ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-TUP095

LESSONS LEARNED ASSEMBLING THE SSR1 CAVITIES STRING FOR PIP-II*

D. Passarelli†, D. Bice, M. Parise, T. Ring, G. Wu, Fermilab, [60510] Batavia, IL, USA
Stéphane Berry, CEA, [91190] Saclay, France

Abstract

The string assembly of the prototype Single Spoke Resonator type 1 (SSR1) cryomodule for PIP-II at Fermilab was successfully completed. Lessons learned from the preparation, assembly and the quality control activities of the final fully integrated assembly will be presented.

INTRODUCTION

The prototype SSR1 cryomodule (CM) is currently being assembled at Fermilab in the framework of PIP-II project and it is the baseline for the design, assembly and testing of the SSR1, SSR2, LB650 and HB650 CMs composing the SRF section of the linac [1–3].

The cavity string assembly of the prototype SSR1 cryomodule (see Fig. 1) consists of eight single spoke resonators type 1 (SSR1) with vacuum end coupler, four superconducting (SC) solenoid and beam position monitor (BPM) subassemblies, with ultra high-vacuum gate valve subassemblies terminating the beamline at each end. All those beamline components had to pass a series of quality inspections prior to being processed in the cleanroom: visual inspection, geometrical check using coordinate measuring machine, leak checks before and after three thermal cycles (cooldown using liquid Nitrogen, warmup in air) and visual inspections of sealing surfaces. In addition, the eight cavities with vacuum-end coupler were successfully prepared, assembled, and tested in the Spoke Test Cryostat (STC) at Fermilab [4] [5], and the four SC solenoids were cold tested and qualified in the Vertical Test Stand (VTS) at Fermilab, prior their integration in the string assembly.

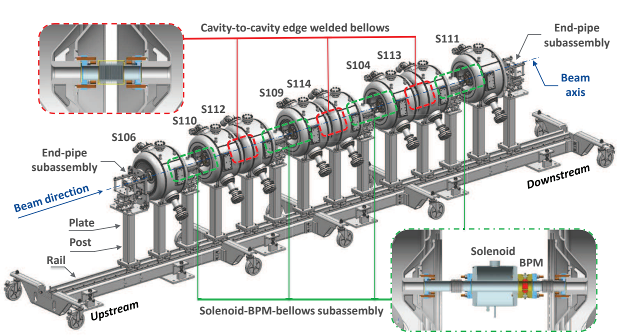

Figure 1: Layout of the proto SSR1 string assembly.

PROCEDURES AND CLEANROOM

Step-by-step operating procedures were written and reviewed by subject matter experts to check that all best practices were considered. Also, critical steps were troubleshooted and verified by performing dry-runs before the final execution of the string assembly [6]. SRF technicians were trained to familiarize the details of the process. An electronic traveler was developed and used to assure the correct application of the procedure during the assembly.

The SRF cleanroom located in the Lab 2 building at Fermilab was used to perform the preparation and integration of the prototype SSR1 cavities string assembly from November 2018 through January 2019. Figure 2 shows the layout of the cleanroom that comprises of Prep suite class 1000 (ISO 6), Gowning suite class 100 (ISO 5), Inspection suite class 100 (ISO 5), Assembly suite class 10 (ISO 4). The Lab 2 cleanroom suites were tested for compliance with standard ISO 14644-1, Part 1 and testing was performed as outlined in standard ISO 14644-2, Part 2 before starting the activities. Also, four SSR1 cavities were prepared (high pressure rinsed and assembled) in that cleanroom and successfully qualified through STC testing to demonstrate the readiness of the facility and the effectiveness of the procedures.

Nitrogen Purging Line

The Nitrogen purging line system for the SSR1 cavities string was designed and assembled to guarantee a flow of 6 L/min at beam pipe flanges of the cavity and to prevent pressure build up inside the cavity of more than a few millibars (specification: < 50 mbar) during assembly.

