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# PREPARATION AND QUALIFICATION OF JACKETED SSR1 CAVITIES FOR STRING ASSEMBLY AT FERMILAB\*

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## Abstract

The qualification of dressed 325 MHz Single Spoke Resonators type 1 (SSR1) to meet technical requirements is an important milestone in the development of the SSR1 cryomodule for the PIP-II Project at Fermilab. This paper reports the procedures and lessons learned in processing and preparing these cavities for horizontal cold testing prior to integration into a cavity string assembly.

## INTRODUCTION

Ten SSR1 cavities were jacketed in US industry and delivered to Fermilab for the first SSR1 cryomodule for PIP-II [1]. Upon delivery, all cavities undergo incoming quality assurance/control (QA/QC) inspections to check structural and RF performance. After QA/QC, cavities are processed and prepared for cold testing in the Spoke Test Cryostat (STC). The testing strategy consists of qualifying each cavity with low power matched coupler (LPC) prior to the final testing with production high power RF coupler (HPC) and tuner to meet PIP-II specifications.

PIP-II requires that SSR1 cavities have a quality factor  $Q \geq 6 \cdot 10^9$  at the nominal accelerating gradient of  $E_{acc} = 10$  MV/m. Frequency sensitivity to helium pressure fluctuations (df/dp) must be less than 25 Hz/Torr. No limit is specified for the intensity of radiation due to field emission.

## INCOMING INSPECTIONS

Jacketed SSR1 cavities are received at Fermilab after passing a pressure test according to ASME BPVC Section VIII and a vacuum leak check. Incoming QC starts with visual inspection to ensure the absence of structural imperfections and to document the status of welded joints, bellows, threaded holes, and sealing surfaces. The cavity also gets the serial number etched on an accessible and visible surface before RF QC. RF QC includes a frequency check, field flatness and accelerating gap effective length measurements performed by bead-pull. Frequency and bead-pull measurements are two useful tools to validate cavity manufacturing and to ensure RF properties are kept within specifications. The target frequency after helium vessel welding is 324.612 MHz (atmospheric pressure in the beam volume and helium space). This frequency target allows to meet the frequency value of 324.434 MHz after the processing and preparation (vacuum in the beam volume), and the final 325.000 MHz when the cavity will be at 2 K with the tuner engaged. Inelastic tuning is performed if the measured

frequency is off by 40 kHz or more using the procedure described in [2].

A coordinate-measurement machine (CMM) is used to check that tolerances of critical interfaces are in the specified ranges. Non-conformities are documented and corrections are made if needed. Measurements of the mechanical center of the beam pipe with reference to lifting lugs (accessible targets for the alignment) will be used as inputs for the final alignment of cavities in coldmass to meet PIP-II requirements.

The final step of the incoming QA/QC consists of checking the integrity of sealing surfaces such that ultra-high-vacuum (UHV) connections are made reliably using diamond Al seals. The conflat knife edges that existed on the original cavity assembly were proved unreliable, thus the sealing surfaces were polished to work with diamond Al seals. Occasionally, surface polishing is required to remove small surface scratches or pits. A final leak check is used to assure the quality of sealing surfaces, as shown in Fig. 1. No leak shall be detectable on the most sensitive scale of a helium leak detector with a minimum sensitivity of  $10^{-10}$  mbar-l/s.

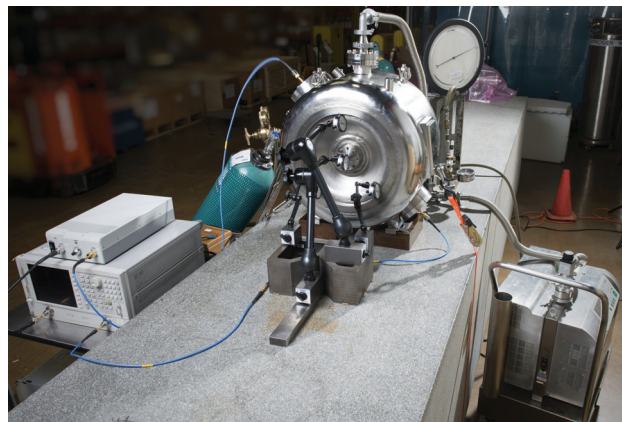


Figure 1: QA/QC inspection of SSR1 cavity.

## PROCESSING AND PREPARATION

After passing incoming inspections, the jacketed cavities are processed and prepared for cold testing. In the Fermilab-Argonne cavity processing facility, jacketed SSR1 cavities receive a light Buffered Chemical Polish (BCP) and ultrasonic cleaning prior to horizontal and vertical high pressure rinsing (HPR). Finally, the testing hardware is assembled to the cavities in the cleanroom before the 120 °C baking and installation in the spoke test cryostat at Fermilab.

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## Light BCP and Ultrasonic Cleaning

The Helium space is washed with De-Ionized (DI) water to remove the metal debris that may have been trapped during the welding process. All blind holes are thoroughly cleaned using nylon pipe brushes, DI water and detergent. Following careful external surface cleaning, the jacketed cavities receive a light BCP (20-30  $\mu\text{m}$ ) to expose the final purified RF surface by removing any deposited contamination introduced during previous production steps. The BCP procedure is carefully controlled for flow and temperature such that all internal surfaces are etched and kept below 12 °C. The BCP etching configuration is shown in Fig. 2.

