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PROTON POWER UPGRADE PROJECT PROGRESS AND PLANS AT THE SPALLATION NEUTRON SOURCE IN OAK RIDGE TENNESSEE*

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Abstract

The Proton Power Upgrade project is well underway at the Spallation Neutron Source (SNS) facility in Oak Ridge, Tennessee. This project aims at increasing the proton beam power capability from 1.4 to 2.8 MW, by adding linac energy, increasing the beam current and implementing target developments to handle the increased beam power. This talk will cover the current status of increasing the beam energy, issues encountered along the way, operational experience with the new SRF cryomodules and target improvements and results from operation with beam so far.

INTRODUCTION

The Proton Power Upgrade (PPU) project currently underway at Oak Ridge National Laboratory, will increase the proton beam power from 1.4 MW to 2.8 MW to maximize the neutron flux at the experimental beam-lines and provide capability to drive a Second Target Station (STS) in the future [1], see Fig. 1. The increased neutron flux will increase the number of experiments conducted during each run as well as expand the scientific capabilities of SNS. From the beginning of SNS construction, additional space was provided for the increase of the linac energy with 10 additional cryomodule slots at the end of the installed High Beta cryomodules. The PPU project and STS project are currently at DOE critical decision 3 and 1 respectively. The scope of PPU project includes fabrication and installation of seven new 0.81 beta cryomodules; High Power RF klystrons and modulators; Low Level RF systems; vacuum and instrumentation controls; equipment racks; site utility upgrades; beam instrumentation; chicane magnets; new injection dump septum magnet; fabrication of 2 test targets; testing of the new targets; conventional facility modifications; utility upgrades and a stub-out added to the ring to target beam transport section to extend the tunnel towards the proposed STS target station location. The stub-out construction will reduce interruptions to beam operations during construction of the second target station tunnel. The scope of the STS project will include a second target hall housing a solid rotating target and additional beam-lines for experiments. For the First Target Station (FTS) improvements to the target design were necessary for the full 2.0 MWs of beam power to increase their lifetime, a portion of the 2.8 MW beam (0.7 MWs) will be sent to the STS once it is complete [1].

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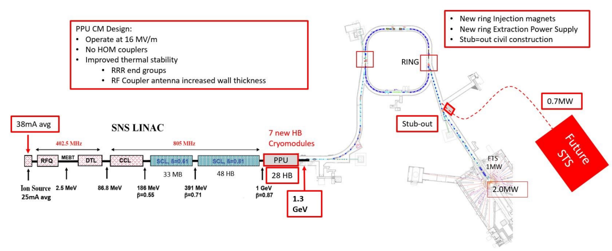

Figure 1: SNS layout and design parameters.

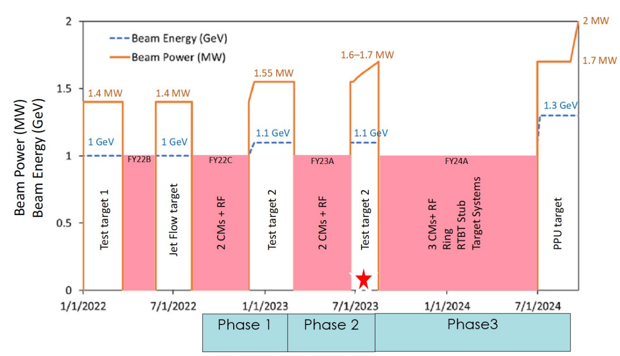

Figure 2: PPU planned outages.

Major Specification	Current operation	PPU full capability	PPU FTS operation
Beam power (MW)	1.4	2.8	2.0
Beam energy (GeV)	1.0	1.3	1.3
Beam current, macro-pulse average (mA)	25	38	27
Macro-pulse length (ms)	1	1	1
Energy per pulse (kJ)	24	47	33
Repetition rate (Hz)	60	60	60

Key Performance Parameter	Threshold	Objective
Beam power on target (MW)	1.7	2.0
Beam energy (GeV)	1.25	1.3
Target operation without failure (hours)	1250 at 1.7 MW	1250 at 2.0 MW
Stored bam intensity in ring (protons per pulse, ppp)	1.60×10^{14} ppp[1]	2.24×10^{14} ppp[2]

[1] corresponds to 1.92 MW at 1.25 GeV and 60 pps
[2] corresponds to 2.80 MW at 1.30 GeV and 60 pps

Figure 3: PPU key performance parameters.

