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CAVITY QUALIFICATION AND PRODUCTION UPDATE FOR SNS-PPU CRYOMODULES AT JEFFERSON LAB*

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Abstract

The Proton Power Upgrade (PPU) project at Oak Ridge National Lab's Spallation Neutron Source (SNS) currently being constructed will double the proton beam power capability from 1.4 to 2.8 MW by adding seven cryomodules, each containing four six-cell high-beta (β= 0.81) superconducting radio frequency cavities. Research Instruments, located in Germany, built and processed the cavities at the vendor site, including electropolishing as the final active chemistry step. Twenty-eight cavities for seven cryomodules and an additional four cavities for a spare cryomodule were delivered to Jefferson Lab and the first qualification tests were completed on all cavities as received from the vendor. The performance largely exceeded the requirements on quality factor and accelerating gradient. Six cryomodules have been assembled into strings with three cryomodules shipped and high power rf tested successfully at SNS to 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 energy 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. Modifications were made to both cavities and helium vessels based on operating experience of earlier SNS cryomodules and one of the prototypes currently installed in the linac [1]. 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. Higher order mode couplers were also removed from the upgrade design, making the cavities easier to chemically polish and clean. Furthermore, some modifications were made to the fundamental power couplers and cryomodule end cans based on the operational experience of the original SNS project. Table 1 shows the cavity parameters for original and upgrade high beta SRF cavities. Here, we present the status of initial cavity qualification tests, rework of unqualified cavities, and final cavity qualification with helium vessel prior to installation in cryomodules. In addition, an update on cryomodule production and high power rf test at SNS will be presented.

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Table 1: Cavity Parameters for Original and Upgrade High Beta SRF Cavities

Parameters	Original Cavities	PPU Cavities
E_{acc} (MV/m)	15.8	16
Q_0	>5×10^9	>8×10^9
FPC Power (kW)	550	700
Q_{FPC}	7×10^5(±20 %)	8 × 10^5(±20 %)
HOM	2	None

Table 2: PPU Acceptance Criteria for Vertical Test

Test Conducted	Acceptance Value
E_{acc} (MV/m)	≥ 18.0
Q_0	>8 × 10^9 at 16 MV/m
Field Emission	≤20 mrem/hr at 16 MV/m
Q_{FP}	(0.7 - 2.0)×10^{12}
Fundamental frequency	805.6 ± 0.25 MHz

CAVITY QUALIFICATIONS

Design modifications to PPU cavities were based on operational experience of original SNS HB cryomodules as well as the results of prototype cryomodules installed in the SNS tunnel. A quality assurance plan was put in place to ensure optimal performance of PPU cavities from production steps at the vendor sites to the cavity qualification at Jefferson Lab [2]. The incoming cavities are checked for RF and mechanical acceptance 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. Analog scans employing a residual gas analyzer before and after baking were recorded. Also, the partial pressure of various gas species were recorded during low-temperature baking. The cavity was cooled down to 2.1 K in a vertical Dewar with a residual magnetic field < 20 mG [3]. The performance acceptance criteria are summarized in Table 2.

Bare Cavities rf Performances

All 32 cavities were rf tested as received from the vendor with only 16 cavities meeting the PPU specification for accelerating gradient (>18.0 MV/m) and quality factor (> 8 ×10^9). Typical failures during rf qualification test were due to gradient limitation either by early field emission onset or final field emission reaching an administrative limit

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(>1 R/hr). A summary of bare cavity qualification tests is shown in Fig. 1. Twelve cavities were reprocessed at Jefferson lab with full disassembly, ultrasonic degreasing in ultra-pure water with detergent followed by high-pressure rinse. The cavities were assembled and attached to a vertical test stand with active pumping during cold rf test. All 12 cavities met the PPU specification with a single cycle of in-house rework with high-pressure rinse. To this date, one last cavity still requires rework either prior to tanking or as part of final qualification after welding. /hr

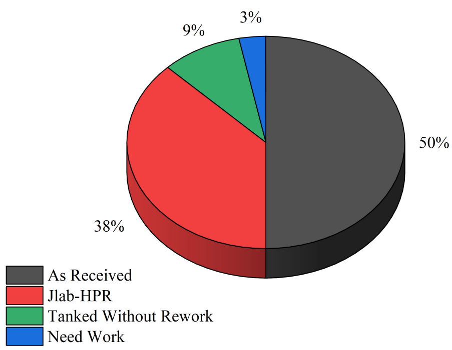

Figure 1: Summary of bare cavity VTRF qualification.

