COLD TESTS OF SSR1 RESONATORS MANUFACTURED BY IUAC FOR THE FERMILAB PIP-II PROJECT*

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Abstract

In the framework of the Indian Institutions and Fermilab Collaboration (IIFC) within the PIP-II project, two Superconducting Niobium Single Spoke Resonators were manufactured at the Inter-University Accelerator Centre (IUAC) in New Delhi and tested at Fermilab. The resonators were subject to the routine series of inspections and later processed chemically by means of Buffered Chemical Polishing, heat-treated at 600°C and cold-tested at Fermilab in the Vertical Test Stand. In this paper we present the findings of the inspections and the results of the cold-tests.

INTRODUCTION

The design of the SSR1 resonator was developed at Fermilab [1] within the scope of the Project X R&D program [2]. A production batch of 10 SSR1 resonators was initiated by Fermilab in US industry [3]. Through the IIFC collaboration, it was possible to develop the manufacturing process and fabricate two additional SSR1 resonators at IUAC. In Figure 1, the two SSR1 niobium resonators developed by IUAC are shown.

Figure 1: The two SSR1 niobium resonators developed by Inter University Accelerator Centre (IUAC), New Delhi.

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MANUFACTURING

The fabrication of the SSR1 resonators was carried out using the model adapted by IUAC for constructing superconducting niobium cavities. The rolling, cold-forming and machining of the major sub-assemblies (e.g. the shell, the spoke and the end wall), along with the RF tuning, associated dimensional measurements and trimming, were all performed at an outside vendor, who has been working with IUAC in the development of niobium resonators. The design, development and fabrication of the dies, punches and of the various fixtures required for machining, chemical treatment and EBW of the resonator parts were done by the outside vendor in consultation with IUAC personnel. The validation of the dies and punches was done on copper material.

Material

All Niobium material was procured from a qualified vendor, inspected at Fermilab and provided to IUAC. The material was subject to visual inspection and immersed in water for 24 hours to reveal any iron contamination. Coupons from different annealing batches were subject to eddy current scanning and RRR measurements.

All brazed joints necessary for the SSR1 flanges were designed and manufactured at ANL [4] and provided to IUAC in the stock condition.

Electro-Polishing of Sub-Assemblies

The chemical treatment, which primarily consisted of electro-polishing of individual sub-assemblies to remove ~125-150 μm of material, was accomplished using the in-house facilities at IUAC.

A standard electro-polishing recipe was used. An electrolytic mixture of HF (48%) and H_2SO_4 (98%) was used in the ratio of 1:9 (Vol./Vol.). The mixture was maintained at a temperature of 30 ± 2°C and a current density of ~60 mA/cm2 at 18 V was achieved during the process. In Figure 2 the electro-polishing setup for the niobium shell is shown.

Electron-Beam Welding

A substantial amount of effort was put in developing the EBW parameters for the different weld joints. The starting point in these developments was the parameters used for constructing niobium resonators for the in-house programs. Some of the critical welds, like the spoke to shell and the end wall to the shell and spoke assembly, were simulated on small samples before doing the actual welding. Figure 3 shows a SSR1 resonator being setup for the final closure welding.

Figure 2: Electro-polishing of the shell sub-assembly at IUAC prior to the EBW of end-walls.

Figure 3: SSR1 resonator being setup to weld the end wall to the shell and spoke assembly.

INSPECTIONS AT FERMILAB

A series of inspections are routinely performed on SSR1 resonators. The inspection activities include visual inspection, dimensional measurements, RF measurements and a leak check.

After the IUAC resonators were received at Fermilab, they were thoroughly inspected and found to have a smaller shell length, smaller shell diameter, smaller accelerating gaps by ~2mm/ea and a longer overall length by ~10mm. Despite the findings being somewhat outside the expected tolerance range, it was decided to proceed with the qualification tests due to the importance of obtaining valuable feedback in view of the production of more cavities through the IIFC collaboration for PIP-II.

RF MEASUREMENTS

As part of the incoming inspection process, several RF measurements are performed on SSR1 resonators including a bead-pull measurement to record the field-flatness.

With atmospheric conditions of T=20.4°C, H=30%, P=987 mbar, the recorded resonant frequency for each of the two cavities was 325.45 MHz and 325.19 MHz with a field flatness of 100% (see Figure 4) and 97.8%. It was decided that the two cavities did not need any permanent deformation to adjust the RF performance.