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CURRENT STATUS OF THE PPU PROJECT

The PPU plan is based on upgrading the linac energy in three phases during planned maintenance outages [2]. The outages include 2 short, roughly 10 weeks and 1 long outage, 8 months in length. Recently the plan was changed so the long outage will follow the two short outages due to delays in equipment delivery. The two short outages were completed with 4 PPU cryomodules installed in the linac along with their supporting systems and are fully operational at design specifications. In the long outage which starts in the August of this year, the remaining three cryomodules will be installed for a total of seven to complete the linac energy upgrade to 1.3 GeV. The PPU cryomodule at the end of the linac will be for reserve gradient to adjust for gradient changes during operations. The beam energy was increased after the first outage to 1.05 GeV and the current linac energy is now maintained at this energy. The beam current will also be slowly increased for this current run to reach 1.7 MW of beam power and gain experience before the August long down. This plan allows for testing the overall linac performance at the higher beam loading prior to the final linac energy and gains valuable operating experience on all systems. This increased energy allows for increased neutron flux for experiments prior to completing the upgrade project, which also helps in preparation for the final beam parameters at the experimental end. The linac layout is shown in Fig. 1, the red boxes indicate PPU project upgrades to SNS. The stub-out construction adds a section of tunnel to allow for the second target station construction without operations interruptions. In Fig. 2, shows the planned outages and energy plan for operations for the project. Currently the first two outages were completed (indicated by the red Star) and the third outage the additional three cryomodules will be installed and the civil construction for the stub-out will be completed. In Fig. 3, shows the key performance parameters for; the operation before the upgrade, the capability after the upgrade is complete and the planned FTS parameters [2].

PPU CRYOMODULE, CAVITY, AND RF COUPLER DESIGN CHANGES

The seven new cryomodules have only minor design changes and are based on a first article HB cryomodule built in-house and installed in 2012 [2, 3]. This cryomodule is operated at the PPU design gradient of 16 M/V/m verifying the design over many years of operation. The major design change of this first article and the new PPU cryomodules is the code stamped vacuum vessel and supply and return end cans to meet pressure vessel codes [3]. Additionally, the primary and shield cryogenic control valves were moved into the main body of the vacuum-vessel to reduce the complexity of the supply end-can. The cavity design and processing also had several changes based on SNS operational experience and SRF process improvements which have incurred since the original build project in 2005. The cavity processing at Research Instruments (RI) was changed from buffered chemical polish (used for cavities in 2005) to electropolishing (EP) for both bulk and final chemistry to help reduce the early onset of field emission. Early in the project, time was taken to establish the EP methodology at Jefferson Lab and at RI for the PPU cavity [4]. RI had to make only minor facility changes to accommodate the PPU cavity. A decision was made to keep the original beta 0.81 design to reduce project risk but several changes were made to the end-groups to improve the cleaning and thermal stability. The end-group niobium material was changed to high RRR (was reactor grade) for fabrication and the HOM couplers were removed from the design because they are not needed for SNS operation [5]. These changes simplified the fabrication and along with the electropolishing improved the cleaning of the surfaces due to the reduced complexity and smoother surfaces. The RF couplers also had a few design changes to increase thermal stability for the higher power requirements. First the inner conductor was shortened by 1 mm to better match the beam loading condition and the wall thickness was increased to 7.0 mm to provide better thermal conduction path.

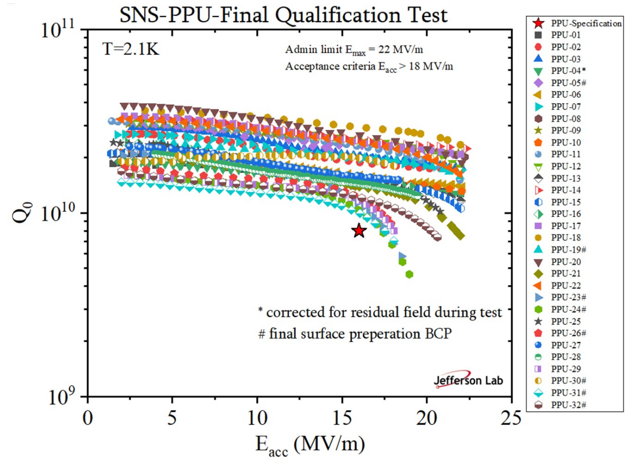

Figure 4: PPU cavity performance at Jefferson Lab.

