ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-MOPCAV005

STATUS OF SNS PROTON POWER UPGRADE SRF CAVITIES PRODUCTION QUALIFICATION*

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Abstract

The Proton Power Upgrade project at Oak Ridge National Lab's Spallation Neutron Source (SNS PPU) currently being constructed will double the proton beam power from 1.4 to 2.8 MW by adding 7 additional cryo-modules, each contains four six-cell high beta (β= 0.81) superconducting radio frequency cavities. The cavities were built by Research Instruments, Germany, with all the cavity processing done at the vendor site, including electropolishing as the final active chemistry step. All 28 cavities needed for 7 cryomodules were delivered to Jefferson Lab, ready to be tested. The cryogenic RF qualifications and helium vessel welding were done at Jefferson Lab. The performance largely exceed the requirements, and greatly exceeded the performance of the original SNS cavity production series. Here, we present the summary of RF test on production cavities to this date.

INTRODUCTION

The Spallation Neutron Source (SNS) at Oak Ridge National Laboratory is the world's first megawatt class pulsed neutron source with the proton power of 1 GeV. The Proton Power Upgrade (PPU) project will double the proton beam power from 1.4 to 2.8 MW by adding 7 additional cryomodules each contains four six cell high beta (HB) β= 0.81 superconducting radio frequency cavities. Some modification were made to both cavities and helium vessels based on the operating experience of earlier SNS cryomodules and one of the prototypes currently installed in the linac [1]. Additionally, some modification were made in the cavity fabrication. The end groups of the cavities were made from high purity niobium whereas the original SNS cavities were fabricated from reactor grade niobium. Cooling blocks were added to the end groups to increase the thermal contact between the end group and the helium bath. Based on the operational experience of machine, the high order mode couplers aren't necessary and those were removed from the PPU cavity design. This removes a complex geometry to chemically process and rinse during the cavity processing reducing the possibility for early field emission and multipacting. Furthermore, some modifications were made to the fundamental power couplers and cryomodule end cans based on the operational experience of the original SNS project [1].

All the PPU cavities were built by Research Instruments, Germany, with all the cavity processing done at the vendor site, including electropolishing as the final active chemistry step. An improvement in performance of the cavities was expected due to electropolishing compared to buffered chemical polishing that was applied to the original SNS cavities. To this date, all cavities needed for 7 cryo-modules were delivered at Jefferson Lab, ready for RF test. The cavities go through incoming mechanical and RF inspection followed by the RF test at 2.1 K. Figure 1 summarize the cavity processing flow chart.

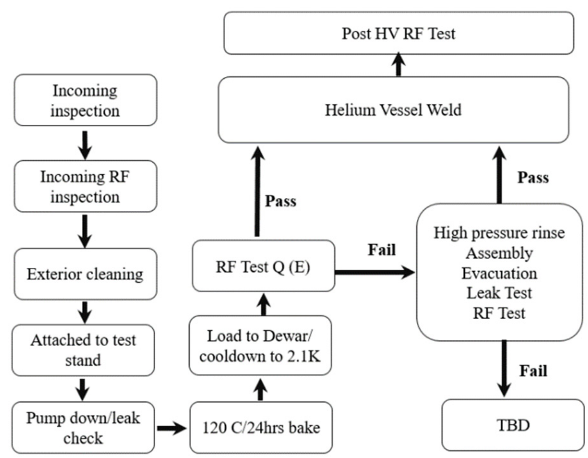

Figure 1: Flow chart of cavity qualification prior to cryo-modules assembly.

RF TEST RESULTS

The design modification to PPU cavities were based on the operational experience of original SNS HB cryo-modules as well as the results of prototype cryomodules installed in the SNS tunnel. A quality assurance plan was put in place to ensure the optimal performance of PPU cavities from production steps at vendor sites to the cavity qualification at Jefferson Lab [2]. The incoming cavities are checked for RF and mechanical issues followed by a wipe down to ensure no particulates are transferred into the clean room. While in the clean room each cavity was attached to a vertical test stand using clean assembly procedures, followed by a leak check. Once on the test stand the cavity is transferred to a bake box, where all cavities were baked at 120°C for 24 hours. The analog scans of the residual gas analyzer before and after baking were recorded. Also, the partial pressure of various gas species were recorded during the low temperature baking. The cavity was cooled down to 2.1 K in a vertical Dewar

* Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177.
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with residual magnetic field < 20 mG. The performance acceptance criteria are summarized in Table 1.