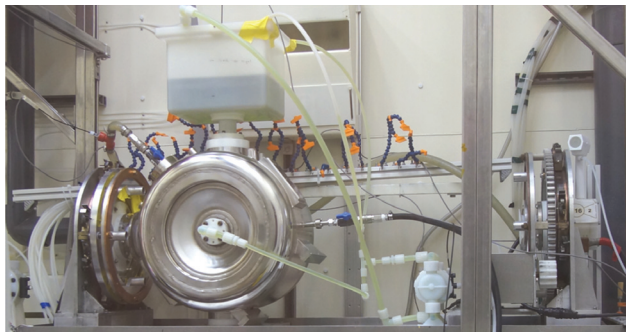


Figure 2: SSR1 jacketed cavity BCP.

To maintain the process temperature below 12 °C, Water is circulated through the helium space with a starting temperature of 8-9 °C. At the end of the light BCP the cavity volume is filled with DI water and drained completely and rinsed sufficiently to raise its pH. This process is repeated five times to remove the residual acid to make the cavity safe for the following handling operations. Despite the DI water rinsing, some salts from the chemical process reside in the cavity which cause field emission. Thus, the cavity, with the four ports fully opened, is submerged in a solution of DI water and an anionic detergent and ultrasonically (US) cleaned in a class 1000 cleanroom for 1 hour at room temperature. After the US cleaning, the blind holes are cleaned again to avoid that any cross-contamination occurs in the next steps.

## Horizontal and Vertical HPR

Both horizontal and vertical HPR are performed to remove any trace of chemical contamination and particulates that may stick to the Nb surfaces. The first HPR is done horizontally under a portable cleanroom by inserting the wand into all the four cavity ports and rinsing three times each. The second HPR is performed similarly, but with a vertical wand orientation in a class 10 cleanroom. Between the HPRs and after the final vertical HPR, the cavity is left to dry overnight in class 10 cleanroom prior to assembly.

## Assembly and Leak Check

All the components needed for assembly are ultrasonically cleaned using a mixture of DI water and detergents the day before the assembly. After cleaning, the components are left to dry overnight in the class 10 cleanroom. Before

the assembly, each component is blown using ionized ultra-pure Nitrogen and the particulates are counted in order to reach the cleaning criteria required for a class 10 cleanroom (less than 28 particulates greater than 0.3  $\mu\text{m}$  in 1 Standard Cubic Foot (SCF) of air [3]). All the assembly operations are performed from the bottom with cavity ports in a vertical configuration (cavity port stays above the component to be assembled) in order to minimize the opportunity for particulates falling into the beam volume. All the UHV connections to the cavity ports are done using silicon bronze set screws, 316 stainless steel nuts, washers and an AlMg gasket. Each flange is tightened using a specific torquing procedure developed to obtain a leak tight connection (Fig. 3). The cavity beam volume is then connected to a vacuum cart and pumped down overnight to reach a vacuum level on the order of  $10^{-6}$  Torr. All the UHV connections are leak checked with a sensitivity of  $10^{-10}$  mbar-l/s or better and the cavity is brought back to Fermilab for low temperature 120 °C baking.



Figure 3: Vertical HPR, cavity assembling and tightening.

## 120 °C Baking

The shape and frequency of the SSR1 cavities result in inherent multipacting barriers that are observed at 4-4.5 MV/m and 5.5-7 MV/m. These are worsened in the presence of water molecules from the cleaning and processing of the cavities. To minimize multipacting due to water, these cavities are baked at 120 °C for 48 h. The ovens at Fermilab for this baking are air ovens, with the cavity RF space being actively pumped by a clean pumping cart having the ability to analyze the evacuated gases using a RGA. The cavities are considered to have been baked sufficiently once the partial pressure of water has decreased by at least an order of magnitude compared to its initial partial pressure when the cavity heats up to 120 °C. The RGA spectrum is also evaluated for the presence of other contaminants in the cavities, such as hydrocarbons. In the event of presence of hydrocarbons, the magnitude of the hydrocarbon peaks are compared with that of water and the total pressure, and determined to be sufficiently clean if the greatest hydrocarbon peak is at least two orders of magnitude smaller. Comparisons between cavities are now made by using spectra that are normalized to the total pressure of the respective scans.

The temperature and water partial pressure evolution as a function of time for one such SSR1 cavity, is illustrated in Figure 4. The RGA spectrum from this same cavity bake is illustrated in Figure 5. This spectrum is clean with no significant presence of masses heavier than 50.

