COLD TESTS OF SSR1 RESONATORS FOR PXIE

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Abstract

Fermilab is currently building the Project X Injector experiment (PXIE). PXIE linac will accelerate 1 mA H^- beam up to 30 MeV and serve as a testbed for validation of Project X concepts and mitigation of technical risks. A cryomodule of eight superconducting RF Single Spoke Resonators of type 1 (SSR1) cavities operating at 325 MHz is an integral part of PXIE. Ten SSR1 cavities were manufactured in industry and delivered to Fermilab. In this paper we discuss surface processing and tests of bare SSR1 cavities at the Fermilab Vertical Test Stand (VTS). We report on the measured performance parameters of nine cavities achieved during tests.

INTRODUCTION

Project X (PX), a multi-MW H^- source, is under development at Fermilab [1]. It will provide intense muon, kaon, neutrino and nuclei beams, allow the study of applications of proton accelerators for energy production, and may become a driver for a future Neutrino Factory and/or Muon Collider. In order to validate the concept of Project X and mitigate technical risks, Fermilab is designing and building the Project X Injector Experiment (PXIE), which will accelerate 1 mA beam of H^- ions up to 30 MeV [2]. The final stage of acceleration in PXIE is performed by a cryomodule of eight superconducting RF Single Spoke Resonators of type 1 (SSR1) operating at 325 MHz [3]. For the PXIE application, SSR1 cavities are required to have 2.4 MeV maximum energy gain per cavity, corresponding to the accelerating gradient $E_{\mathrm{acc}} = 12$ MV/m, and the quality factor $Q_0 \geq 5 \times 10^9$. The assembled cavity, jacketed in a helium vessel with tuner, is required to have sensitivity to the LHe bath pressure variations less than 25 Hz/Torr.

Results of high gradient tests of two prototype SSR1 cavities have been reported elsewhere [4]. Another ten SSR1 cavities have been recently manufactured by C.F. Roark [5] and delivered to Fermilab. Details of SSR1 design, manufacturing and mechanical measurements are reported in [6]. We present the cavity surface preparation procedure and results of the cold tests of nine SSR1 bare cavities in the Fermilab VTS.

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CAVITY TESTS

Preparation of Cavities for Tests

Upon delivery, all cavities undergo incoming quality control/assurance (QC/QA) inspection, which includes visual inspection, coordinate machine measurements, RF QC and vacuum leak check. Then cavities enter a processing cycle at the Fermilab-Argonne cavity processing facility, beginning with ultrasonic (US) degreasing and ultra-pure water (UPW) rinsing. In the next step, 120–150 μm BCP etching is done in two sessions, 60–75 μm each. For the etching, cavities are oriented with their vacuum and power coupler ports in the vertical direction. Between etching sessions, cavities are flipped from top to bottom to balance material removal throughout the cavity. After the 2^{nd} US degreasing/UPW rinse and high pressure rinse (HPR) hydrogen degassing is performed for 10 hours in ultra-high vacuum (UHV) at 600 C. Then final RF tuning is done, followed with 3^{rd} US degreasing/UPW rinse and subsequent light (20–30 μm) BCP. Prior to the cleanroom assembly, cavities undergo final HPR, which is done in two orientations, with the cavity axis vertical and horizontal, in order to provide better reach to the internal cavity surface. After assembly, cavities are evacuated and checked for leaks (10^{-10} mbar-l/s or better). In the final step of processing, cavities are baked for 24–48 hours at 120 C to reduce surface water content. Exhaust of the vacuum pump is analyzed with an RGA during baking. Partial pressure of hydrogen, water and some other gases is monitored. Typically, the water partial pressure drops by a factor of 100 after 24 h.