Table 1: RF Acceptance Criteria for PPU Cavities at 2.1K

Test conducted	Acceptance Value
Gradient limit	≥ 18 MV/m
Q_0	> 8×10^9 at 16 MV/m
Field emission	< 20 mrem/hr at 16 MV/m
Field probe coupling	7×10^{11} - 2×10^{12}
Fundamental frequency	805.6 ± 0.25 MHz

Jefferson lab received the cavities in batches with the first batch of cavities arriving on September 04, 2020 (Fig. 2). The first batch of production cavities under vacuum were equipped with burst discs installed on the field probe end of beam line flange. The burst disc was implemented to prevent any accidental over-pressurization during the transport of the cavity from vendor site to the Jefferson Lab as well as an option to RF test the cavity in a cryogenic environment without any active pumping. All three cavities failed the RF test due to early field emission. All three cavities were reprocessed with high pressure rinse and reassembly was done with some hardware modification on PPU-01 and no burst disc on PPU-02 and PPU-03. All three cavities reached admin limit 22 MV/m on the second test, with no field emission up to 17 MV/m, higher than the PPU acceptance gradient limit for field emission onset.

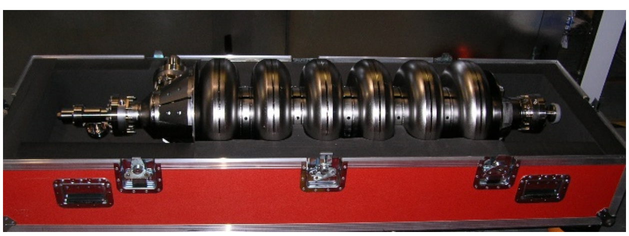

Figure 2: The first cavity (PPU-01) delivered to Jefferson Lab. The cavity was under vacuum with an all-metal right angle valve (left end) and burst disc (right end).

After testing the first 3 cavities, it was suspected that the burst disc attached to the beam line flange could be a source of contamination of the cavity and it was completely removed from the subsequent assembly process at the vendor site. The next two cavities received without the burst disc performed better than first three cavities. PPU-04 still showed early field emission with onset ~ 10 MV/m, however the second cavity, PPU-05 was field emission free up to 22 MV/m. The project decided to remove the burst disc from the assembly process at vendor site for the rest of the cavities. Based on the cavities performance at Jefferson Lab, some processing changes were made at the vendor site. Some of the changes were: installation of input coupling probe during the final assembly, replacement of the ethanol rinsing after the electropolishing with detergent degreasing and DI water rinsing. To this date 15 cavities have been RF tested with 8 cavities meeting the SNS specifications as received from the vendor. The rest of the cavities needed reprocessing with high-pressure rinse and clean assembly at Jefferson Lab. All cavities met specification with reprocessing with high-pressure rinse. Figure 3 shows the summary of the RF performance of first 15 cavities.

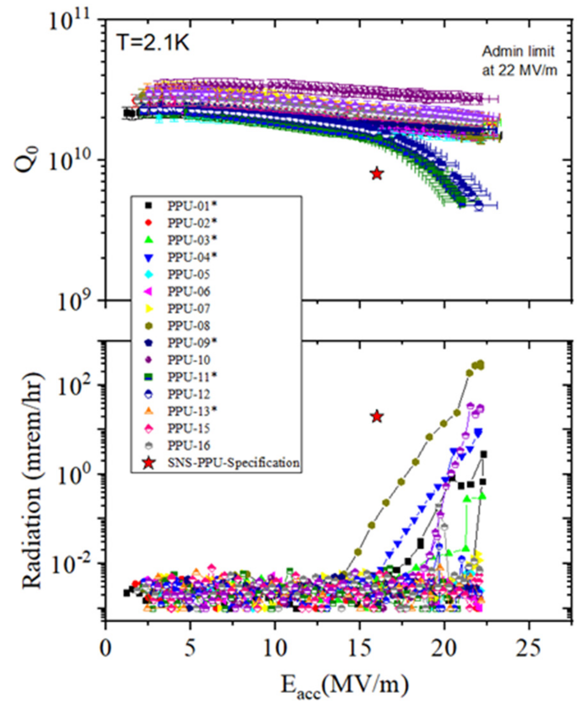

Figure 3: The summary of qualified PPU cavities from vertical test to this date. PPU-11 was limited at 21 MV/m due to availability of RF power. Symbol '*' denotes the cavities that needed JLab reprocessing with high pressure rinse.

As shown in Fig. 3, 15 bare cavities were RF tested and qualified to this date for helium vessel welding. Out of 15 cavities, 8 cavities required the Jefferson Lab reprocessing with high-pressure rinse. All 8 cavities passed PPU specifications after the reprocessing. It was clear that the early field emission was a result of surface contamination and easily processed with high-pressure rinse. Furthermore, none of the cavities needed any additional chemical removal showing that the fabrication and EP process of PPU cavities at vendor site was successful and the quality of niobium used to fabricate cavities was good. Figure 4 shows the field emission onset during vertical RF test of bare cavities that required high-pressure rinse at JLab.

HELIUM VESSEL WELDING

Once the cavities were qualified in vertical RF test, they were kept under vacuum and transferred to the helium vessel welding work station. The helium vessel welding process was developed before it was applied to production cavities [3]. A 100 W heater, two temperature sensors and a pair of liquid level sensors on every 4^{th} cavity were installed during the helium vessel welding. On average ~100 kHz drop in fundamental frequency was observed during the welding process, however, the change in frequency can be easily compensated by the tuner attached

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during the machine operation. The helium tanked is leak checked for possible leak at the welded joints.