The system used two mass flow controllers to control and measure the total volume of nitrogen into the two system manifolds. Each manifold had a bypass vent with a mass flow meter on the vent. The flow through the cavities string could then be calculated by the difference between the inflow and the flow out the bypass vent. The bypass vent would flow approximately 0.25 L/min when the cavity string was open, and 6 L/min would be flowing through the string or the connecting cavity. As a connection would be made and sealed, all nitrogen would flow out of the bypass vent keeping the internal pressure in the string below 2 mbar. LabView was used for control and data collection. The system used electric and mechanical valves along with differential pressure transducers and switches to protect the cavities from, loss of nitrogen pressure, electrical power loss, unsafe opening of valves if pressure in string was too high or low, etc.

* Work supported by Fermi Research Alliance, LLC under Contract No. DEAC02- 07CH11359 with the United States Department of Energy
† donato@fnal.gov

ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-TUP095

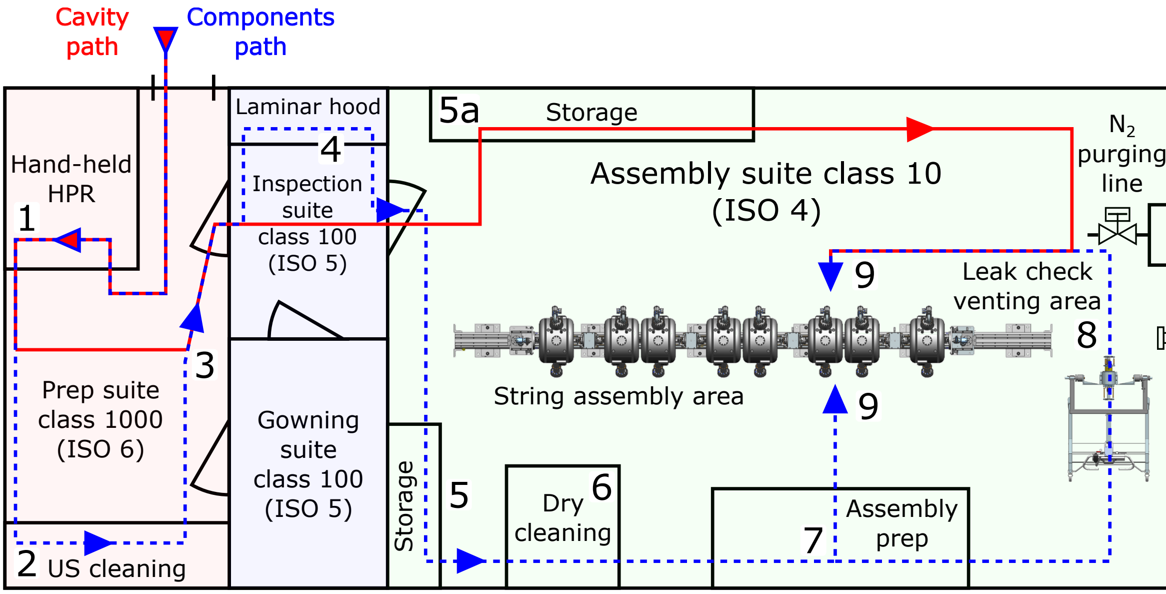

Figure 2: Layout of the SRF cleanroom at Lab 2.

ASSEMBLY SEQUENCE

Figure 2 summarizes the flow of parts from entering the cleanroom to being integrated in the string assembly. The blue line represents the path of components for subassemblies and tooling, while the solid red line shows the path of the SSR1 cavities. Several stations from 1 through 9 can be identified: 1, here the components receive the hand-held High Pressure Rinse; 2, Ultrasonic (US) cleaning station; 3, components are dried using ionized nitrogen guns and bagged if needed; 4, in the inspection suite parts are left to dry overnight. Small parts are positioned under the laminar flow hood equipped with High-efficiency Particulate Air (HEPA) filters. Also, here parts are visually inspected and wiped with alcohol before being entered to the assembly suite; 5/5A, storage areas for the subassemblies/tooling components and cavities respectively; 6, components are dry cleaned using ionized nitrogen and Quality Check (QC) is performed using a particle counter; 7, subassemblies and string tooling are assembled in the assembly prep station; 8, leak check and venting area with access to the vacuum cart; 9, string assembly area is where cavities and the other components are positioned on the rail system and then assembled.

