ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPAL049

SNS PROTON POWER UPGRADE STATUS*

M.A. Plum†, J. Galambos, G. Bloom, M. Champion, M. Howell, S-H. Kim, J. Moss, B. Riemer, R. Saethre, K. White, W. Steffey, Oak Ridge National Laboratory, Oak Ridge, Tennessee, US

Abstract

The Spallation Neutron Source (SNS) Proton Power Upgrade (PPU) project aims to double the proton accelerator beam power from 1.4 to 2.8 MW. Over the past year PPU has completed the reviews necessary for Critical Decision-1 approval. The baseline design choices are being refined, and a cost-effective approach has been identified. The beam energy will be increased by 30% and the beam current capability improved by ~50%. The sub-system improvements, expected beam loss increases, and anticipated schedule will be discussed.

INTRODUCTION

The Proton Power Upgrade project at the Oak Ridge Spallation Neutron Source [1] will double the proton beam power from 1.4 to 2.8 MW. This will be accomplished by a ~50% increase in beam current, from 25 to 38 mA (averaged over the 1-ms macropulse), and an increase in the final beam energy from 1.0 to 1.3 GeV. To achieve the current increase some warm linac RF systems will be upgraded to higher power. To achieve the energy increase seven cryomodules containing 28 high-beta elliptical superconducting cavities will be added to the end of the linac. The baseline design has already been well described elsewhere [2,3]. In this paper we will describe recent project developments, the expected increases in beam loss and activation, and the ongoing baseline refinement efforts.

BASELINE REFINEMENT

Warm Linac RF System

To accommodate the increase in peak beam current more RF power is needed to maintain the cavity fields with the increased beam loading. This is only an issue in the warm linac, where the required cavity gradients are determined by their physical geometry. The superconducting linac is flexible enough that the cavity gradients can be lowered where necessary [4]. Some warm linac RF systems have sufficient margin already, while others are close to the acceptable limits. We have embarked on a series of measurements to determine exactly how much margin we have in the warm linac as-installed systems. The PPU baseline plan calls for upgrading the DTL-4 and DTL-5 klystrons from 2.5 to 3.0 MW, but some adjustments to this plan may be necessary depending on the outcome of these measurements.

Both beam-based and cavity-independent measurements began in 2017. The beam-based measurements quantify the PPU beam loading by turning off the ~1 MHz beam chopper systems. Adding the normally-chopped beam back into the macropulse increases the current averaged over the macropulse to the PPU design value of 38 mA. A macropulse length of just a few hundred microseconds at 1 Hz of this type of beam is sufficient for the measurement.

The cavity-independent measurements separately quantify the power available from each of the RF systems. Work is now underway to characterize four (of six) of the 2.5-MW, 402.5-MHz DTL klystrons; and one (of four) of the 5-MW, 805-MHz CCL klystrons; by disconnecting each system from its RF cavity and operating it directly into a passive load with calibrated RF power measurements. Once these measurements are combined with the empirical beam loading measurements we will have determined which RF systems require an upgrade.

Ring Extraction Kicker System

Beam extraction from the SNS storage ring is accomplished by simultaneously pulsing a set of 14 magnetic extraction kickers. The PPU baseline plan calls for adding two additional kickers to accommodate the increase in beam energy. However, there is another option, to instead increase the kicker pulse voltages. This would avoid the need to build the new magnets, extend the associated beam-line vacuum tanks, and install the infrastructure needed to support the new kicker systems; and it would save over $2M.

The existing systems use DC power supplies to charge capacitor banks that feed pulse forming networks. Using only existing kickers, these supplies are not capable of delivering enough current to charge the capacitors to the increased PPU levels in the allotted time between pulses. A new resonant charging system has been proposed to replace the DC system. The charging time would be reduced from ~14 ms to just 1 or 2 ms, and it would charge the capacitor banks to the higher PPU-required voltages. To date single pulse testing of a prototype circuit has shown promising results. In the coming months the prototype will be tested at the full 60-Hz, ~46 kV duty factor.

BEAM LOSS

Beam loss is always a concern at high power accelerator facilities, due to radioactivation that impacts hands-on maintenance, and due to beam line equipment damage. With the higher beam currents and beam energy in the PPU project we expect more beam loss and increased activation.

* This manuscript has been authored by UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE). The US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).
† plum@sns.gov

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPAL049

Beam loss at SNS comes from several different mechanisms, and the relative contributions vary depending on the location in the accelerator. In the warm linac the beam loss is dominated by residual gas stripping and halo scraping. In the superconducting linac (SCL) it is dominated by intrabeam stripping (IBSt). In the transport line from the linac to the ring (HEBT) it is dominated by halo scraping and residual gas stripping. In the ring it is dominated by scattering in the charge-exchange injection stripper foil, and in the transport line from the ring to the target (RTBT) it is dominated by halo scraping.

Gas Stripping and Halo Scraping

Beam loss due to residual gas stripping is proportional to the average beam current, so in the locations where this effect is dominant the PPU project will increase the dose rate by a factor of (38 mA / 25 mA) = 1.52. We expect the beam loss due to halo scraping to also scale with the average current.