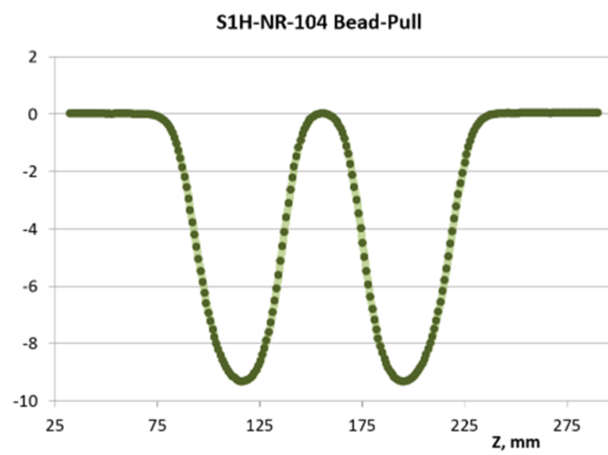

Figure 4: Bead-pull measurement showing 100% field-flatness on cavity S1F-IU-104.

CHEMICAL PROCESSING AND HEAT TREATEMENTS

In preparation for the chemistry, necessary for the removal of the damage layer, the cavity is immersed in a bath of ultra-pure water (UPW) with a degreasing agent and ultrasonically cleaned.

Buffered Chemical Polishing (BCP)

The BCP uses the standard $HF:HNO_3:H_3PO_4$ (1:1:2) acid mixture. During BCP, acid flow and temperature are controlled in the following manner. The bare cavity is immersed in a bath of UPW initially cooled to 7.5ºC. The cavity interior, sealed from the water bath, is connected to a pump for acid circulation. The cavity is oriented with the power coupler port and the vacuum port along the vertical axis and the beam pipes along the horizontal axis. In order to begin etching, acid (earlier chilled to 14ºC) is pumped up through the bottom port to fill the interior of the cavity. After shutting off the source of acid, the closed loop circulation pump draws acid from the top of the cavity and sends it back to the cavity through flanges on both beam pipes. Heat generated by the etching is dissipated through the cavity walls (including the spoke walls) to the continuously cooled water bath.

In order to obtain a total etching of ~120 µm and keep the niobium content in the acid below 10 g/l, spent acid is replaced with fresh acid about half way through the etching. Given the asymmetry in the acid flow pattern, the

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cavity is flipped top to bottom between the two etching sessions. The reduction in wall thickness is monitored at 20 locations using an ultrasonic thickness gauge.

High Pressure Rinsing (HPR)

After BCP, the cavity is moved to the class 10 clean area for HPR. The UPW distribution consists of a long wand with a nozzle at the end that produces six water jets, two each at +45º, 90º, and -45º to the wand axis. The wand rapidly rotates about the axis and travels along the axis (into or out of the cavity) at ~3 cm/min. In order for a jet to directly spray on all the interior cavity surfaces, including ports and beam pipes, the orientation of the SSR1 is changed six times with the HPR lasting ~20 minutes at each orientation for a total of 2 hours.

Hydrogen Degassing

In order to reduce hydrogen content and avoid Q-disease, SSR1 cavities are baked with a 10 h plateau at 600 °C. Treating cavities at higher temperatures (e.g. 800 °C) would reduce considerably the plateau time but risk of damaging the existing copper braze joints. Figure 5 shows the temperature in the cavity and partial pressures of various gasses during the bakeout. After this heat treatment, cavities receive a light BCP etch and again a round of HPR prior to being prepared for cold tests.

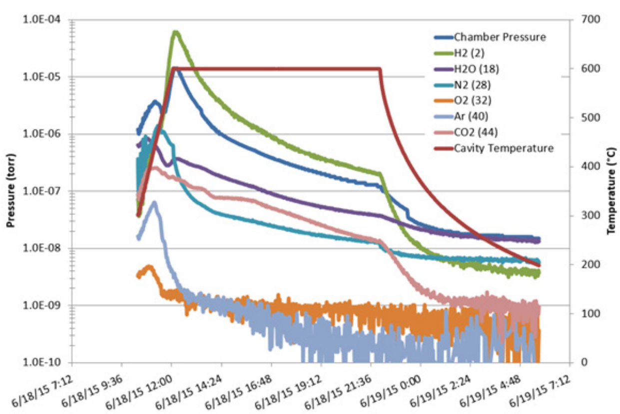

Figure 5: In this bake data plot, the cavity temperature is shown in red. The partial pressure of H_2 is shown in green, the partial pressure of H_2O is shown in purple.