Typical Test Sequence

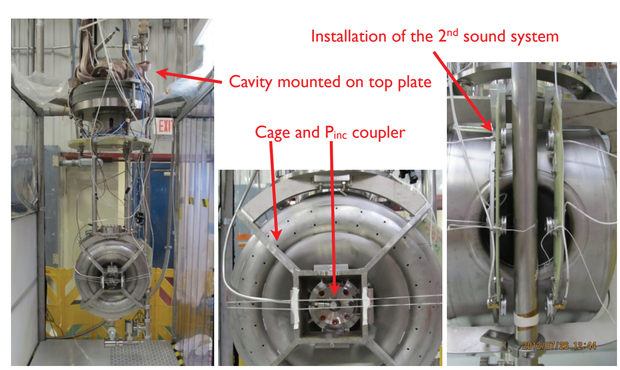

Figure 1: SSR1 cavity attached to the VTS top plate.

Cold tests of bare SSR1 cavities are performed in the Fermilab VTS cryostat. Cavities are connected to the vacuum pump, but usually are not actively pumped during tests. Vacuum in the warm cavity is 10^{-7} Torr. The final tuning of the cavity resonance frequency is performed at this stage. Cavities are instrumented with Oscillating Superleak second-sound Transducers (OST) to detect second-sound emitted by a quench [7]. OSTs are positioned close to the spoke-to-sidewall transition area, near the maximum magnetic field region, where the quench is most likely to happen. Fig. 1 shows the attachment of SSR1 cavity to the VTS top plate and connection to the vacuum system (left), cavity suspension Ti cage and input RF power coupler (center), and layout of OSTs (right).

We place a radiation detector on the top plate outside the cryostat in order to monitor X-ray radiation when field emission (FE) is present in the cavity. Note that due to internal radiation shielding installed at VTS [8], our sensitivity to the FE induced X-ray radiation is lower compared to the vertical test stands in other laboratories. In our tests, axis of the SSR1 cavity is oriented horizontally. The major part of the FE X-rays is radiated along the cavity axis and only small fraction of the radiation reaches the detector. Because of these, the direct comparison of our FE measurements to the results obtained in other laboratories can be difficult.

At the first stage of the test, multipactor (MP) conditioning is performed at 4.4 K. With 150 W of RF power available at VTS, it usually takes from 3 to 8 hours to process most of the MP "barriers". The very first production SSR1 cavity was not baked at 120 C before it came for the cold test. We observed strong MP in this test, which did not completely process away even after 20 hours of conditioning. The cavity was warmed up and baked. In the subsequent cold test all MP was processed in just 3 hours. We incorporated 120 C baking during 48 hours as the final step of cavity preparation for cold test. Fig. 2 shows typical behavior of SSR1 cavity during MP conditioning. Strong multipactors were observed at 4.5 and 6.5 MV/m. It took 3.5 hours to clear MP in cavity S1H-NR-107, while in the first test of another cavity, S1H-NR-108, 6.5 MV/m MP was present even after 9 hours of processing. We also observed mild field emission during this test. The cavity was warmed up, re-rinsed and baked at 120 C and then re-tested. During the second test of this cavity all MP barriers were cleared after 4 hours of conditioning.

After MP conditioning the cavity is cooled down from 4.4 to 2 K. During cool-down cavity is usually kept on resonance at low field (2–3 MV/m) and measurements of the cavity frequency shift Δf *vs* LHe bath pressure and Q_0 *vs* T are performed. Measurement of the slope parameter df/dp of the bare cavity is important for the validation of the computer model, which has been used for the optimization of the sensitivity of the jacketed cavity to the LHe bath pressure variations. Data on the temperature dependence of Q_0 can be used to fine tune the cavity processing procedure.

Results of measurements of the resonance frequency shift Δf as a function of LHe bath pressure are shown in

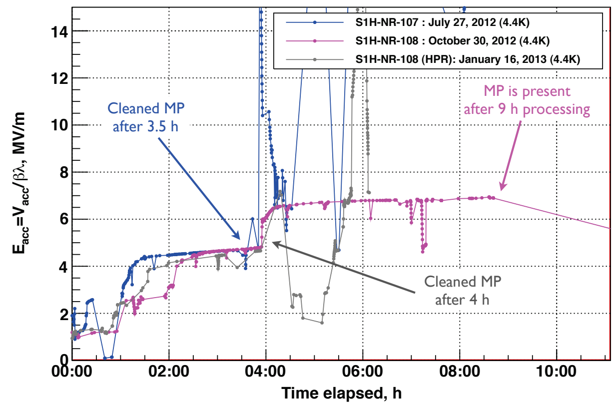

Figure 2: Multipactor processing.