PPU CRYOMODULE PRODUCTION

Currently, five of the eight PPU cryomodules have been received at SNS from our partner lab, Jefferson lab (JLab) in Newport News, Virginia. Seven of the cryomodules will be installed in the linac for the energy upgrade and one will serve as a spare for operations. For the fabrication of these cryomodules, SNS procured thirty five (35) high-power RF couplers from Cannon in Japan and thirty two (32) HB cavities from Research Instruments (RI) in Germany. RF Couplers were assembled and conditioned at SNS and delivered to Jlab in batches to meet the cryomodule production schedule. The PPU cavities were fabricated, processed and assembled at RI and shipped under vacuum to JLab for vertical test qualification, following the XFEL methodology [6]. RI procured all niobium materials for the 32 cavities from Ningxia in China. Additionally, several cavities worth of niobium sheets were purchased by PPU from Tokyo Denki in Japan, to reduce project risk and two of the thirty two cavities were fabricated from this cell material. DESY performed all the material scanning and quality assurance steps on the niobium sheets under contract from RI. The processing steps and hold points used for the project at RI were very similar to the XFEL and LCLSII project and ended with cavities assembled and shipped ready for vertical test. Once the cavity processing started at RI and given the time for feed back from vertical test results, only a few process changes were made at the beginning to try to reduce field emission. An example of changes that was made was to remove the input feed through probe and burst disk for the final High Pressure Rinse (HPR) because they were collecting water during the rinse. These components were then assembled to the cavity after drying. RI then shipped completed assemblies to JLab where they received incoming inspection. Next JLab installed each cavity on a test-stand and they performed an 120 °C bake. Once the bake was complete they were inserted into a vertical Dewar and the qualification testing was performed,see Fig. 4. The vertical test qualification requirements for the PPU cavities was: radiation less then 20 mrem/hr at 16 MV/m as measured at the Dewar top plate, greater or equal to 18.0 MV/m gradient, less then or equal to 22 MV/m, the upper gradient administrative limit, Q0-value of greater then 8x10e9 at 16 MV/m. The cavities were actively vacuum pumped during the cold test. The vertical test results from “as received cavities”, were excellent with twenty one of the thirty two passed as received from RI and the remaining eleven required additional HPR’s before all passing [7]. Cavities that qualified, then had helium vessel welded (dressed) to them at JLab while still under vacuum. These dressed cavities were then vertical tested again after an additional HPR and assembly. Several dressed cavities showed early onset of field emission which was determined to be caused by insufficient cleaning of the cavity after the helium vessel welding process. Eight of the dressed cavities that failed had an additional (10 μm) etching with buffered chemical processing. The gradient upper limit was adjusted to 18 MV/m for these cavities to reduce risk of early field emission reoccurring and to meet string assembly schedules. The typical multipacting band of 10-15 MV/m was encountered on the majority of the cavities and had to be processed through to reach higher gradients. Ultimately, twenty two (22) of the thirty two (32) cavities reached the 22 MV/m administrative limit dressed. Overall the vertical test gradient performance was excellent and all thirty two cavities made it into assembled strings. Once 4 PPU dressed cavities were qualified, string assembly was scheduled. String assembly also required a final HPR of the cavities and assembly on a cleanroom rail. Completed strings were leak checked and passed out of the cleanroom to JLab cryomodule rail system for completion of the cryomodule. Completed cryomodules were then cooled down to 2.1 K at JLab to check instrumentation and vacuum integrity. Tested cryomodules were then delivered to SNS on a cryomodule shipping frame, leaving early in the morning from Jlab and arriving late in the afternoon at SNS. Arriving at SNS the beam-line vacuum status was checked and vibration data sensors were removed. So