Cleaning

The preparation phase started entering tooling and equipment for string assembly [7] to the assembly suite class 10 after being cleaned: ultrasonic bathed and/or high pressure rinsed, and carefully wiped and inspected in the inspection suite class 100.

Parts and hardware for subassemblies (four solenoid-BPM-bellows subassemblies, three cavity-to-cavity edge welded bellows, two beam pipe end subassemblies) went through the same cleaning path as well. Attention was given to the three cavity-to-cavity edge welded bellows that were fully extended using the adjusting cages before being high pressure rinsed and dried.

The eight SSR1 cavities were received after being fully qualified with high-power coupler in the Spoke Test Cryostat. Prior to enter the assembly cleanroom their exterior was hand-held high pressure rinsed in the prep suite, and dried, inspected and wiped in the inspection suite.

Preparation of Cavities and Subassemblies

The RF volume of the SSR1 cavities was kept under vacuum throughout the testing phase until they were ready to be positioned on the rail posts for the integration in the string assembly. They were slowly back filled with Nitrogen to atmospheric pressure by means of the vacuum cart equipped with mass flow controller. During the venting phase, an assessment of the vacuum level was done but an explicit leak check was not conducted. The position of each cavity in the string assembly (see Fig. 1) was decided based on the combination of two qualifying figure of merits measured during STC testing: quality factor Q_0 at 10 MV/m and gradient of the onset radiation due to field emission. The cavity having the highest Q_0 at 10 MV/m and the lowest gradient of the onset radiation due to field emission is considered the best performing cavity and it is located downstream.

Following the operating procedure, parts and hardware kits for subassemblies and tooling were pulled out from the storage area to start their preparation (see Fig. 3).

Then, the four solenoid-BPM-bellows subassemblies and two beam pipe end subassemblies were “particle free” assembled, dry cleaned, leak checked (Fig. 4 and dry cleaned again by blowing with ionized nitrogen until a total count of particles > 0.3 µm is less than 10 for 1 sample volume of 1 standard cubic foot. Those subassemblies were found leak tight at the first attempt with a minimum detectable leak rate of $2 \cdot 10^{-10}$ mbar·L/s. To minimize the generation of

ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-TUP095

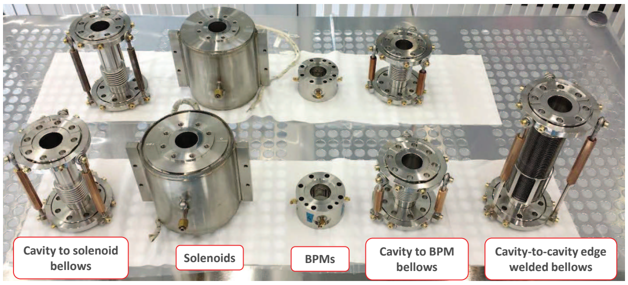

Figure 3: Several parts for subassemblies and tooling.

particles and to maintain the quality of the sealing surfaces, rubber O-rings with a custom Teflon spool were used at both ends of the subassembly to connect the blank-off flange and the flex hose going to the vacuum cart. The same type of sealing along with a 5 mm thick Al disk (because lighter than the regular stainless steel blanks) were used to cap the ends of the subassemblies during positioning and staging on the rail posts.

The three cavity-to-cavity edge welded bellows mounted fully extended on the adjusting cage were dry cleaned, leak checked and dry cleaned before being assembled onto the cavity string. Long-term storage of the components was avoided.

Using a laser tracker the geometrical axes of cavities and solenoids were aligned to the “ideal beam axis” in order to minimize unwanted loads on hydroformed bellows and ultra high vacuum flanged connections. Using reference surfaces machined on the cavities and solenoids, it was ensured that all the beamline components had the same angular alignment (clock) along the beam axis.