Intra-Beam Stripping

Beam loss due to IBSt is proportional to the square of the beam density [5]. Since, in the linac, the longitudinal beam size will remain about the same, the IBSt dose rate in the existing part of the linac will increase by approximately a factor of $(38\text{ mA} / 25\text{ mA})^2 = 2.31$. We do not yet have a good model for the IBSt beam loss rate in the new part of the SCL. However, we have empirically found that the dose rates in the existing linac are roughly constant along its length. Therefore, it is reasonable to expect this pattern to continue into the new section, such that the dose rates there will be similar to the increased dose rates in the existing part of the linac.

Dose Rate vs. Beam Energy

In the HEBT and RTBT transport lines we expect the fractional beam loss to be the same, so the number of particles lost will increase is proportion to the average current increase. The dose rate also has a beam energy dependence. For a given amount of beam power lost, the dose rate scales like $(E\text{-}9)^{1.8}/E$, where E is the beam energy in MeV [6]. Therefore, for a constant number of particles lost per unit time, the beam energy increase alone will increase the dose rate by a factor of $(1300\text{-}9)^{1.8}/(1000\text{-}9)^{1.8} = 1.61$. The total increase in the HEBT and RTBT is therefore expected to increase by a factor of 1.61 x 1.52 = 2.45.

Stripper Foil Scattering

Beam loss due to stripper foil scattering is a combination of Rutherford (Coulomb) scattering and nuclear scattering. It is also the cause of the high radioactivation levels in the ring injection section as shown in Fig. 1. At the LANL PSR, which is very similar to the SNS ring, Rutherford and nuclear scattering contribute nearly equal amounts to the stripper-foil-induced beam loss (~35% due to large angle Rutherford and ~30% due to nuclear [7]). In the following discussion we will assume equal contributions for the SNS case.

The probability that a large angle Rutherford scattering event will result in beam loss can be estimated by [7]:

$$P = \left(\frac{2Zm_e r_e}{\gamma M\beta^2}\right)^2 N_0\left(\frac{\rho t}{A}\right)\left[\frac{1}{\theta_{xl}\theta_{yl}} + \frac{1}{\theta_{xl}^2}\tan^{-1}\left(\frac{\theta_{yl}}{\theta_{xl}}\right) + \frac{1}{\theta_{yl}^2}\tan^{-1}\left(\frac{\theta_{xl}}{\theta_{yl}}\right)\right]$$

where P is the probability, Z is the charge number of the target nucleus, m_e and r_e are the electron's mass and classical radius, M is the mass of the incident particle, γ and β are the usual relativistic factors, ρt is the areal thickness of the target, A is the atomic mass of the target, N_0 is Avogadro's number, and θ_{xl} and θ_{yl} are the limiting aperture angles.

The scattering probability is directly proportional to the foil thickness ρt, and inversely proportional to the beam energy by $\gamma^2\beta^4$. The PPU stripper foil will be about 8% thicker to achieve the same stripping efficiency at the higher beam energy. When put together with the 35% reduction in scattering probability due to beam energy alone, there is a net reduction of about 30% in the fractional beam loss caused by foil stripping.

To account for the effect of the beam energy on the dose rate we use the $(E\text{-}9)^{1.8}/E$ scaling. The final result is

$$\text{dose rate} \propto \left(\frac{1}{\gamma\beta^2}\right)^2 (\rho t)(E-9)^{1.8}\,.$$

For a given number of injected protons, the dose rate at 1.3 GeV is 12% higher than at 1.0 GeV. At the PPU power level of 2.8 MW the proton number increases by the factor of 1.52, for a net overall increase in dose rate by a factor of 1.71.

To estimate the impact of nuclear scattering we note that p-p and p-n cross sections are nearly the same at 1.0 and 1.3 GeV [8]. The dose rate due to nuclear scattering in the stripper foil should therefore increase in proportion to the foil thickness and then scaled for beam energy:

$$\text{dose rate} \propto (\rho t)(E-9)^{1.8}\,.$$

The total effect from both large angle Rutherford and nuclear scattering is then

$$\text{dose rate} \propto \left[1 + \left(\frac{1}{\gamma\beta^2}\right)^2\right](\rho t)(E-9)^{1.8}\,,$$

and at 2.8 MW we expect the dose rate due to stripper foil scattering to increase by a factor of 2.38.

Ring Collimation Losses

In addition to large angle Rutherford and nuclear scattering in the stripper foil there is also small angle scattering. This type of scattering causes a slow growth in the beam tails that primarily causes beam loss in the collimation section. The collimators are well shielded and so the activation levels in this part of the ring are only slightly elevated.

