ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB199

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

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Abstract

The Proton Power Upgrade (PPU) Project at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory will double the proton power capability from 1.4 to 2.8 MW [1]. This will be accomplished through an energy increase from 1.0 to 1.3 GeV and a beam current increase from 26 to 38 mA. The energy increase will be accomplished through the addition of 7 cryomodules to the linear accelerator (Linac). The beam current increase will be supported by upgrading several radiofrequency (RF) systems in the normal-conducting section of the Linac. Upgrades to the accumulator ring injection and extraction regions will accommodate the increase in beam energy. A new 2-MW-capable target and supporting systems will be developed and installed. Conventional facility upgrades include build-out of the existing klystron gallery and construction of a tunnel stub to facilitate future beam transport to the second target station. The project received approval to proceed with construction in October 2020. Procurements are in progress, and some installation activities have already occurred. Most of the installation will take place during three outages in 2022-2023. The project early finish is planned for 2025.

INTRODUCTION

The SNS accelerator routinely delivers a 1.4 MW proton beam to a liquid mercury spallation target to provide neutrons to 19 instruments. The existing Linac produces a 1 ms pulse train of H^- ions at a repetition rate of 60 Hz. The H^- ions are stripped of their electrons as they enter the accumulator ring, which compresses the proton beam to a sub-microsecond pulse, that is extracted and sent to the target. The Linac presently provides a beam energy of 1.0 GeV, which will be increased to 1.3 GeV through the addition of 28 superconducting cavities contained in seven cryomodules. The Linac H^- current will be increased from 26 to 38 mA, which will increase beam loading throughout the Linac. Three drift tube linac RF stations will be upgraded to provide needed additional power by means of new higher-rated klystrons. Otherwise, the existing Linac is capable of accelerating the increased H^- current.

The mercury target and supporting utilities in the existing first target station (FTS) are being upgraded to accept 2 MW of proton beam power, and the remaining beam power will drive the future second target station (STS), that is being constructed as a separate project. The 2 MW beam delivered to the FTS will improve performance across the entire existing and future instrument suite, and the future STS will provide a wholly new capability in the form of a transformative new source optimized to produce the world's highest peak brightness of cold neutrons.

SUPERCONDUCTING LINAC

The superconducting Linac will be upgraded by the addition of seven cryomodules, each containing four high-beta superconducting radiofrequency cavities (Fig. 1). The cryomodules will be installed downstream of the existing Linac in tunnel space that was built during the SNS construction in anticipation of a future energy upgrade. The cryomodule design follows closely the spare high-beta cryomodule that was designed and constructed at SNS and has been in operation since 2012. Due to increased beam loading, the fundamental power coupler design has been modified for improved cooling of the inner conductor. The PPU cavities differ from the original SNS cavities in that the end groups are fabricated from high purity Niobium for improved conduction cooling, and the higher-order mode couplers have been omitted because it has been learned through operational experience that they are unneeded [2].

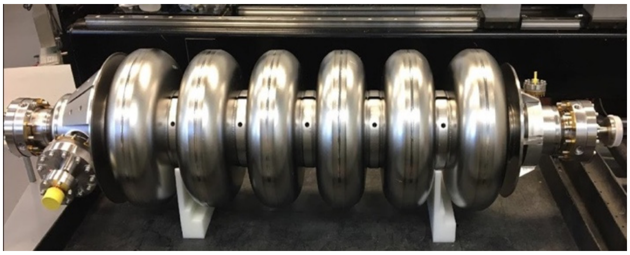

Figure 1: One of 28 beta=0.81, 16 MV/m accelerating gradient superconducting cavities that will be installed by the PPU project.

The cryomodules are being fabricated at the Thomas Jefferson National Accelerator Facility (TJNAF). The cavities were procured from industry and delivered ready for testing. To date, approximately 50% of the tested

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* ORNL is managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the U.S. Department of Energy. This research was supported by the DOE Office of Science, Basic Energy Science, Scientific User Facilities.

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cavities have met performance requirements upon initial vertical testing at 2K. The remaining cavities have met requirements following an additional high-pressure rinse at TJNAF.

The first cavity string has been assembled in the clean room and is now being prepared for cold mass assembly (Fig. 2). The first cryomodule is expected to arrive at SNS in early 2022 after undergoing cryogenic testing at TJNAF. Upon arrival at SNS, it will be fully tested in the cryomodule test facility.