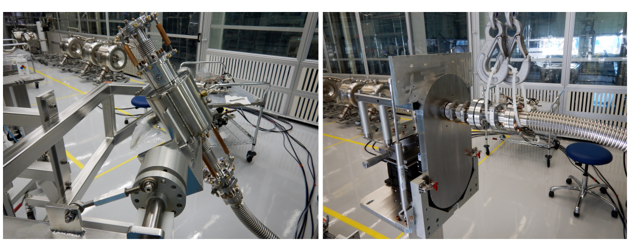

Figure 4: Leak check of subassemblies.

String Assembly

Sixteen “particle free” connections had to be performed after all cavities and sub-assemblies were positioned and aligned on the rail system. The assembly was performed starting from upstream and following the sequence of connections to complete the assembly with the latest connection downstream.

Two purging lines were used to actively protect the RF volume of cavities from migration of particulates: one was mounted on the first cavity upstream (S106) and the other one was moved downstream from cavity to cavity (from S110 through S111) as the assembly was progressing. Anytime that a “particle free” connection had to be made, the exterior surfaces of all cavities, subassemblies, tooling positioned in the assembly area were dry cleaned by blowing with ionized nitrogen until a total count of particles $> 0.3\,\mu$m is less than 10 for 1 sample volume of 1 standard cubic foot (see Fig. 5). To expedite this cleaning phase, all potential sources of particles (i.e. blind holes, low surface finishing, etc.), not explicitly needed to perform the Ultra High Vacuum (UHV) connections, were masked by using cleanroom tape.

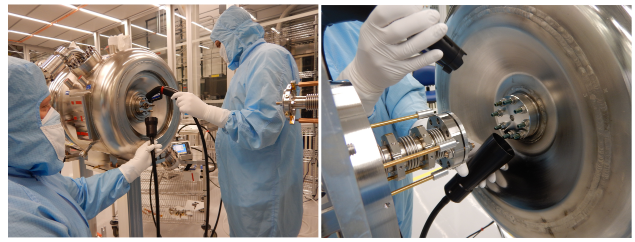

Figure 5: Dry cleaning by blowing with ionized nitrogen.

A local alignment check of mating flanges was performed before removing blanks from cavities and subassemblies to assess that holes patterns matching (see Fig 6). If corrections had to be made, each subassembly (and not cavity) was moved accordingly by adjusting their aligning/supporting tooling system. Never a cavity or solenoid was adjusted rotating it around the beam axis to avoid unwanted torsion momentum on bellows during future alignments of beamline components. Rotatable flanges were properly set in the subassemblies to match the cavities hole pattern.

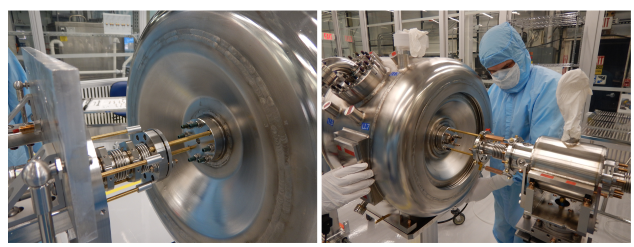

Figure 6: Checking the alignment of flanges: cavity and beam pipe end subassembly (left), cavity and solenoid-BPM-bellows subassembly (right).

Once the flanges are aligned with each other, and Nitrogen purging lines were turned on, a local series of dry cleaning were performed to allow the removal of studs and cleaning of blind holes until the blank off flange along with the Al gasket was removed from the cavity beam pipe flange. Sliding the post of the downstream mating part on the rail system the flanged connection was made using new hardware and Al sealing. All beamline components were staged and positioned on the posts of the rail system with the exception of the cavity-to-cavity edge welded bellows. They were manually positioned on their first connection with the cavity upstream while held fully extended with the adjusting cage. The circularity of the Al gaskets was slightly modified to allow them to stay in the groove of the flange during the assembly. A specific torque procedure was used to properly

ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-TUP095

crash the Al sealing in the flanged connection using Silicon Bronze set screws in blind Stainless Steel threaded holes and Stainless Steel washers and nuts (see Fig. 7). A maximum torque of 300 in-lbf (33.9 Nm) was applied to the stainless nuts while the set screws were held with an Allen wrench.

