PROGRESS ON THE PROTON POWER UPGRADE OF THE SPALLATION NEUTRON SOURCE*

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Abstract

The Proton Power Upgrade Project is underway at the Spallation Neutron Source at Oak Ridge National Laboratory and will double the proton beam power capability from 1.4 MW to 2.8 MW to provide increased neutron intensity at the first target station and to support future operation of the second target station. This will be accomplished by increasing the beam energy to 1.3 GeV and the beam current to 38 mA (average during the macropulse). Installation of 28 additional superconducting cavities and their associated technical systems will provide for the energy increase. Increased beam loading throughout the accelerator will be accommodated primarily through the use of existing margin in the RF systems and the installation of 700-kW klystrons to power the new superconducting cavities. Upgrades of a few existing RF stations may also be needed. The injection and extraction regions of the accumulator ring will be upgraded, a ring to second target station tunnel stub will be constructed, and a 2-MW target will be developed for the first target station. The project anticipates attainment of Critical Decision 1 in 2017 to ratify the project conceptual design and cost range.

INTRODUCTION

The Proton Power Upgrade (PPU) Project [1] at Oak Ridge National Laboratory will increase the neutron production capability of the Spallation Neutron Source by increasing the Linac H- beam energy from 1.0 to 1.3 GeV and the beam current from 26 mA to 38 mA (average during the 1-ms macropulse). The energy increase will be accomplished by adding 28 superconducting cavities contained in 7 cryomodules to the end of the existing Linac. The beam current increase is achievable based on already demonstrated ion source performance. Additional beam current margin will be provided through the installation of a new radio-frequency quadrupole in 2018 as part of an operational upgrade to the SNS accelerator. High-current accelerator physics studies are underway and 38-mA beam current in the Linac has been achieved. However, RF system upgrades are planned to provide adequate RF power margin throughout the Linac.

The benefits of the PPU include increased science capability at the existing first target station (FTS) and a foundation for the planned second target station (STS) upgrade [2]. The PPU will enable new capabilities and reduced experiment durations with the 18 existing FTS instruments, which are heavily oversubscribed. The STS will include 22 additional instruments. The layout of SNS and the planned STS is shown in Fig. 1.

The PPU scope of work is spread across five main subject areas: superconducting Linac, radio-frequency systems, accumulator ring, first target station, and conventional facilities.

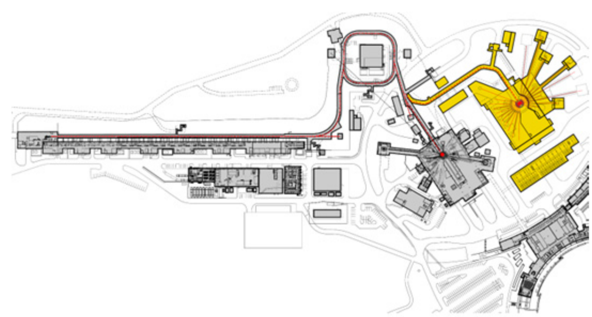

Figure 1: Overview of the Spallation Neutron Source with the planned Second Target Station highlighted in yellow.

SUPERCONDUCTING LINAC

The existing superconducting Linac consists of 81 cavities that accelerate the beam from 186 MeV to approximately 1 GeV. An upgrade to 1.3 GeV was envisioned in the design of the SNS, and tunnel space was reserved for nine additional cryomodules (36 cavities) at the high-energy end of the Linac. Improvements in cavity performance, achieved through electropolishing and other process improvements, have made possible the energy of 1.3 GeV with only seven additional cryomodules (28 cavities) [3]. This improved performance has already been demonstrated in a spare cryomodule [4] that was developed at SNS and installed in 2012 (Fig. 2). The required accelerating gradient is 16-MV/m in the 6-cell 805 MHz cavity.

Cavities for the upgrade will be procured from industry. The cell shape is unchanged from the original SNS high-beta cavity design, but the higher order mode couplers will be omitted, and the end groups will be fabricated of high purity (high RRR) niobium instead of reactor-grade. Electropolishing will be used to process the cavity interior surfaces in contrast to the buffered chemical polishing

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that was used during preparation of the original SNS cryomodules. The helium vessel will be fabricated from titanium. New fundamental power couplers will feature an increased inner conductor wall thickness to improve heat conduction. Prototypes of the coupler have already been received and tested.

The cryomodule design is based on the original SNS design with a few modifications already implemented in the spare cryomodule. Notable changes include the design of the end cans, the deletion of the piezoelectric tuners, and the utilization of a code-stamped vacuum vessel to meet pressure vessel requirements. The cryomodules will be fabricated by a partner laboratory and will be tested in the SNS cryogenic test facility prior to installation in the accelerator.

