SNS proton power upgrade

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Abstract. The Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL) is preparing for the Proton Power Upgrade (PPU) project to increase the output energy of the accelerator from 1.0 GeV to 1.3 GeV. As part of this project with the combination of increasing the output energy and beam current, the beam power capability will be doubled from 1.4MW to 2.8MW. In this project, seven new high beta cryomodules housing 28 superconducting niobium cavities will be added to the LINAC tunnel. Lessons learned from over ten years of operation will be incorporated into the new cryomodule and cavity design. The design and the fabrication of these cryomodules and how these will be integrated into the existing accelerator will be detailed in this paper.

1. Introduction

The Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL) is the world’s first megawatt class pulsed neutron source. Researchers from all around the world come from universities, industry, and national laboratories to solve challenging technical problems that are best addressed using neutrons. SNS generates the world’s highest peak brightness neutron beams, enabling researchers to make innovative discoveries in a wide array of scientific fields of study. To maintain the SNS at the forefront of neutron science, a Second Target Station (STS) is planned which will open opportunities for new science using higher peak brightness cold neutron beams. To enable the development of the STS and to maximize productivity of the First Target Station (FTS), a Proton Power Upgrade (PPU) is planned. This upgrade will double the power capability of the accelerator from 1.4 MW to 2.8 MW. With this upgrade in place, a 2-MW beam can be directed to FTS resulting in improved performance of the existing instrument suite.

To accomplish the increase in proton beam power, the beam energy will be increased from approximately 1 GeV to 1.3 GeV by adding seven new high beta cryomodules to the linear accelerator. The SNS was designed with expansion capability for up to nine additional modules. However, only seven cryomodules are required to meet the design energy of 1.3 GeV while keeping three cavities in reserve for energy margin. During the original project, the transfer line and waveguide penetrations were installed to facilitate a future upgrade. The helium cryogenic system was designed to handle the additional heat load of upgraded cryomodules. Therefore, there is no planned upgrade of the helium cryogenic system.

Some changes that do not require modification of the overall layout will be made based on lessons learned from the last ten years of operation. Additionally, some changes are required based on
pressure vessel code compliance. The design changes required by the pressure vessel code were implemented in the high beta spare cryomodule and are discussed below. Table 1 summarizes the design changes between the original SNS high beta cryomodule and the cryomodule for PPU. The design changes are discussed in the following subsections.

| Parameters                                                                 | Original SNS high-beta cryomodule | PPU high-beta cryomodule |
|----------------------------------------------------------------------------|-----------------------------------|--------------------------|
| $E_{\text{acc}}$ ($=E_0 T_p, T_p$: Transit time factor at $\beta=0.81$) (MV/m) | 15.8                             | 16.0                     |
| Fundamental power coupler (FPC) rating, peak and average (kW)              | 550, 50                           | 700, 65                  |
| External Q of FPC, $Q_{\text{ex}}$                                        | $7 \times 10^5$ (±20%), fixed type | $8 \times 10^5$ (±20%), fixed type |
| Material of cavity                                                         | High RRR niobium (RRR>250) for cells, reactor-grade niobium for end groups | High RRR niobium (RRR>250) for both cells and end groups |
| Higher-order mode couplers per cavity                                      | Two (one at each end group)       | None                     |
| Tuner                                                                     | One mechanical tune, one fast piezo tuner | 1 mechanical tuner (no fast piezo tuner) |
| Pressure vessel                                                            | Good engineering practice         | Code stamp required       |

RRR = residual resistivity ratio

2. Operating history of SNS cavities
The original SNS cavities exhibit electron loading from field emission and multi-pacting below the design accelerating gradients. This is the main limiting factor of the superconducting linac and ultimately limits the output energy below the original design. In addition, collective effects have been observed within high beta cryomodules. If there is one bad acting cavity, it can negatively affect the neighboring cavities within a high beta cryomodule. This is less of a concern in medium beta cryomodules because they are not as efficient for electron acceleration. When electrons impact the surface of the cavity, it can result in a release of trapped hydrogen gas and trigger the vacuum interlocks. This can lead to redistribution of adsorbed gases within the cavity and force the operating gradients to be lowered. Each cavity is set at a stable gradient based on the collective limiting gradients achieved through a series of SRF cavity/cryomodule performance tests at SNS, whereas the design calls for setting uniform gradients [1]. Developments in the spare high beta cryomodule and additional proposed design changes for the PPU cryomodules are being applied to mitigate these performance limitations.