Tanked Cavities rf Performance

To ensure the cavities were clean during string assembly, the cavities were rf tested in a vertical Dewar after helium vessel welding. Helium vessel welding was done outside the clean room with a process that involves some machining and grinding steps. The helium vessel welding protocol was developed prior to the start of tanking production cavities [4]. Even though the helium vessel was welded keeping the cavity under vacuum, there is a high likelihood that the particulates can transfer into the cavity interior during the disassembly process prior to string assembly. The cavities were externally cleaned with high-pressure wash, dried overnight, and blowing off of any remaining particulate from the surface of the tanked cavities. Even with the utmost care, several rf tests of tanked cavities were limited by early field emission. The problem was eventually solved with additional exterior cleaning with high-pressure wash and rework with high-pressure rinse. Figure 2 shows the summary of rf performance of all tanked cavity qualifications prior to string assembly. 21 out of 27 tanked cavities qualified reached 22.0 MV/m, the administrative limit. Of those remaining 6 cavities, 4 cavities were limited by rf power availability during the vertical test. Some cavities showed field emission with an average onset of ~16 MV/m. Figure 2 (b) shows the summary of the quality factor at E_{max} and at 16.0 MV/m. The average quality factor at E_{max} is 1.16×10^{10} and at 16.0 MV/m the average quality factor is 1.63×10^{10} easily meeting the specification of PPU upgrade.

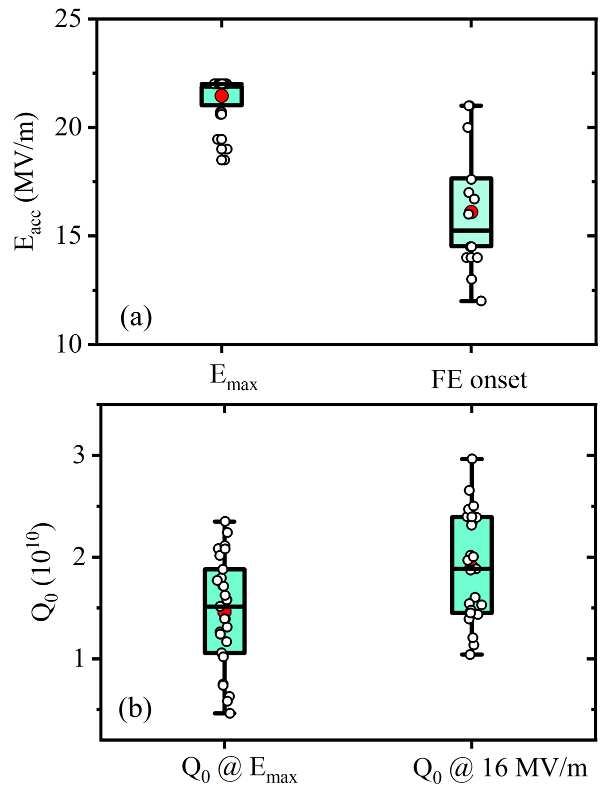

Figure 2: Summary of tanked cavity rf qualifications.(a) The maximum accelerating gradient and field emission onset gradient and (b) The quality factor at E_{max} and at 16 MV/m. The box are drawn for 25-75 % percentile.

Cavity Rework with Buffer Chemical Polishing

As mentioned earlier, the performance of some tanked cavities didn't meet PPU specifications in terms of field emission onset (20 mrem/hr at 16.0 MV/m). Some cavities met the PPU specification after additional rework with high-pressure rinse. Those cavities that failed to meet the specification for field emission onset were reprocessed with 10 μm buffered chemical polishing (BCP) in closed cycle cabinets. 5 cavities so far were processed with BCP and subsequently met PPU specifications without 120 °C baking. Typically cross-contamination was eventually removed by BCP, that was not initially removed after several cycles of high-pressure rinse.