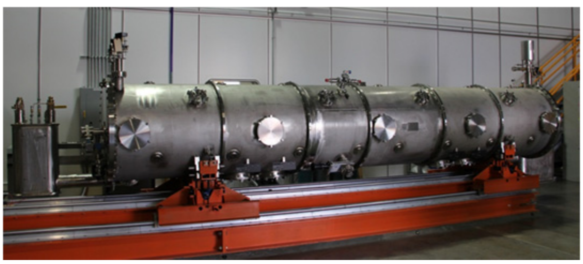

Figure 2: Prototype PPU high-beta cryomodule meets performance requirements and has been in service in the SNS Linac since 2012.

Cryogenic transfer lines for the upgrade were installed during SNS construction, and the existing cryogenic plant has sufficient capacity to handle the heat load of the new cryomodules. It may be necessary to revise the pump-down sequence used to cool the cryomodules from 4.2 K to 2.1 K. New u-tubes will be fabricated to service the new cryomodules.

The cryomodules will be installed in the tunnel during planned maintenance periods in three phases with quantities of 2, 2, and 3, for a total of 7 upgrade cryomodules. The RF systems required for operation of the cryomodules will be installed in advance of the cryomodules.

RADIO-FREQUENCY SYSTEMS

The essential scope of the Radio-Frequency (RF) Systems work breakdown structure (WBS) is the addition of 28 high-power RF klystrons and ancillary equipment to power the 28 new superconducting cavities. The klystrons will provide up to 700 kW at 805 MHz with a cathode voltage of 82 kV. The maximum repetition rate and pulse length are 60 Hz and 1.3 ms, respectively. The RF stations will be installed at the high-energy end of the existing klystron gallery as depicted in Fig. 3.

Three new high voltage converter modulators (HVCMs) will be installed to drive the 28 klystrons in groups of 9, 9, and 10. The klystrons are supported by a transmitter that includes filament, solenoid, and ion pump power supplies, a solid-state drive amplifier, electrical distribution, interlocks, and a PLC controls interface. The transmitter also houses the temperature compensation units for the RF circulators that protect the klystrons from reflected RF power. Five transmitters will be installed to service the 28 klystrons (one transmitter can support up to six klystrons).

The HVCM design is an evolution of the existing 15 modulators that have been in operation >10 years. The Alternate Topology Modulator (ATM) features modified circuitry and components within the modulator oil tank to maximize reliability. A prototype ATM is presently undergoing long term testing [5].

A new low-level RF control system will be developed for the PPU because the existing system can no longer be produced due to parts obsolescence and because it cannot provide functionality needed for the STS upgrade. The MicroTCA platform has been chosen as a basis for the development. Planned performance improvements include increased data processing at the FPGA level and full 60-Hz processing capability.

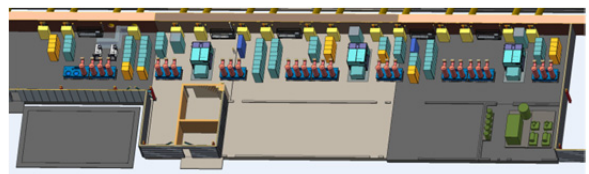

Figure 3: Klystron gallery layout for 28 new RF stations.

The RF Systems WBS includes upgrades to existing HVCMs and klystrons to support the increased beam current. In particular, the conceptual design includes upgrading two of the Drift Tube Linac (DTL) klystrons to 3 MW compared to the existing 2.5-MW klystrons.

A new water cooling system will be constructed to service the 28 new RF stations for the superconducting Linac, and various improvements will be made to existing water cooling systems. All necessary racks, cables and control system hardware are included in the RF Systems WBS.

ACCUMULATOR RING

The accumulator ring was designed to accommodate a 1.3-GeV proton beam, and most of the magnets and magnet power supplies have already been tested at the operating points required for the PPU.

In the injection region, two new injection chicane magnets and one new injection dump magnet must be installed. These will be designed and fabricated by a partner laboratory. The power supplies for the 8 existing injection kicker magnets will be upgraded. The electron stripping foil thickness must be increased to maintain stripping efficiency. Development is underway to ensure the performance and lifetime of the stripping foil under PPU operating conditions.

Two additional extraction kicker magnets will be fabricated and installed adjacent to the 14 existing magnets (Fig. 4) to accommodate the increased beam energy. The possibility of using the existing magnets at increased operating levels is being studied. This would reduce the cost of the upgrade despite the concomitant need to upgrade the charging power supplies for the pulse forming networks.

Due to the increased operating power for all the ring magnets, the ring magnet power supply water cooling system will be upgraded by means of an additional cooling loop, pumping station, and heat exchanger.