3. High beta spare cryomodule
A high beta cryomodule was developed in house and has been installed in the tunnel for operation since the summer of 2012. All four of the cavities within that cryomodule were commissioned at 17 MV/m or higher at the full duty factor. Only one cavity of the four shows minor x-rays starting from 15.5 MV/m, and all four cavities have been running at 16 MV/m during the production runs [2,3]. The available RF power limits the operating gradients of the high beta cavities to 16 MV/m. The performance of the original SNS cavities was limited by field emission and multi-pacting resulting in lower operational gradients in the high beta cryomodules. The average operating gradient of a high beta cryomodule at SNS is 13.5 MV/m.
The changes that led to the improved gradients within the high beta spare cryomodule will be utilized in the production PPU cryomodules. The improvement in gradient can be mainly attributed from changing from Buffered Chemical Polishing (BCP) to electropolishing (EP). EP produces a smoother finish and has typically shown higher operating gradients as well as higher field emission onset. The original cavities were fabricated with reactor grade end groups. This material was used in the end groups to reduce cost. The surfaces of these end groups were very rough due to the high aspect ratio deep drawing and the subsequent heat treatments. The increased grain size coupled with BCP resulted in preferential etching of the grain boundaries creating this rough finish on all the original SNS end groups. The EP process that was applied to the spare cryomodule cavities improved the surface of both the cells and the end groups and allowed for more effective cleaning of the cavity after chemical processing. The cavity performance observed in the high beta spare cryomodule offers high confidence that the PPU cryomodules will meet the gradient specification by using EP instead of BCP for the final chemistry and by improving the cavity end groups.

4. Cavity upgrades

As mentioned in the previous section, the original end groups were constructed of reactor grade niobium as opposed to high residual resistivity ratio (RRR) material. Analysis showed that it would not impact the performance of the cavity, which did not include thermal stability against electron activity such as field emission and multi-pacting. However, the long conduction path of the end group to the liquid helium has resulted in thermal instability of the end group with additional heating from electron activity. For the PPU cavities, it is proposed to construct the end groups of high residual resistivity ratio (RRR) material. This higher purity material has a higher thermal conductivity and thus should result in a more thermally stable end group. Additionally, cooling blocks will be added to the end groups to increase the thermal contact between the end group and the helium.

The original cavities were equipped with a Higher Order Mode (HOM) coupler on each end group to filter any unwanted RF energy present in the cavity due to radiative excitation of the cavity by the particle beam [4]. In actual operations, the HOM couplers have been problematic. Within 1 year of operation, all the attenuators for the HOM couplers were damaged. To date in four cryomodules removed from the tunnel, half of the HOM feedthroughs had leaks and had to be removed. In 2007, a review was held concerning HOM couplers and it was concluded that these couplers were not needed for SNS cavities. A recommendation was put forth to remove all HOM couplers from cryomodules removed from the tunnel for repairs. Therefore, HOM couplers will not be used in the PPU cavities. This also removes a complex geometry to chemically process and rinse during the cavity processing evolutions. It is anticipated that this design change will reduce electron activity within the end group of the cavities. Figure 1 shows a test cavity end group constructed without a HOM coupler.

![Completed end group replacement.](image-url)
The original SNS fundamental power coupler (FPC) was designed and scaled from the one KEK developed for 508 MHz. A design requirement of the FPC was to transmit 2 W or less of thermal radiation to the end group. The outer conductor of the FPC has a direct conduction path from room temperature to the cavity. Therefore, it is cooled with supercritical helium at 3 atm and 5 K to remove approximately 30 W static and dynamic load. The inner surface of the outer conductor is copper plated stainless steel which is designed to reduce heat dissipation. The inner conductor of the FPC is made of copper and is not actively cooled. Figure 2 shows a FPC schematic, the inner conductor assembly, and the outer conductor assembly.

![FPC Schematic](image)

**Figure 2.** SNS fundamental power coupler (A: schematics, B: inner conductor assembly, C: outer conductor assembly).

The SNS FPCs have been reliably performing at over 550-kW peak power in operation at various standing wave ratios, limited only by the operational envelope in the linac. The FPC for the PPU cavities must be able to transfer up to 700-kW peak power over a 1.3 ms pulse width at a repetition rate of 60 Hz. Based on the testing and operational experience, the RF performance of the original FPC can satisfy the PPU requirements. However, a design modification is needed to maintain the inner conductor temperature sufficiently low. Since the thermal radiation from the inner conductor will be higher because of the increased average RF power, a thicker inner conductor will be used for the PPU, which is sufficient and provides the simplest solution. The PPU inner conductor will be twice as thick as the original, 3.5 mm to 7 mm. With a 7-mm thick inner conductor, the inner conductor tip temperature at the PPU condition can be kept below that of the FPCs presently operating at SNS. The prototype FPC for the PPU with the increased wall thickness was manufactured by the vendor that provided the original FPCs, installed in a horizontal test apparatus, and successfully tested. Except for the wall thickness of the inner conductor, all other aspects of the FPC design are the same. The $Q_{ex}$ value chosen for the PPU in Table 1 is optimized to reduce the RF power requirement.