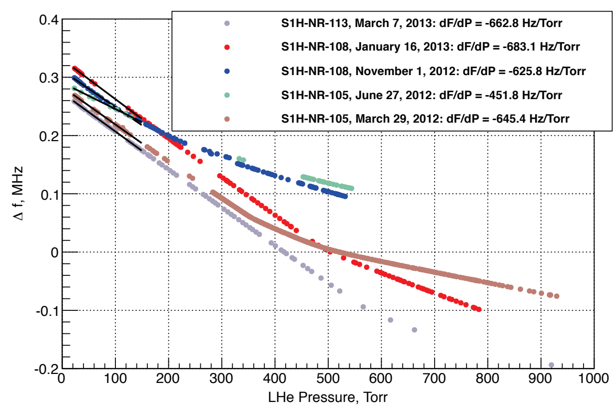

Figure 3: Measurement of the resonance frequency shift *vs* LHe bath pressure during cool-down from 4.4 K to 2 K.

Fig. 3 for two cavities in four separate tests. The curve of Δf *vs* pressure has two linear parts. The high pressure (4.4 K) regime with smaller slope df/dp corresponds to the cavity constrained by the Ti cage. At low pressure (2 K), the cavity becomes unconstrained and df/dp slope increases. The measured value of df/dp of the unconstrained cavity is approximately 650 Hz/Torr and agrees well with simulation.

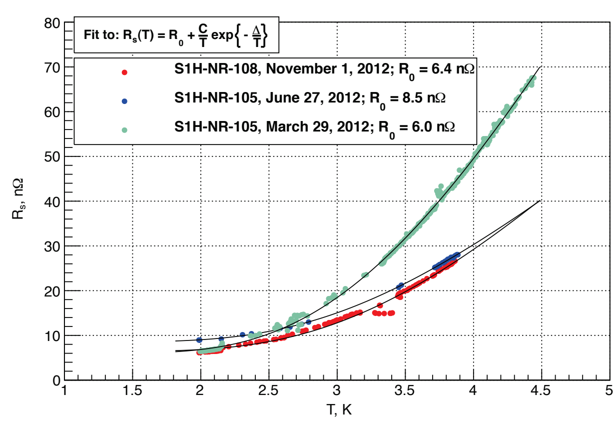

Figure 4: Measurement of surface resistance *vs* temperature.

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Table 1: Summary of Cold Tests of SSR1 Cavities

Cavity ID	Test #	Performance		Limitation	Status
		E_{acc}, MV/m	Q_0(12 MV/m), $\times 10^{10}$		
S1H-NR-105	1			MP	
S1H-NR-105	2 (120C)			FE	
S1H-NR-105	3 (HPR+120C)	19.5	0.8	quench	**Qualified**
S1H-NR-107	1	21.7	0.8	quench	**Qualified**
S1H-NR-108	1			MP + FE	
S1H-NR-108	2 (HPR+120C)	21.3	1.2	quench	**Qualified**
S1H-NR-109	1	19.6	0.98	quench	**Qualified**
S1H-NR-110	1			MP + FE	
S1H-NR-110	2 (light BCP+HPR+120C)	17.3	0.8	quench	**Qualified**
S1H-NR-111	1			MP	to be re-tested
S1H-NR-112	1	17 (at 4.4 K)	1.3 (at 6 MV/m)	MP	**Qualified**
S1H-NR-113	1	18.5	1	quench	**Qualified**
S1H-NR-114	1			MP + FE	to be re-tested

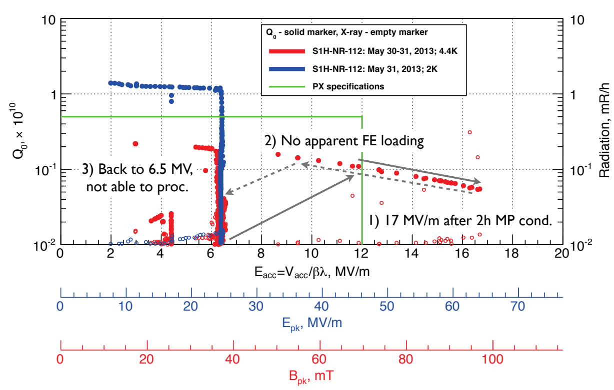

Figure 5: Multipactor conditioning is S1H-NR-112.

