.0	6.0	6.0
Average macropulse H- current [mA]	26	42	65
Peak macropulse H- current [mA]	38	59	92
Linac average beam current [mA]	1.6	2.5	3.9
SRF cryo-module number (med-beta)	11	11	11
SRF cryo-module number (high-beta)	12	12 + 8 (+1 reserve)	12 + 8 (+1 reserve)
SRF cavity number	33+48	33+80 (+4 reserve)	33+80 (+4 reserve)
Peak surface gradient (β=0.61 cavity) [MV/m]	27.5 (+/- 2.5)	27.5 (+/- 2.5)	27.5 (+/- 2.5)
Peak surface gradient (β=0.81 cavity) [MV/m]	35 (+2.5/-7.5)	31	34
Ring injection time [ms] / turns	1.0 / 1060	1.0 / 1100	1.0 / 1110
Ring rf frequency [MHz]	1.058	1.098	1.107
Ring bunch intensity [10^{14}]	1.6	2.5	3.8
Ring space-charge tune spread, ΔQ_{SC}	0.15	0.15	0.2
Pulse length on target [ns]	695	691	683

A further 50% increase in peak current is required to achieve the ultimate SNS capability, and is a subject for future research.

Linac Upgrade

Nine additional high-beta cryomodules will be installed in the linac tunnel, increase the beam energy to 1.3-1.4 GeV. As is shown in Table 1, 1.3 GeV beam energy is obtained while keeping an entire cryomodule in reserve (to facilitate rapid recovery from cavity faults) 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. Thus far in the SNS cryomodule production, accelerating gradients in the medium-beta linac average 50% greater than the baseline specification. Therefore, the increased beam energy required in the upgrade is considered very straightforward and conservative.

An extension of the existing klystron gallery is required to accommodate the associated high-power RF systems for the new cryomodules. Thirty-six additional SCL klystrons 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 along the linac compared to the installed klystron power rating. In addition to the beam power, RF power margin must be reserved for waveguide losses (3%), RF control margin (7%), and Lorentz-force detuning in the case of the SCL (< 7% with piezo compensation). At 42 mA average macropulse current, non-optimal waveguide to cavity coupling requires less than 1% increase in RF power, while at 65 mA macropulse current, an additional 8% RF power is needed in the medium-beta linac, and the rest of the linac requires less than 5% without rematching. It should be pointed out that the klystron limits shown in Figure 1 are design specifications which have been met or exceeded in all cases. In the case of the SCL klystrons, we expect to reliably exceed the design specification of 550 kW by at least 20% based on recent test results and operational experience. We therefore expect the baseline SNS klystron plant to satisfy the needs of the 3 MW upgrade.

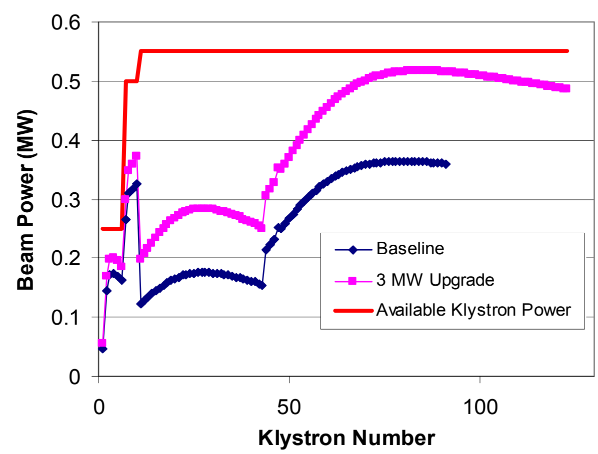

Figure 1: Beam power requirements per klystron in the baseline and 3 MW upgrade scenarios. Note that for the first 10 klystrons, the power values are divided by ten.

Upgrades to some of the HVCMs are required to handle the increased average power.

Accumulator Ring Upgrade

Although the SNS baseline calls for 1 GeV beam energy and 1.44 MW beam power, much of the ring hardware was designed with a future upgrade in mind. Aspects of the hardware modifications and beam physics for a 3 MW upgrade were presented earlier [6].

Most magnets and associated power supplies can accommodate 1.3 GeV beam parameters. 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, iv) increased shielding near the collimators.