The original tuner design shown in Figure 3 was adapted from a Saclay design for TESLA Test Facility Cavities [5]. It is attached to the cavity at three points. Two of the points were standard stand offs and the third was a Piezo fast tuner. The tuner is adjusted by a harmonic drive and motor giving a tuning range of approximately 400 kHz [6].
One key change to the tuner for the PPU cavities will be the removal of the Piezo tuner. The original design included this to address any unexpected mechanical resonance conditions driven by Lorentz force. Since the SNS cavity RF circuit has a large bandwidth, and the SNS cavities do not have adverse mechanical resonance conditions, the cavity phase and RF amplitude are well managed within the requirements by the Adaptive Feed Forward (AFF) implemented in the SNS low-level radiofrequency (RF) system [7]. The piezo tuners have never been actuated in operation at SNS. Moreover, several failures with piezo stacks have occurred because of pressure changes in the cryomodules either during the 2 to 4 K transition or during upset conditions. The piezo tuners were replaced with the standard standoffs used on the other two legs of the tuner. Because of this history, it was decided to eliminate them from future cryomodules built for SNS.

5. Cryomodule upgrades

Seven cryomodules like the original high beta cryomodules will be fabricated for the PPU. Because there is existing infrastructure in place including transfer line and RF waveguide penetrations, the interface points of a cryomodule need to be held constant. The design features of the PPU cryomodule that will be identical to the original cryomodules are the bayonet positions, coupler positions, cold mass assembly, and overall footprint. Figure 4 shows a diagram of the design features that were fixed versus those which were free to move.

![Figure 3. Schematic of the original SNS tuner assembly.](image)

![Figure 4. Cryomodule reference interface locations.](image)
The PPU cryomodules must meet the pressure requirements put forth in the 10 CFR 851, “Worker Safety and Health”. A three, pressure stamp approach will be used for these cryomodules. The vacuum vessel, supply end can, and return end can will each be code stamped on the vacuum boundary. This adheres to the ASME Boiler and Pressure Vessel Code (B&PVC). This approach was developed during the construction of the high beta spare cryomodule.

Enacting the code forced the removal of the bridging ring from the original design concept. That required that the main part of the vacuum vessel be longer than the original cryomodule. Removing the bridging ring and the adjustment capability of the external beam line position on the cryomodule complicated the assembly of the warm to cold transition at each end of the cryomodule. The changes affected the flexibility of the alignment of the string to the warm beam line flange. Therefore, modelling of the string within the vacuum vessel had to be very precise because the movement of the warm-to-cold transition in the old design was eliminated. The alignment during the spare high-beta cryomodule assembly was performed with a laser tracker, and the modelling was successful, so that the string aligned with the warm valve within the specification limit of 1 mm [2]. Figures 5 and 6 depict changes in the design of the vacuum vessel.

![Weld Ring Diagram](image1)

**Figure 5.** Original (A) versus new (B) vacuum vessel.

![Bridging Ring Diagram](image2)

![Flat Head Diagram](image3)

**Figure 6.** Original (A) versus new (B) vacuum jacket design.
To simplify the supply end can as much as possible, the primary and secondary JT valves were moved from the end can to the vacuum vessel. This required a change in the vacuum vessel design, and more piping was added to the main body of the cryomodule. Figure 7 depicts this change.

![Figure 7. JT valve positions for the PPU cryomodule (A) and the original (B) cryomodule.](image)

Piping was also redesigned within the end cans to make the can easier to fabricate. Because these are now pressure stamped vessels, the vacuum boundary had to change shape to meet the code. The piping was designed such that it could fit within the end can and give the same functionality as the original design. Diagrams of the end can piping are shown in Figures 8 and 9.

![Figure 8. Original (A) versus new (B) supply end can.](image)

![Figure 9. Original (A) versus new (B) return end can.](image)
The original cryomodules were equipped with many in-process diodes for accurate temperature measurement of helium streams. With the elevated radiation levels within the linac tunnel, many of these diodes have failed. In the PPU cryomodules, Cernox sensors will be primarily used due to the radiation resistance of these sensors. Pressure instruments containing electronic components have had multiple failures on the cryomodules and were subsequently replaced with strain gauges. The pressure and other instrumentation will be kept the same as what is currently used in cryomodules in the tunnel.

6. PPU approach
During the PPU, SNS intends to partner with another institute to fabricate and assemble these seven new cryomodules. SNS has critical experience into building a cryomodule of this type after producing the SNS high beta spare cryomodule in 2012. This insight will be transferred to a partner. The partner will use this technical information along with their larger production capacity to supply the seven cryomodules to SNS. With the design changes detailed in this paper, there is confidence in meeting the gradient specification and producing the required beam energy with adequate margin.

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Acknowledgements
This work was supported by SNS through UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the U.S. DOE.