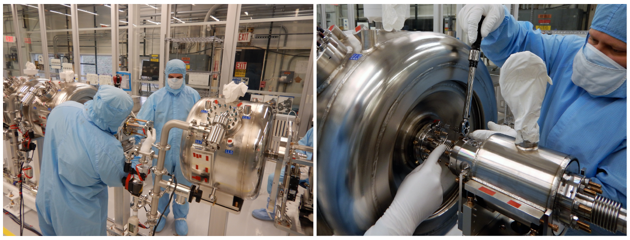

Figure 7: Positioning of the Al sealing in the flange groove (left), tightening bolts of a flanged connection (right).

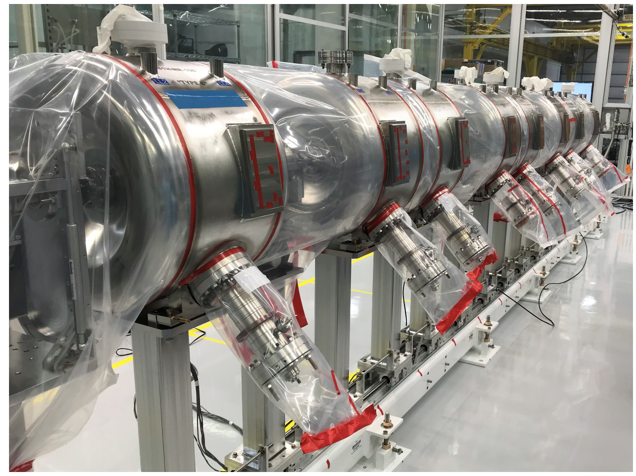

Figure 8: Final leak check of the full assembly.

Final Inspections

Upon completion the full string assembly was visual inspected. Torque was verified on all bolted connections as follows: cavity beam pipe flanges: 300 in-lbs; solenoid-BPM-bellows subassemblies: 250 in-lbs; cavity side flanges: 250 in-lbs.

The leak check of the entire beam volume was performed as follows:

1. String beamline volume evacuated at 80 mbar·L/s using a custom skid with Scroll and turbo pumping system, RGA, MFC, and He source;
2. Rough leak check done at $\sim 1 \cdot 10^{-7}$ Torr;
3. Final Leak check was performed at $\sim 1 \cdot 10^{-8}$ Torr;
    - Warmed RGA at least 3 hours
    - Checked calibration prior to leak check using $2 \cdot 10^{-10}$ mbar·L/s calibrated leak
    - String sprayed with Helium gas
    - Vacuum-end couplers then checked individually, bagged and isolated
    - Entire string covered for He saturation as in Fig. 8.

During first leak check cycle, two ceramics of the vacuum-end coupler mounted on cavities S109 and S111 were found leaking at $4.6 \cdot 10^{-8}$ mbar·L/s and $2.5 \cdot 10^{-8}$ mbar·L/s respectively. It was decided t slowly venting the entire string beamline (at 250 sccm) and replace the two vacuum-end couplers.

Leak check procedure was repeated again and no leak was found above $2 \cdot 10^{-10}$ mbar·L/s (specification). The string assembly base pressure was $2.3 \cdot 10^{-7}$ Torr at the final leak check. The helium background was at $2.7 \cdot 10^{-10}$ mbar·L/s.

LESSONS LEARNED

The step-by-step procedure was written and revised multiple time before freezing it for the final assembly. Several dry-fit activities were performed to troubleshoot the entire process. However, during the execution of the final assembly several issues were found. The high level communication among the teams (SRF techs, designers, engineers, scientists) involved in the activity played a strategic role to overcome the challenges presented by those activities where each single detail matters.

The electronic traveler collecting all the results and notes at each step of the assembly was extremely useful to track the progress. Also, it will serve as starting point to define possible improvements for future optimization design activities. Below some of them are reported:

- Design beamline components shall satisfy not only the final operational requirements but all scenarios presented in the lifetime cycle of the sub-assembly (i.e. manufacturing, assembly/disassembly, transportation, handling, testing, etc.);
- Blind and threaded holes to be avoided to interconnect beamline components;
- The beam pipe flanges of the cavity shall be extended in order to be “exposed” to the air laminar flow. It is currently “hidden” by the helium vessel wall;
- Improve the surface finishing and avoid hidden areas to facilitate wet and dry cleaning;
- Flanges with slotted holes in place of rotatable flanges might be easier to handle and assemble;
- Edge welded bellows in place of hydroformed bellows would relax the alignment requirements;
- Simplify shapes and complexity of tooling to minimize particle generation during assembly.