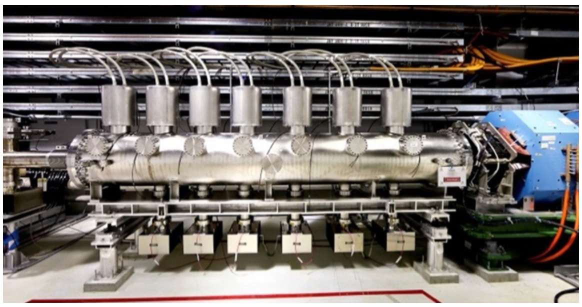

Figure 4: One of two existing extraction kicker tanks that contains seven kicker magnets. The tank will be extended to accommodate installation of an additional magnet.

FIRST TARGET STATION

The PPU will enable delivery of a 2-MW, 1.3-GeV proton beam to the FTS at 60 Hz. Much of the FTS was designed to accommodate a 2-MW, 1.0-GeV beam, but the target module itself (Fig. 5) was designed for a 1.4-MW, 1.0-GeV beam. Therefore, a key deliverable for the PPU is increased target capability, which essentially means acceptable target lifetime when operating with a 2-MW beam.

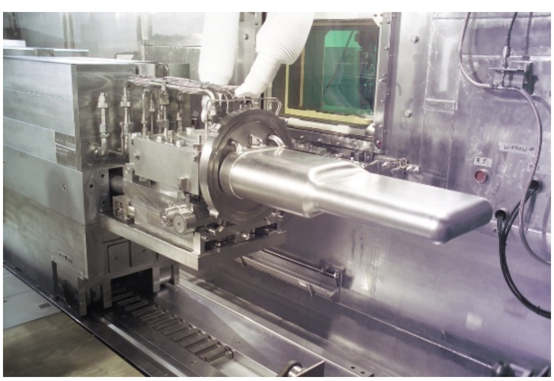

Figure 5: Target module mounted to carriage and ready for installation. The proton beam strikes the nose of the target at the right side of the photograph.

Target lifetime will be ensured by two primary techniques: gas injection and jet flow. The pressure waves created when the proton pulses strike the target will be damped via injection of helium gas bubbles in the mercury, and the cavitation damage at the nose of the target will be further mitigated via high velocity mercury flow (jet flow). Gas injection has been shown to be effective and is expected to reduce pressure-induced stresses by about 40%. Likewise, mitigation of cavitation damage by jet flow has been demonstrated at SNS. Post irradiation examination techniques have been developed and utilized at SNS to improve understanding of target failures and to measure the efficacy of the mitigations. Target Operations and Target Development plans are documented and explain how ongoing operations will inform development of the 2-MW target for the PPU [6, 7].

Additional FTS scope includes neutronics studies to evaluate increased heating and radiation damage rates due to the increased beam energy and upgrades to the mercury process systems, the neutron moderator cryogenic system, vessel and shielding systems, target utilities, instrument systems, and the mercury off-gas treatment system.

CONVENTIONAL FACILITIES

The PPU utilizes existing facilities with a few exceptions. A new 625 ft^2 pump room will be constructed for the water cooling systems that will service the 28 new RF systems, and the existing upgrade portion of the klystron gallery will be outfitted with heating and cooling equipment, electrical power, lighting, and fire protection. Downstream of the accumulator ring, in the Ring to Target Beam Transport (RTBT) tunnel, a RTBT stub (Fig. 6) will be constructed during the 6-month outage that is planned for installation of the accumulator ring components. The stub will enable tie-in to the STS beam transport line without impacting FTS operations.

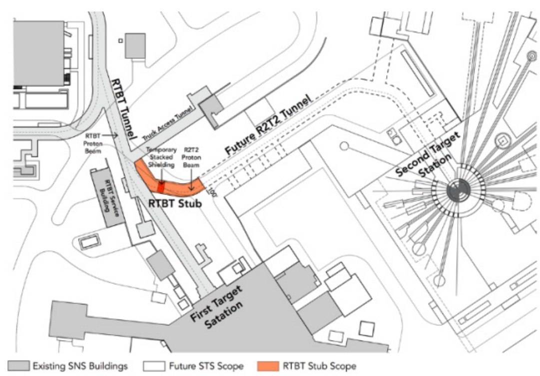

Figure 6: Illustration of RTBT stub relative to existing systems and the planned Second Target Station

PROJECT SCHEDULE

The PPU Project will conduct a Department of Energy Critical Decision 1 (CD-1) review in May 2017. The primary goals of the review are to validate the project conceptual design and establish a cost range. The CD-2 review is anticipated approximately 12-16 months later, and full CD-3 approval is planned in 2020. The early completion date (CD-4) for the project is March 2024. The proposed schedule is based on minimizing disruptions to the neutron science user program and is subject to the availability of project funds.

CONCLUSION

The Proton Power Upgrade Project is underway and has established a sound conceptual design, cost range, schedule, and project team. In many areas, the design is well beyond conceptual since the upgrade includes substantial duplication of existing systems.

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