Fig. 4 shows results of measurements of the cavity surface resistance as a function of LHe bath temperature. We determine surface resistance from Q_0 using the following relation, $R_s = G/Q_0$, where the geometry factor of SSR1 cavity is $G = 84\ \Omega$ [6]. We approximate R_s *vs* T data with the expression $R_s(T) = R_0 + \frac{C}{T}\exp\left[-\Delta/T\right]$. Here R_0 is the temperature independent *residual* resistance, while the temperature dependent part describes *BCS* resistance. At 2 K and 325 MHz of RF frequency, the *BCS* component is typically small (~ 1 nΩ) compared to ~ 6 nΩ of residual resistance.

Cavity performance is evaluated at 2 K, including measurements of Q_0 vs E_{acc} curve, maximum achievable field, Q0 and radiation level at the maximum field, onset field of field emission (FE), if present.

A study of performance degradation due to quenching in magnetic field has been done on few a SSR1 cavities during their cold tests. Results are reported elsewhere [9].

RESULTS

Since March 2012 we have tested nine SSR1 cavities in 13 cold cycles. Table 1 summarizes the results of the tests and cavity status.

Three cavities (S1H-NR-107, -109 and -113) had very mild MP, which was completely conditioned within 3–9 hours of the test. These cavities demonstrated good performance, reached parameters ($E_{acc} \geq 12$ MV/m and $Q_0 \geq 5\times10^9$) required for PXIE and were qualified for cryomodule assembly. Note, that operational conditions for SSR1 cavities in Project X linac ($E_{acc} = 10$ MV/m and $Q_0 \geq 5\times10^9$) are less limiting, and all cavities that are qualified for PXIE automatically satisfy PX requirements.

Four cavities (S1H-NR-105, -108, -110 and -114) showed performance limited by strong field emission during the initial tests. Two of these cavities (105 and 108) received additional HPR and 120 C baking before the second test. Additional light (20-30 μm) BCP was performed on two other cavities (110 and 114) before HPR and 120 C bake. Cavities 105, 108 and 110 were subsequently retested, showed improved performance and qualified for the PXIE cryomodule. Cavity 114 has yet to be re-tested.

Cavity S1H-NR-111 showed strong MP during its initial test. The cavity will receive additional 48 hours baking at 120 C and it will be re-tested.

Cavity S1H-NR-112 had strong MP at 6.5 MV/m. Data taken during MP conditioning of this cavity are shown in Fig. 5. The cavity temporarily reached 17 MV/m at 4.4 K, but when the input power level was decreased, the accelerating gradient dropped back to the 6.5 MV/m MP barrier. Subsequent conditioning at 100–120 W of input power for more than 10 hours did not clear MP and we were not able to increase field in the cavity above 6.5 MV/m. At 2 K and $E_{acc} \leq 6.5$ MV/m we measured a quality factor $Q_0 = 1.3\times10^{10}$ comparable to the other qualified cavities at the same field level. We expect that the additional light BCP and HRR, which the cavity will receive during