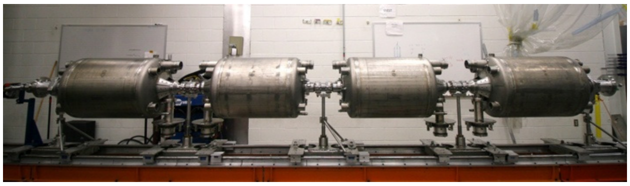

Figure 2: The cavity string for cryomodule #1 in the cold mass assembly area after removal from the clean room.

RADIOFREQUENCY SYSTEMS

Twenty-eight klystron-based RF systems will be installed in the PPU portion of the klystron gallery to power the new superconducting cavities. These systems include 700 kW peak-power klystrons, transmitters, high-voltage converter modulators (HVCMs), low-level RF (LLRF) control systems, and associated waveguide, cabling and racks. A new deionized water system will provide cooling for the RF equipment. All of the RF components are in production at this time. The first klystrons have arrived at SNS.

The 28 new RF stations will be powered by three HVCMs that utilize an alternate topology – compared to existing HVCMs – in the high voltage tank to minimize component stress [3]. The prototype HVCM was extensively tested before issuing a contract to industry to fabricate the production units. The layout of the HVCM is depicted in Fig. 3.

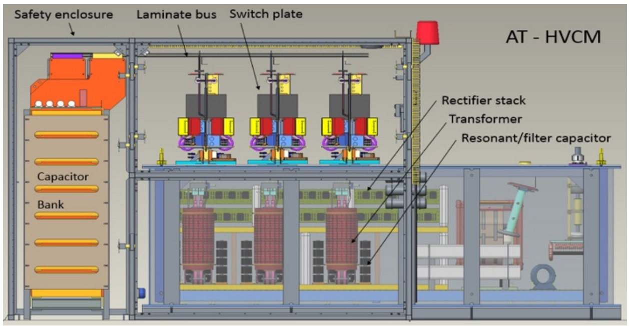

Figure 3: Layout of the Alternate Topology – High Voltage Converter Modulator that will power the PPU klystrons.

Three drift tube linac (DTL) RF stations will be upgraded from 2.5 to 3.0 MW peak-power klystrons to accommodate increased beam loading [4]. The high-voltage modulators for these stations will be upgraded to provide the increased pulsed power needed for the new klystrons. The prototype modulator is presently undergoing testing with good results to date, and the klystrons are in production.

The LLRF control system is a new development (Fig. 4) that builds on the existing LLRF system that has been in operation since the SNS construction was completed in 2006 [5]. The existing system is no longer manufacturable due to obsolescence of key components, so a new system has been developed that utilizes the MicroTCA platform. Key features of the new system include improved diagnostic capabilities, faster adaptive feedforward correction, and mode capabilities that will support operation of the future STS.

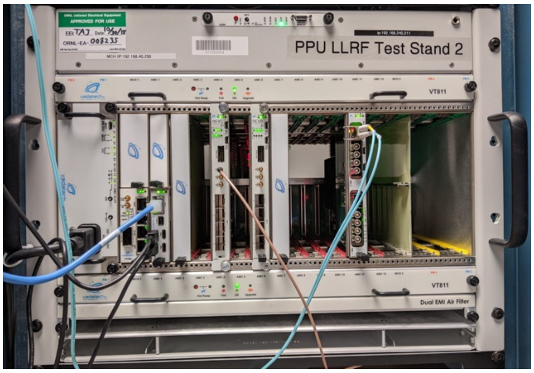

Figure 4: The development test stand for the new low-level RF control system.

RING SYSTEMS

Most of the accumulator ring components were designed to accommodate a 1.3 GeV beam when the SNS facility was constructed. For example, the ring magnets, power supplies, and RF systems do not need to be upgraded for PPU. However, the injection region requires modifications including two new chicane magnets, an injection dipole magnet, and an injection dump quadrupole magnet. The injection kicker magnet power supplies required a minor controls upgrade, which has already been completed, and the extraction kicker magnets required an upgrade to the charging power supplies for the pulse-forming networks. The kicker magnets themselves did not require any modifications.

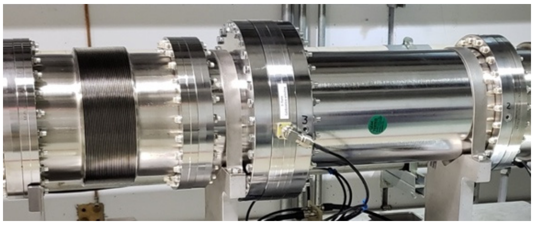

Figure 5: The fast current transformer installed in the RTBT beam line for measurements with beam.

The ring injection dump will potentially receive more beam power due to the increased Linac energy, so an injection dump quadrupole magnet will be added, and an injection dump imaging system has been developed for monitoring the beam pattern on the dump.