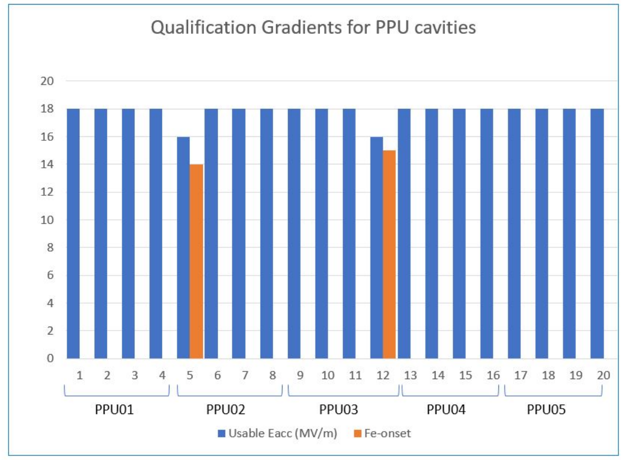

Figure 5: Test cave gradient and field emission onset data from the first 5 PPU cryomodules.

far no beam-line or insulating vacuum leaks were detected on shipped cryomodules. Once received at SNS, 2 critical lifts were made by cranes to transfer the cryomodule into the RF test building and onto their transfer carts. Following the receiving steps, the PPU cryomodules were then moved into the test-cave and prepped for qualification testing. Full testing of each cryomodule has been completed on the four cryomodules which takes about four days each to complete. Tests consist of cooling the cryomodule down to 2.1 K and testing cavities individually to determine their operational limits up to the administrative limit of 18 MV/m. The high power is supplied from a 5 MW klystron and modulator system just outside the test cave. Inside the cave, 8 radiation detectors are placed around the cryomodule to verify onset the radiation. The five PPU cryomodules tested had excellent results with only 2 of the 20 cavities having minor field emission at 16 MV/m and the rest were operated to the 18 MV/m administrative limit with no field emission at all, see Fig. 5.

PPU COUPLER CONDITIONING AND PERFORMANCE

The RF couplers were assembled and tested at SNS and shipped to Jefferson lab for the fabrication of the eight cryomodules. Pairs of RF couplers were tested on a bridge waveguide RF structure to 700 kW travelling wave, 1 ms pulses at 60 Hz and standing wave at 600 kW, 0.5 ms, 60 Hz and 400 kW, 1.0 ms, 60 Hz for 7 different standing wave positions with a sliding short. Typically a bias of 1000 Volts DC is used to reduce multipacting during the conditioning which took up to 4 days to complete. One of the RF couplers failed during testing due to a single arc during the standing wave conditioning at full power which fractured the ceramic and vented the waveguide system. The leak was 10-4 Torr L/s range with visible cracks in the AL2O3 from center conductor to outer conductor, see Fig. 6. This type fracture has never occurred in operations, however seven RF coupler ceramics were determined to have leaks on installed

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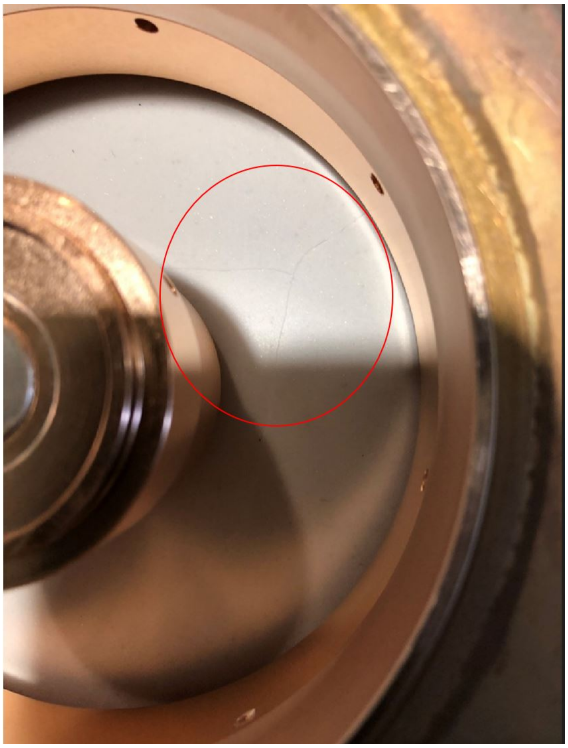

Figure 6: PPU coupler failure during conditioning.

cryomodules with 10-7 range leak rates since start of operations in 2006. These RF coupler leaks were all located under the outer conductor choke joint presumably near or at the braze joint to the ceramic.