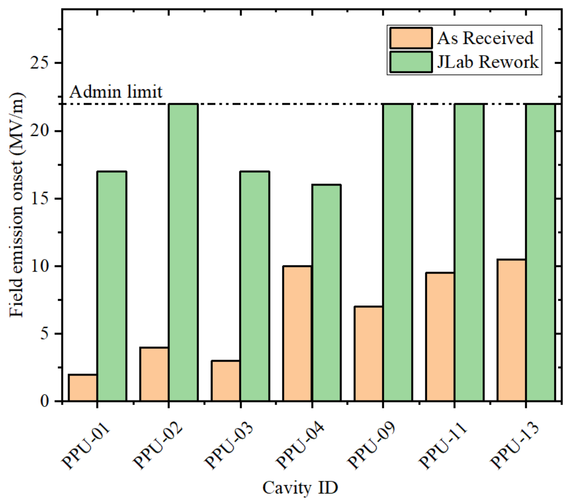

Figure 4: Final field emission onset on bare cavity as received from vendor and JLab reprocessing with HPR.

POST HELIUM VESSEL RF TEST

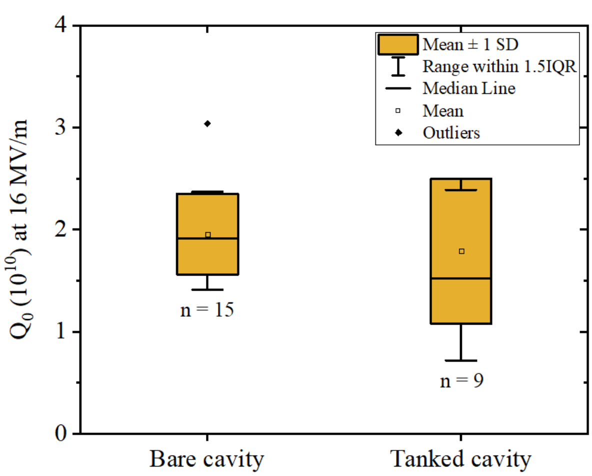

Figure 5: Summary of Q_0 at 16 MV/m before and after helium vessel welding.

The PPU project required a second RF test after the helium vessel installation, to validate cavity performance. During the preparation for RF test in the vertical Dewar the RF performance was reproduced, however in some cases, early field emission was observed, likely due to cross contamination during the transfer of the cavity from the welding area to the vertical attachment in preparation for RF test. Adopting thorough cleaning of the exterior of the cavity prior to moving into the clean room and additional high pressure rinse followed by clean assembly resulted in RF performance the same as prior to the helium vessel welding. The same cleaning procedure (exterior and interior) was applied to the cavities prior to the first string assembly. A process revision and improvement on cavity cleaning and preparations for vertical test of tanked cavities, as well as prior to string assembly to ensure the cleanliness of cavities in cryomodules is ongoing. All cavities tested after the helium vessel welding reached the 22 MV/m admin limit. Figure 5 shows the summary of Q_0 at 16 MV/m before and after helium vessel welding. The average Q_0 at 16 MV/m before the helium vessel was ~2.0×10^{10} and after HV welding is ~1.9×10^{10}. The small drop in Q_0 may be due to the different cool down condition of tanked cavities in the vertical Dewar. The first 4 cavity string assembly was completed as shown in Fig. 6.

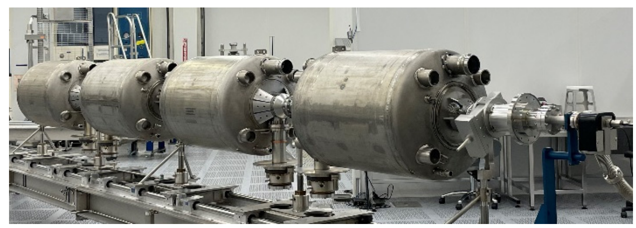

Figure 6: First PPU string assembly in clean room.

SUMMARY

Jefferson lab received 30 PPU cavities from Research Instruments, ready to be RF tested. Up to now ~50% of cavities passed vertical RF test as received from vendor and rest of the cavities qualified after only additional high-pressure rinse. All cavities reached well above the acceptance criteria for gradient (>18 MV/m) with average quality factor ~2 $\times 10^{10}$. The first string assembly was completed in March 2021 and it is on track to complete the cryomodule assembly and preliminary test before the end of 2021. During the production run, two cavities were ordered from the vendor for a total of 32 and an additional cryomodules (8th) is planned to be added to the PPU upgrade as a spare.

ACKNOWLEDGEMENT

We would like to acknowledge to all the technical staff who helped with processing and handling of the cavities under very difficult circumstances during the pandemic.

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