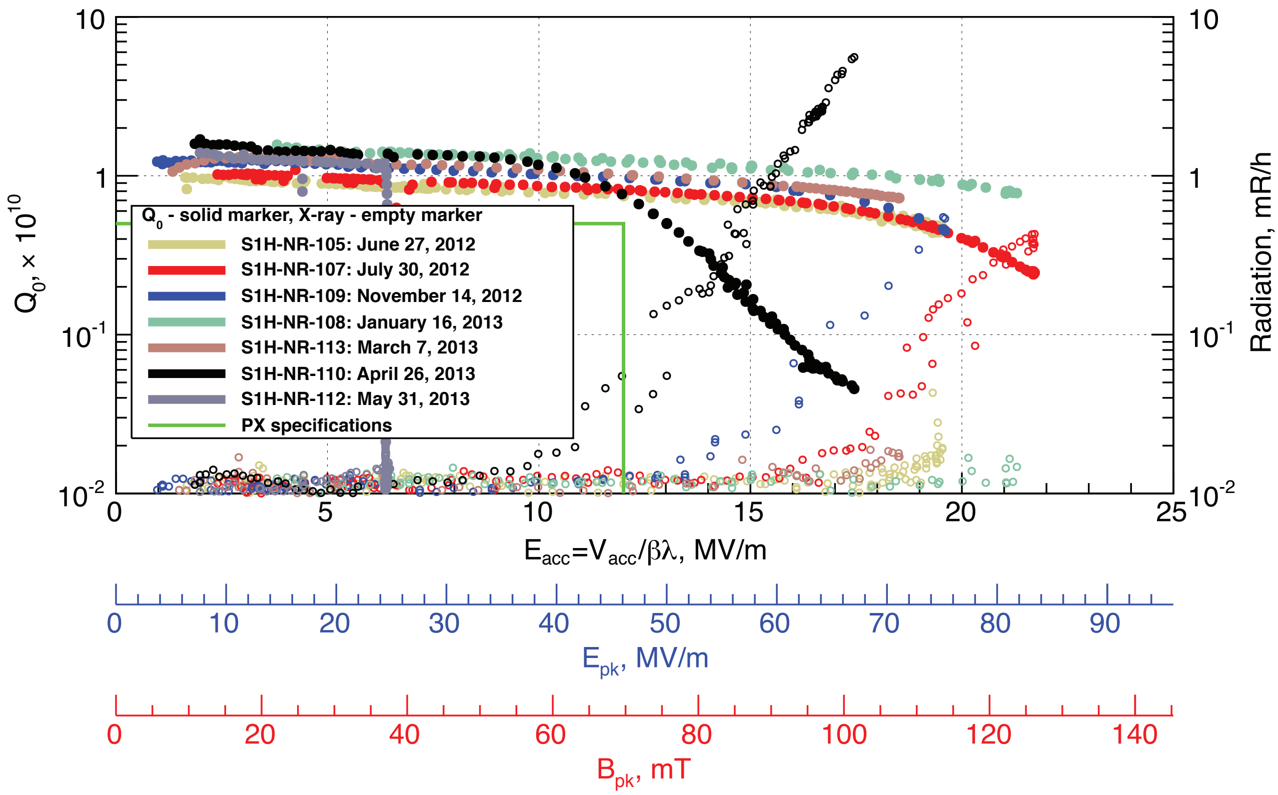

Figure 6: Summary of results of SSR1 cavity tests at 2K.

jacketing, will reduce MP level. Since this cavity showed potentially good performance and we did not find any performance degradation associated with the manufacturing, we "conditionally" qualified this cavity for PXIE cryomodule.

Fig. 6 shows results of 2 K tests for all SSR1 cavities qualified for the PXIE cryomodule assembly. Maximum achievable field in these cavities is in the range from 17 to 22 MV/m and is limited by quench in all cavities but S1H-NR-112. OST system detected quench signals near the spoke to sidewall transition area in four cavities. In one test, OST signals were not detected during quench and we conclude that the area of the quench in this case is on the cavity end-wall.

Four cavities (S1H-NR-105, -108, -112 and -113) show very little radiation, while three other cavities (107, 109 and 110) have FE onset at 10, 13 and 17 MV/m. Cavities will receive additional light BCP (20–30 μm) and HPR during jacketing. We expect that additional processing and HPR will reduce the level of FE in cavities 107, 109 and 110.

SUMMARY

We performed cold tests of nine production SSR1 cavities. Seven cavities demonstrated $E_{acc} \geq 12$ MV/m and $Q_0 \geq 5 \times 10^9$ and were qualified for PXIE cryomodule assembly. Two other cavities will receive additional processing and be re-tested. Strong MP is an issue in the cold tests of SSR1 cavities. UHV baking at 120 C for 48 hours helps to reduce the time needed to condition MP during tests.

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