It is not exactly correct to say that the beam loss scales with the rms scattering angle, but we can use it as a rough

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPAL049

estimate. The rms scattering angle of a proton beam passing through a very thin film is [9]

$$\theta_{rms} = \frac{14.1\text{ MeV}}{p\beta c}\sqrt{\left({}^{x}/_{x_{rad}}\right)}\,,$$

where p is the proton beam momentum, βc is the proton velocity, x is the stripper foil thickness, and $x_{\rm rad}$ for carbon is 42.7 g/cm^2. (This is similar to the equation for multiple scattering, but without the logarithmic term). For our case, at 1.0 GeV and for a 0.385 mg/cm^2 thick foil, θ_{rms} = 2.2x10^{-5} rad; and at 1.3 GeV and a 0.416 mg/cm^2 thick foil (8% thicker), θ_{rms} = 2.0x10^{-5} rad. The rms scattering angle is 9% lower at 1.3 GeV.

Including both the energy and the angle then,

$$\text{dose rate} \propto \theta_{\rm rms}(E-9)^{1.8}\,,$$

and we find that for a given number of injected protons, keeping everything the same except for the beam energy and the foil thickness, the dose rate at 1.3 GeV is expected to be 1.46 times higher than at 1.0 GeV. Adding in the factor of 1.52 times more protons for the 2.8 MW case compared to the 1.4 MW case gives an estimated dose rate 2.22 times higher. Table 1 summarizes the expected dose rate increases in the different parts of the accelerator.

Table 1: Dose Rate Increases in the Accelerator, Comparing 1 GeV, 1.4 MW to 1.3 GeV, 2.8 MW

Location in Accelerator	Dose Rate Increase Factor
Warm linac	1.52
SCL (up to 1.0 GeV section)	2.31
SCL (1.3 GeV section)	2.31
HEBT	2.45
Ring injection	2.38
Ring collimation	2.22
RTBT	2.45

ACCELERATOR ACTIVATION

Typical activation levels in the SNS accelerator after high power operation at 1.3 MW are shown in Fig. 1. Dose rates after the PPU upgrade with operations at 2.8 MW are expected to be higher by approximately the factors shown in Table 1, plus another 8% to account for 1.4 MW baseline vs the 1.3 MW case for the figure. A key point is that the levels will be still be low enough that hands-on maintenance will be straightforward in every area except the ring injection area. Fortunately, the activation levels drop quickly in the first few days after the beam is shut off, so even in the ring injection area we will be able to continue to perform hands-on maintenance but some extra cool down time may be desirable.

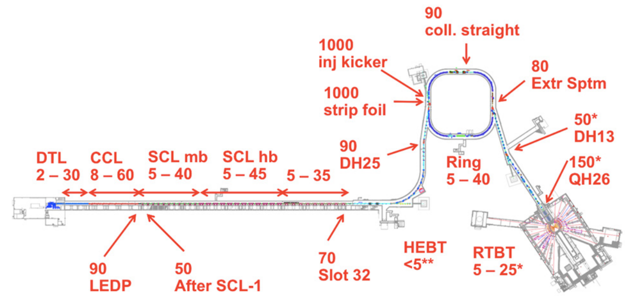

Figure 1: Typical activation levels in the SNS accelerator after 1.3 MW operations and 3 – 5 hour cool down. The numbers are in units of mrem/h at 30 cm. (Figure reproduced from [10].)

PROJECT SCHEDULE

The US Dept. of Energy approved the Mission Need for the PPU project (CD-0) in 2009. The Alternative Selection and Cost Range (CD-1) was approved in April 2018, and the initial project funding was also approved in April 2018. The early project completion is projected for 2025.

REFERENCES

[1] S. Henderson *et al.*, “The Spallation Neutron Source accelerator system design,” *Nucl Instrum Meth A*, vol. 763, pp. 610-673, 2014, doi: 10.1016/j.nima.2014.03.067
[2] “Conceptual Design Report for the Proton Power Up- grade Project,” ORNL, Oak Ridge, TN, USA, Rep. ORNL/TM-2016/672, Feb. 2017.
[3] M. S. Champion *et al.*, in *Proc. IPAC’17,* Copenhagen, Denmark, May 2017, pp. 2445-2448, doi.org/10.18429/JACoW-IPAC2017-TUPVA147.
[4] S-H. Kim *et al.*, “Superconducting Linac Upgrade Plan for the Second Target Station Project at SNS,” in *Proc. SRF’15*, Whistler, Canada, paper MOPB069, pp. 268-271.
[5] V. Lebedev *et al.*, in *Proc. Linac’10*, Tsukuba, Japan, Sep. 2010, paper THP080, pp. 929-931.
[6] J. Galambos *et al.*, “SNS Beam Loss, Activation, and Collimation,” in *Snowmass 2001*, Snowmass Village, June 30 - July 21, 2001.
[7] R. Macek, “PSR Beam Losses at Injection,” in *Fermilab H− Transport and Injection Mini-Workshop*, December 9-10, 2004.
[8] C. Patrignani *et al.* (Particle Data Group), “Review of Particle Physics,” *Chin. Phys. C,* vol. 40, no. 10, p. 100001, 2016.
[9] F. Hinterberger, T. Mayer-Kuckuk, and D. Prashun, *NIM A275,* pp. 239-245, 1989.
[10] M. Plum, “High Power Operation of SNS SC Linac,” in *Proc. Linac’16*, East Lancing, MI, USA, Sep. 2016, pp. 348-352, doi.org/10.18429/JACoW-LINAC2016-TU1A05