COLD TESTS

Once the resonator was prepared for the cold tests, it was subjected to the routine 120°C bake for 48h (see Figure 6). This bake has been demonstrated to reduce multipacting during RF processing and medium field Q-slope during cavity performance.

The first cavity from IUAC (S1F-IU-104) was RF-tested in the Fermilab Vertical Test Stand (VTS).

RF measurements of SRF cavities at the operating temperature typically involve measuring the intrinsic quality factor Q_0 as a function of the accelerating field E_{acc} in a vertical test stand.

Vertical tests of SSR1 cavities at Fermilab consist of two stages. In the first stage, processing of multipacting barriers is carried out at 4K. Once processing is complete, the cavity is cooled down to 2K (which is the operating temperature for SSR1 in the accelerator) and measurements are taken for Q_0 versus E_{acc}.

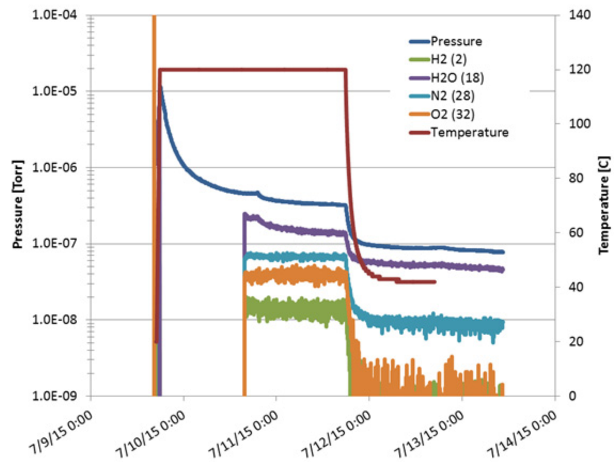

Figure 6: This plot shows the temperature of the cavity and partial pressure of various gasses during the 120°C bake prior to cold tests.

SSR1 cavities are known to have multipacting barriers. Once a multipacting barrier is reached, when the energy supplied to the cavity is increased the field level remains constant. Strongest SSR1 multipacting barriers typically occur at 3-5 MV/m and 6-8 MV/m (accelerating field defined with effective length βλ).

In order to overcome multipacting, the cavity is filled with energy which is mostly consumed by multipacting electrons in the cavity. Multipacting is left to progress for a certain amount of time until eventually, and sometimes abruptly, Q_0 improves and multipacting ceases.

In order to achieve efficient multipacting processing at 4K care is taken in the design and fabrication of the input coupler antenna. The antenna length is chosen in such a way that the external quality factor of the input coupler port (usually denoted as Q_1) is similar to the intrinsic quality factor of the cavity at 4K (typically on the order of a fraction of 10^8). Multipacting is processed at 4K in order to reduce the amount of cryogenic system resources used in the test.

During tests of S1F-IU-104, multipacting was processed at 4K and quench field was first reached at 4K within one day of processing. Typical multipacting barriers mentioned above were observed and overcome.

The 2K measurements demonstrated that the cavity satisfied PIP-II project specification of Q_0=0.5x10^{10} at accelerating field 12 MV/m at 2K (field defined at effective length). We measured Q_0 = 1.3x10^{10} at 12MV/m at 2K. Quench field was found to be 18 MV/m at 2K. The effective length used to define E_{acc} is equal to βλ .

The uncertainty on measurements of Q_0 is 17% while the uncertainty on E_{acc} is 5%. These estimations were done considering sources described in [5]. Figure 7 shows the Q_0 vs E_{acc} curve for the IUAC cavity at 2K (magenta solid markers) overlaid with curves of previous measurements of single spoke resonators from the production batch at Fermilab.