A beam power limit system (Fig. 5) is being developed to ensure no more than 2 MW of beam power is delivered to the FTS [6].

FIRST TARGET STATION

The FTS systems scope includes the 2 MW mercury target along with mercury process and utilities, helium gas injection, off-gas treatment, and moderator cryogenic systems needed for operation at increased beam power on target.

The 2 MW target design (Fig. 6) implements lessons learned over more than a decade of operational experience [7]. Extensive computational structural analysis coupled with strain measurements on operational targets have led to a robust mechanical design. Cyclic stress fatigue and cavitation damage, that have been problematic in the past, are being mitigated through the injection of helium gas into the mercury stream. The small helium bubbles, 100's of microns in size, absorb and disperse the pressure waves created by the 60 Hz proton beam, and they inhibit the cavitation process that would otherwise occur where the proton beam strikes the front of the target [8-10].

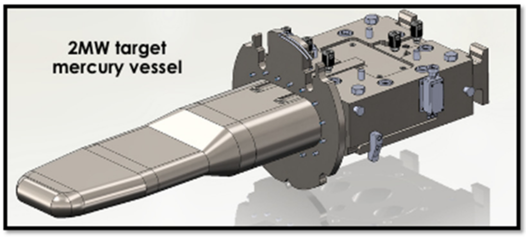

Figure 6: Depiction of the PPU 2 MW mercury target.

The FTS systems components are in procurement or nearing procurement, and it is planned to install these in the first two PPU installation outages.

CONVENTIONAL FACILITIES

The PPU project includes two conventional facilities activities: buildout of the existing high-energy end of the klystron gallery (Fig. 7), which was completed in April 2021, and construction of a tunnel stub that penetrates the wall of the Ring to Target Beam Transport (RTBT) line and will facilitate connection to the future STS without interrupting operation of the existing FTS. The RTBT stub construction is scheduled to be carried out during the PPU long outage that will begin in 2023.

The PPU portion of the klystron gallery was constructed during the SNS construction project in anticipation of a future upgrade and included only the shell of the building with basic utilities. The PPU buildout of the klystron gallery provided installation of electrical power, a deionized water system including a new pump room, an HVAC system, cable tray, fire protection, lighting, and a support system for RF waveguide components – all of the infrastructure needed to support installation and operation of the high-power RF systems. The buildout was designed using Building Information Modeling (BIM) whereby a complete 3-dimensional model was created that included all conventional facilities, deionized (DI) water, and RF systems components. Laser scans were carried out periodically during the construction to confirm adherence to the design model. Much of the DI water piping was constructed off-site and then installed in the klystron gallery. In general, the BIM process was successfully utilized for this construction, but it was a learning experience for SNS and the construction contractor.

Figure 7: The PPU portion of the klystron gallery with new pump room in the foreground and new exterior electrical switchgear in the background along the previously existing klystron gallery.

STATUS AND OUTLOOK

The PPU project received Department of Energy (DOE) Critical Decision 2 and 3 approvals in October 2020. With these approvals, the cost and schedule baseline was established, and construction was authorized to proceed. The total project cost is $271.6M, and the project is scheduled for completion in 2028 with a planned early finish in 2025.

The majority of PPU components will be installed during three maintenance outages beginning in the latter part of 2022 (Fig. 8). Two new cryomodules will be installed in the first outage, and it's planned to commission and operate them in the following neutron production run. Three additional cryomodules will be installed in the second outage, and the final two cryomodules will be installed in the third outage. The supporting radiofrequency systems will be installed during SNS operations. The second outage will be of long duration (~8 months) to accommodate installation of the majority of the PPU components, in particular, ring injection systems, FTS systems, and the RTBT stub construction.

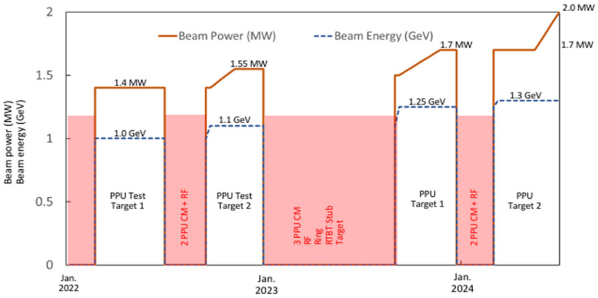

Figure 8: Planned ramp up of beam energy and power as equipment is installed and commissioned over three outages in 2022-2024. Red shaded area are outages.

ACKNOWLEDGMENTS

The authors would like to acknowledge and thank all PPU staff members and others from ORNL or SNS for their support in executing the PPU project.

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