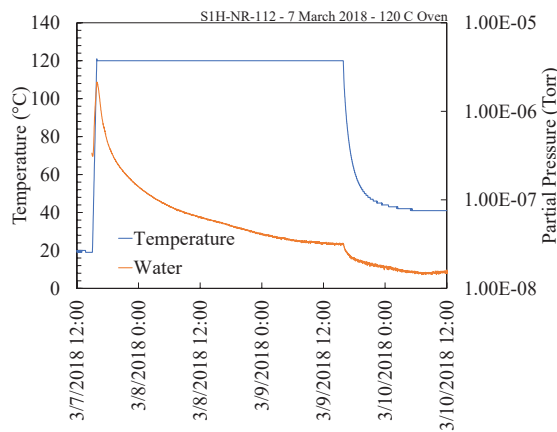


Figure 4: Temperature and water partial pressure evolution during a 120 °C 48 h baking of a SSR1 cavity.

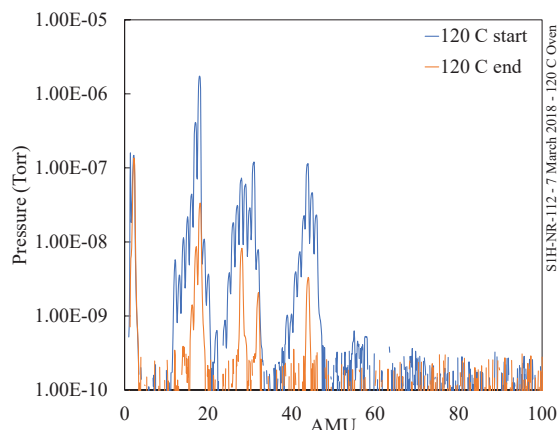


Figure 5: RGA spectrum, at the beginning and end of the 48 h hold, during a 120 °C 48 h baking of a SSR1 cavity.

## TESTING IN THE STC

All of the SSR1 cavities destined to be part of the first SSR1 cryomodule for PIP-II are tested in the Spoke Test Cryostat (STC). Jacketed SSR1 cavities are tested and qualified as fully dressed entities with high-power coupler (HPC) and tuner, after being previously qualified with a low-power matched input coupler (LPC). Once cavity is cooled down to 2K, calibration of LLRF cables is performed and tuner functionality (if so equipped) is verified followed by cavity performance qualification measurements including:

- maximum accelerating gradient (or administrative limit)
- onset and intensity of field emission
- cavity frequency pressure sensitivity,  $df/dp$
- tuner range, resolution, and hysteresis [4]
- Lorentz force detuning sensitivity
- cavity quality factor

Quality factor measurements are performed calorimetrically in the case the cavity is equipped with a high power coupler, and by RF power balance measurements if the cavity has a low power coupler. Additionally, processing of field emitters

or multipacting (MP) barriers is performed as necessary in order for the cavity to meet performance standards. Average MP processing time to date is 14 hours. Resonance control studies have also been performed using some of the SSR1 cavities during their qualification tests in the STC [5].

To date a total of five cavities have been qualified in STC with low power coupler (LPC) and one with a high power coupler (HPC) and tuner. Summary performance data are shown in Fig. 6. The cavities show  $df/dp$  values below 10 Hz/Torr (no tuner engaged), while average value of Lorentz force detuning is  $-6.2$  Hz/(MV/m)<sup>2</sup>. It is expected that all cavities will eventually be tested and qualified in the STC with high power prior their integration in the string assembly.

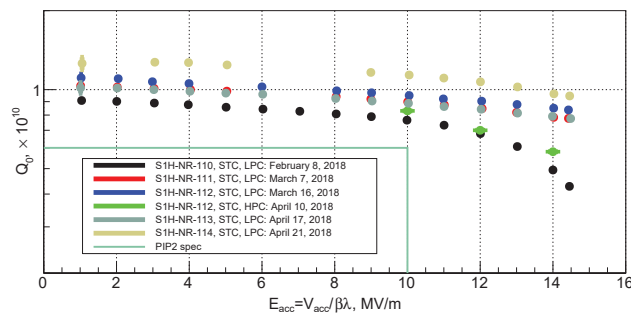


Figure 6: Qualified SSR1 cavities with low power coupler (LPC) and high power coupler (HPC).

## LESSONS LEARNED

Cold tests failed several times (9 tests) before achieving PIP-II requirements in STC (Fig. 6). Ultimately, several sources of the failures were identified including particulate contamination from the HPR system and non-conforming vacuum sealing materials used by a vendor for the RF couplers. These and other reasons highlight the importance to continuously maintain processing facilities and equipment and to carefully monitor and oversee vendors of highly sensitive components like SRF vacuum-end couplers.

Unexpectedly, DI water trapped in between blind-tapped holes of the 304 stainless steel flanges and Silicon Bronze C65500 resulted in oxide formation (particulates) near the cavity ports. Fully drying these holes prior to assembly eliminated this problem.

The processing time of multipacting barriers drastically drops if a SSR1 cavity receives the proper 120 °C baking treatment and if the level vacuum in the beam volume is  $\leq 5 \cdot 10^{-5}$  Torr. This value agrees with requirements presented elsewhere [6].

## CONCLUSION

QA/QC inspections were extremely useful to address structural and RF non-conformities. Procedures to successfully prepare SSR1 cavities for cold testing are understood and the plan is to qualify eight cavities with HPC and integrate them into the string assembly by end of CY 2018.

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