CRYOMODULE PRODUCTION

To this date, 6 cryomodules have been built with 2 more remaining. Once the cavities were qualified from the vertical rf test, the cavities are externally cleaned with high pressure wash and any particles are blown off with ionized nitrogen prior to disassembly of cavities for string assembly. To further ensure the cleanliness of qualified cavities in final string assembly, the cavities received 2 passes (4 hours long) of high-pressure rinse and were subsequently dried overnight. String assembly was completed by installing a fundamental power coupler into a cavity then placing the cavity assembly onto the horizontal assembly rail. One cavity per cryomodule is equipped with a liquid helium level sensor. The PPU cryomodule consists of 4 tanked cavities with FPC and field probe, two end cans, a vacuum vessel, a space frame, a thermal shield, two layers of magnetic shielding with bellows between the cavities similar to original SNS cryomodules [5]. Selected cryomodule production steps are shown in Fig. 3.

Prior to shipping the cryomodules to SNS, each cryomodule was cooled down at Jefferson Lab's Cryomodule Test Facility. The set of tests includes an integrated leak on beam line and cryogenic supply and return lines, verifying rf connections, temperature sensors and liquid level sensors, fundamental frequencies, Q_{ext} and tuner operations. To this date, 3 cryomodules successfully completed preliminary cooldown and rf tests at Jefferson with 4^{th} cryomodule currently under test. 3 cryomodules have been shipped to SNS for high power rf tests. To this date, all three cryomodules have been rf tested and the performance significantly exceeding all PPU specifications. Only two cavities out of 12 (in 3 cryomodules) showed some field emission onset at 14.0 MV/m, stilling making the operating goal of 16.0 MV/m.

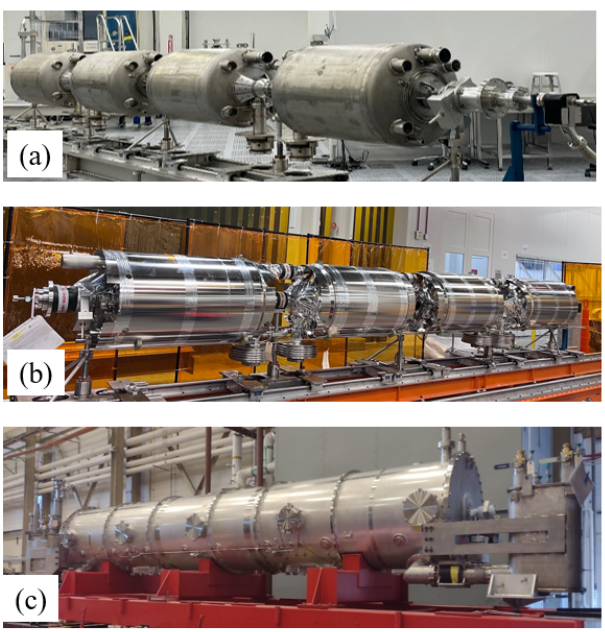

Figure 3: Cryomodule Production at Jlab. (a) 4 cavities string in clean room, (b) 4 cavity string with magnetic shielding, and (c) fully assembled cryomodule in shipping trailer prior to shipping to SNS.

LESSON LEARNED

During the production run, some setbacks were encountered, a major issue was retaining cavity cleanliness after the helium vessel welding. With continuous process improvement and monitoring, the cavities eventually were qualified, meeting PPU specifications. Another setback related to BCP of tanked cavities. Since the electropolishing facility was not set up for tanked cavities, we chose BCP for any rework of tanked cavities. The vertical BCP process in the close cabinet cycle typically removes the material unevenly along the cavity's interior (top-to-bottom). The etch rate was determined with Nb coupon samples before the actual run on tanked cavities. The BCP process was able to remove any stubborn field emitters from the cavities' rf surface. The average number of rf qualification tests for bare cavities was 1.4 while the average qualification rf tests was 2.3 per tanked cavity. With no spare cavities to work with, we are optimistic that the performance of all 32 cavities will meet PPU specifications.

SUMMARY

All 32 cavities delivered from a vendor and rf tested as received. Although, 50 % of cavities' rf performance met PPU specification as received from vendor, the remaining cavities eventually qualified after Jefferson Lab rework via high-pressure rinse and clean assembly. To this date, 28 cavities for 7 cryomodules have been qualified for final string assembly, 6 string assembly completed, 3 cryomodules have been delivered to SNS and high power rf commissioning tests have been completed. Three cryomodules have been qualified with superior performance and two of them will be installed in SNS tunnel in near future [6].

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