CRYOMODULE TESTING AND LINAC PERFORMANCE

Currently four of the eight cryomodules have been tested in the test cave. The first two cryomodules PPU01, and PPU02 were installed in the down in August 2022 and all were collectively operating at 16 MV/m during the conditioning phase but two were then turned off for the run due to klystron over current trips. These klystrons were spares from inventory and were deemed to be defective. During the second short down which started the end of February 2023, the two defective klystrons were replaced, PPU03 and PPU04 were added to the linac and all cavities were conditioned at 16 MV/m. Experience is being gained on these four operational PPU cryomodules towards determining the stability of each cavity at the design gradient. Several of the existing HB cavity gradients were turned down to reduce the risk of trips at the higher beam loading due to limited RF power available for these cavities. During the May run we will gain significant operational experience with these new cryomodules with beam and identify any operational issues before the final three are installed in August. The plan is to operate at 1.3 MeV energy once all seven PPU cryomodules are installed. PPU05 was already received at SNS and PPU06 should arrive in June and PPU07 in August.

TARGET PERFORMANCE AND UPGRADES

The first target station will be receiving increasing the beam power from 1.4 MW to 2 MW and therefore the development ant testing of two test targets is in PPU project plan. The validation of these test targets with beam is specifically designed to verify the improvements made in the design from ongoing research that addresses cavitation and fatigue damage, the main limitations to target lifetime. Targets and their support facilities are very complex systems and failures typically lead to long down times. Target development also has a very long feedback loop of approximately 2 years for design changes to be fully tested with beam. The main failure mode for targets in operation has been leaks developed due to erosion of metal fatigue. The erosion occurs on the walls of the target housing mainly at the nose cone where the beam interacts with the Mercury flowing in the vessel. This erosion is caused by cavitation due to direct beam interaction with target shell and the mercury flow. The pounding of the beam at the nose cone of the target also sees very high stress and fails due to crack opening due to fatigue. Both erosion and fatigue can lead to leaks which limit the lifetime of the target and significantly increase operation down time. The PPU project test targets were fabricated with design improvements to reduce cavitation damage and reduce beam induced stress on the metal shell for extended lifetime at the PPU beam power. New target designs have stemmed from ongoing target research and the continued effort to improve target systems and availability. The ongoing research has shown that injecting helium gas into the target mercury flow will significantly reduce stress induced from beam impact and reduce erosion on target walls. The first test target was installed in 2022 and the second in 2023. The design improvements were verified after the run and removal of a test target 1 with post irradiation examination (PIE). The PIE consists of cutting out samples from the nose cone of the used target where erosion typically occurs. This work is performed with remote operations due to the activation levels of these targets. The recent run of test target 1, showed reduced target stress from strain measurements on the target and cut PIE samples showed significant reduction of erosion from surfaces due to the helium gas injection [8]. This deeper understanding will lead to improved targets designs for the future. The first test target accumulated 1931 MWh of production beam with a 3.8 slpm helium gas injection, see Figs. 7, 8, and 9.

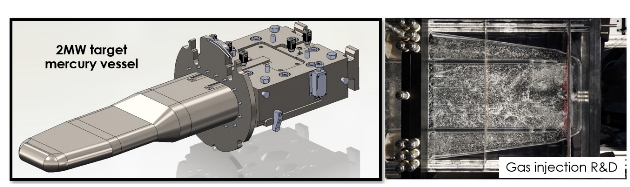

Figure 7: 2 MW Target Design and gas injection development on target test stand.

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Figure 8: Test target 1 before installation.

Figure 9: PIE sample cut from test target 1 after January to March 2022 run shows no damage.

CONCLUSION

The Proton Power Upgrade is well underway at SNS with the first two of the three phases completed. Four of the seven cryomodules and their support systems for the project were installed and are operational at the design goal. The beam current will be increased during this current run to establish operation at 1.05 GeV linac energy and up to 1.7 MW of beam power. Testing of the PPU05 cryomodule is ongoing and PPU06 will be received in June. PPU07 cryomodule is planned for delivery mid August. The both test targets were operated with beam and PIE results from test target 1 show no cavitation damage. Preparation for the phase 3 down is underway and SNS is gaining experience operating the linac and target systems at higher beam energy and using the upgraded beam power and additional neutron flux to carry out user experiments in advance to completing the PPU project.

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