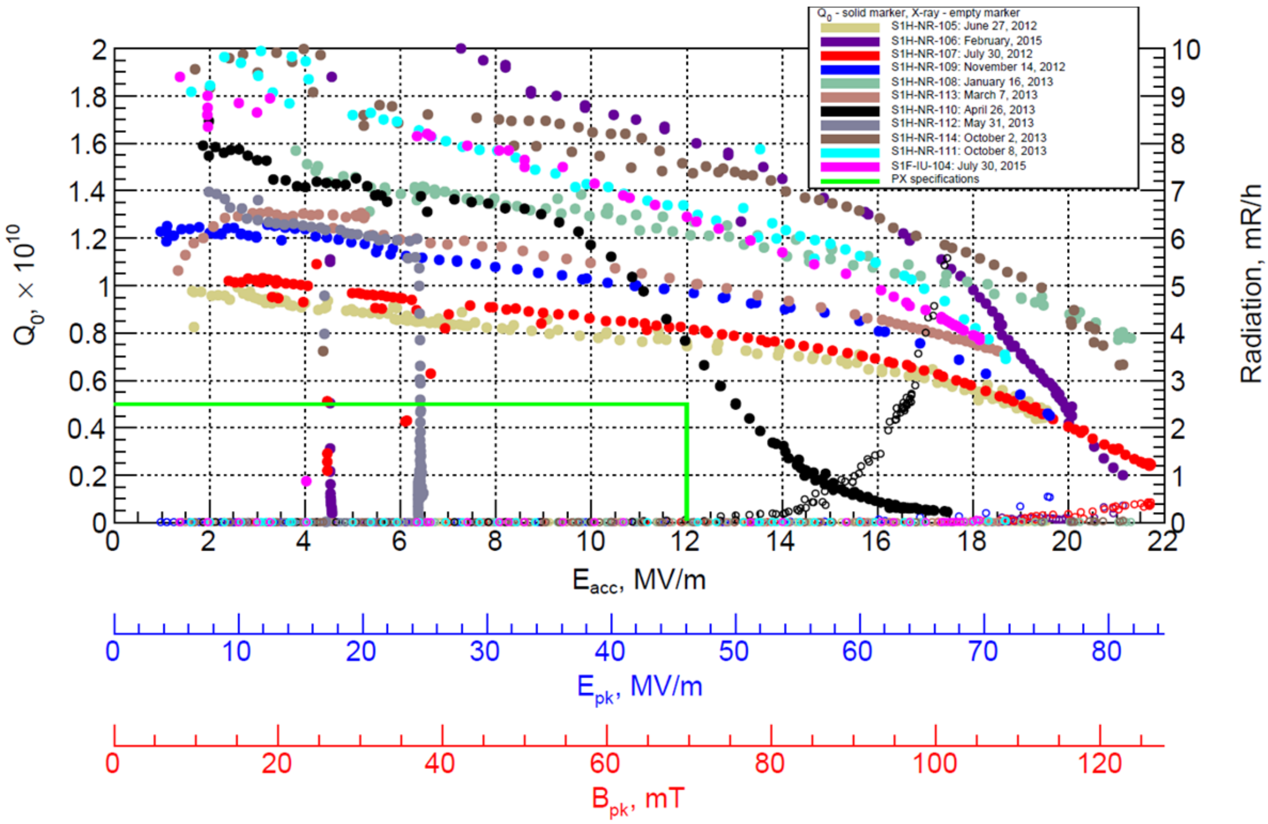

Figure 7: Summary plot showing results of tests at 2K for all SSR1 resonators tested at Fermilab as of August 2015. The IUAC resonator (S1F-IU-104) is shown in magenta and reached 18 MV/m with a Q_0 of 1.3 10^{10} at 12 MV/m (design gradient). PIP-II specifications ($E_{acc} > 12$ MV/m, $Q_0 > 0.5\ 10^{10}$) are shown with a green box.

CONCLUSION AND OUTLOOK

Two bare SSR1 resonators were manufactured by IUAC and received at FNAL within the scope of the IIFC collaboration. The first resonator was chemically processed, heat-treated and tested at Fermilab where it exceeded PIP-II project requirements. The second resonator will be tested in the next month. Both resonators will be shipped back to India where they will be welded into their helium vessels by other collaborating institutions. After their completion, Fermilab will perform fully-integrated tests in the Spoke Test Cryostat (STC) with the plan of integrating the cavities in a SSR1 cryomodule for PIP-II.

ACKNOWLEDGMENTS

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