The cleaning, handling and assembly of edge welded bellows had been considerably less complicated than expected and predicted during design phase. Unless issues will be

ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-TUP095

found during CM testing with beam, it is definitely an option to consider for future CM design.

Viton sealed gate valves were used at the ends of the cryomodule beamline. SSR1 cryomodule design is full segmented as well as the other CMs for PIP-II. The gate vales are at room temperature and Viton seal becomes a good alternative compared to all metal gate valves. Viton sealed gate valves showed much less particle counts during actuation. The radiation hardness of Viton seal is enough for machine's lifetime. One disadvantage is the Viton seal is prone to helium permeation. To help with high precision leak check, Viton sealed gate valves need to be isolated from surrounding air while under nitrogen purging or connected to another metal sealed isolation valve. SSR1 cryomodule beam line leak checking initially suffered high helium background until the valves were bagged and flushed with boil-off nitrogen.

The nature of failure that led to open a leak in the ceramic of the vacuum-end coupler is unknown but it most likely due to mishandling during testing and/or inter-facilities transportation. However, an explicit leak check should be performed on all cavities prior to venting them to atmospheric pressure to verify their leak tightness with a minimum detectable leak rate of $2 \cdot 10^{-10}$ mbar·L/s. Also, the design of such couplers should be made more robust to improve their reliability throughout the entire life cycle.

CONCLUSION

The string assembly was successfully completed and leak check in January 2019, see Fig. 9. The lessons learned will be used to feedback future design and assembly activities in order to improve the quality of the end result. The final assessment of the work presented in this proceeding will be made based on CM testing results.

Figure 9: String assembly for the prototype SSR1 CM.

ACKNOWLEDGMENT

The completion of this challenging activity was accomplished thanks to the excellent support provided by many people from the Fermilab staff: A. Akimov, S. Adams, R. Kirschbaum, B. Bieritz, L. Elementi, R. Pilipenko, D. Plant.

REFERENCES

[1] G. Wu, "SRF Cryomodules for PIP-2 at Fermilab", presented at the 19th Int. Conf. RF Superconductivity (SRF'19), Dresden, Germany, Jun.-Jul. 2019, paper WETEA2.

[2] V. Roger, S. K. Chandrasekaran, and D. Passarelli, "Design Strategy of the PIP-II Cryomodules", presented at the 19th Int. Conf. RF Superconductivity (SRF'19), Dresden, Germany, Jun.-Jul. 2019, paper MOP094.

[3] V. Roger, S. Cheban, T. H. Nicol, Y. O. Orlov, D. Passarelli, and P. Vecchiolla, "Design Update of the SSR1 Cryomodule for PIP-II Project", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 2721–2723. doi:10.18429/JACoW-IPAC2018-WEPML019

[4] D. Passarelli *et al.*, "Preparation and Qualification of Jacketed SSR1 Cavities for String Assembly at Fermilab", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 2714–2717. doi:10.18429/JACoW-IPAC2018-WEPML015

[5] A. I. Sukhanov *et al.*, "Characterization of SSR1 Cavities for PIP-II Linac", presented at the 19th Int. Conf. RF Superconductivity (SRF'19), Dresden, Germany, Jun.-Jul. 2019, paper THP090.

[6] M. Parise, Preparation, processing, assembling and testing of spoke resonators: from SSR1 jacketed cavities to string assembly , Invited oral talk of TESLA Technology Collaboration (TTC) Meeting, Milan, Italy, 2018.

[7] D. Passarelli, F. Di Ciocchis, M. Parise, and V. Roger, "Tooling Systems for the Assembly and Integration of the SSR1 Cryomodule for PIP-II Project at Fermilab", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 2710–2713. doi:10.18429/JACoW-IPAC2018-WEPML014