There are beam physics issues that limit separately the achievable beam energy and beam power reach. The achromatic bend in the HEBT sets a limit on linac output energy of about 1.4 GeV due to Lorentz-stripping losses. On the other hand, for a given beam energy, the intensity will be limited by losses due to collective effects, namely, halo growth due to space-charge and beam instabilities.

To consider the space-charge limit, one can assume that the space-charge tuneshift is the relevant parameter and scale directly from the baseline. Assuming that the accumulated beam is painted to the same physical dimensions, and that the bunching factor is independent of energy, then the space-charge tuneshift is proportional to the factor $N/\beta^2\gamma^3$, where N is the intensity and β, γ are the relativistic parameters. Figure 2 shows two curves of constant $N/\beta^2\gamma^3$, the lower of which scales from the baseline SNS parameters (and corresponds to $\Delta Q_{SC} \cong 0.15$) while the upper curve scales from existing beam dynamics simulations showing acceptable losses at 2MW (and corresponds to $\Delta Q_{SC} \cong 0.20$). Therefore, the 3MW upgrade can be viewed as a straightforward extension of the baseline ring, at least as regards space-charge effects.

The situation for collective instabilities is somewhat more involved. The ring impedance is dominated by the extraction kicker magnets, for which a transverse instability threshold (at 1 GeV) of 2.5-3x10^{14} protons/pulse is predicted by multiparticle simulations. There are three factors that influence the scaling to higher beam energy: i) increased beam rigidity, ii) two additional extraction kicker modules are required for 1.3 GeV extraction, and iii) the chromatic contribution to the tune spread is reduced at higher energy. The tune spread is given by $\Delta\omega/\omega_0=(\xi-n\eta)\delta$ where ξ is the chromaticity, η is the slip-factor, and δ is the momentum spread. The slip-factor is reduced from -0.198 at 1 GeV to -0.139 at 1.3 GeV, and therefore reduces the available tune-spread at sidebands for lower n. The net result of these effects is a small reduction in threshold at 1.3 GeV relative to 1.0 GeV. Indeed, with multiparticle simulations including 3D space-charge and the measured extraction kicker impedance, we find that the instability threshold lies just above 2.5x10^{14} for 1100 turn accumulation, whereas for 1500 turn accumulation, the beam is unstable before extraction. Therefore, for the 3 MW upgrade parameters we expect the beam to be stable against conventional transverse and longitudinal instabilities, but with little stability margin. From the standpoint of collective instabilities, there is a benefit to achieving increased proton intensity by higher linac current, as opposed to a longer linac pulse.

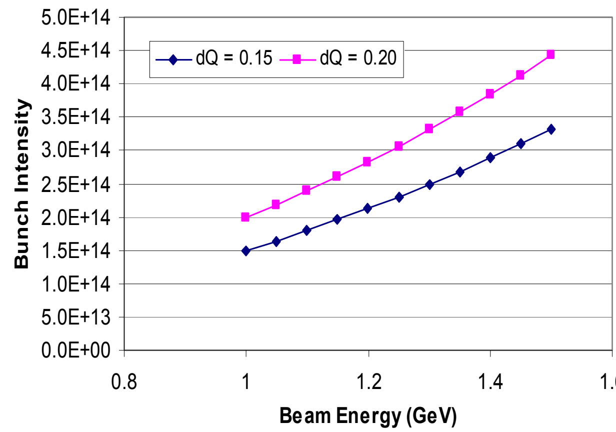

Figure 2: Ring bunch intensity vs. beam energy for constant space charge tuneshift.

The "electron-proton" instability threshold is predicted to lie above the 3MW upgrade intensity [6]. Given the uncertainties in predicting instability thresholds for conventional impedances, as well as from the electron cloud, we plan to install a wideband feedback system which spans the frequency bands of interest: from 5-30 MHz for the extraction kicker impedance, and from 50-200 MHz for the e-p instability.

CONCLUSIONS

A 3 MW upgrade to the SNS accelerator complex is a relatively straightforward extension of the baseline configuration. The main elements of the 3 MW upgrade are an increase in ion source current, an increase in linac beam energy, and increased RF power delivered to the beam. Extension of the SNS beam power to 5 MW requires a more aggressive approach, extending the state-of-the-art in ion source technology, and upgrading the RF plant to provide even higher beam power.

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