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CHARACTERIZATION OF SSR1 CAVITIES FOR PIP-II LINAC[*]

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Abstract

A cryomodule of 325 MHz Single Spoke Resonator type 1 (SSR1) superconducting RF cavities is being built at Fermilab for the PIP-II project. Twelve SSR1 cavities were manufactured in industry in USA (10 cavities) and India (2 cavities) and delivered to Fermilab. In this paper we present results of characterization of fully integrated jacketed cavities with high power coupler and tuner at the Fermilab Spoke Test Cryostat (STC).

ITRODUCTION

The Proton Improvement Plan II (PIP-II) project is under construction at Fermilab [1]. The mission of the project is to deliver intense beam of neutrinos to the international LBNF/Dune project. Integral part of PIP-II is super-conducting RF (SRF) linac, consisting of 5 different types of cavities (see Fig. 1): Half-Wave resonators (HWR) at 162.5 MHz, 2 types of Single-Spoke Resonators (SSR1 and SSR2) at 325 MHz and 2 types of 5-cell elliptical cavities, low- and high-beta at 650 MHz, (LB650 and HB650).

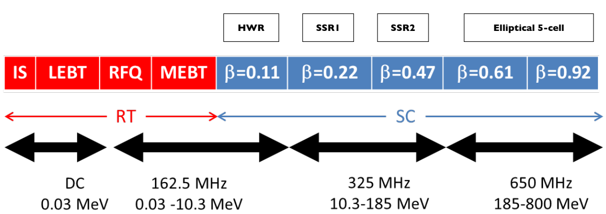

Figure 1: PIP-II Linac.

Currently we built a prototype SSR1 cryomodule, consisting of 8 fully integrated SSR1 cavities, jacketed in Helium vessel and assembled with high power coupler (HPC) and tuner, Fig. 2. Baseline performance specification of SSR1 cavities are shown in Table 1. Twelve bare SSR1 cavities built in US (10) and India (2) industry and delivered to Fermilab. All these cavities were tested and qualified at the Fermilab Vertical Test Stand (VTS). Results of VTS qualification can be found elsewhere (REF).

After VTS qualification, all 12 SSR1 cavities were jacketed in Helim vessels. In this paper we describe results of characterization of fully integrated SSR1 cavities with HPC and tuner in the Fermilab Spoke Test Cryostat (STC). Figure 3 show STC and SSR1 cavity installed for testing.

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Table 1: Baseline Performance Specifications of SSR1 Cavities

Parameter	Specification
Operating Field	10 MV/m
Q_0	$> 6 \times 10^9$
Tuning Constant	40 N/kHz
Tuning Sensitivity	$<$ 20 Hz/Torr

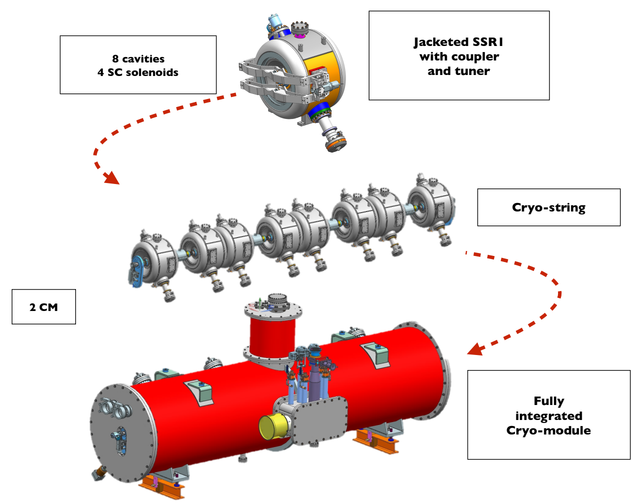

Figure 2: SSR1 Cryomodule.

PREPARATION OF SSR1 CAVITIES FOR STC TESTING

All jacketed SSR1 received ultrasonic cleaning, 5–10 μm buffered chemical polishing (BCP) and high pressure rinse (HPR) with ultrapure water. After processing, cavities assembled with HPC[1] in clean room, evacuated and leak checked. Prior STC testing all SSR1 cavities are baked at low temperature (120 C) in convection oven for 48 hours. During bake cavities are actively pumped with vacuum pump while continuously analyzing outgassing with RGA. Figure 4 shows typical RGA spectra at the beginning (blue trace) and at the end (red trace) of bake. As the result of 120 C baking partial water pressure (peaks at 18 AMU) drops by two

[1] For development of STC testing procedure and debugging cavity processing sequence few SSR1 cavities assembled with small antenna providing critical coupling for low power coupler (LPC) RF testing and without tuner. LPC equipped cavities are much easier to install in STC, leading to faster tests turnaround time. Critical coupling allows for cavity Q_0 measurements based on RF signals thus cross-checking standard calorimetric Q_0 measurements.

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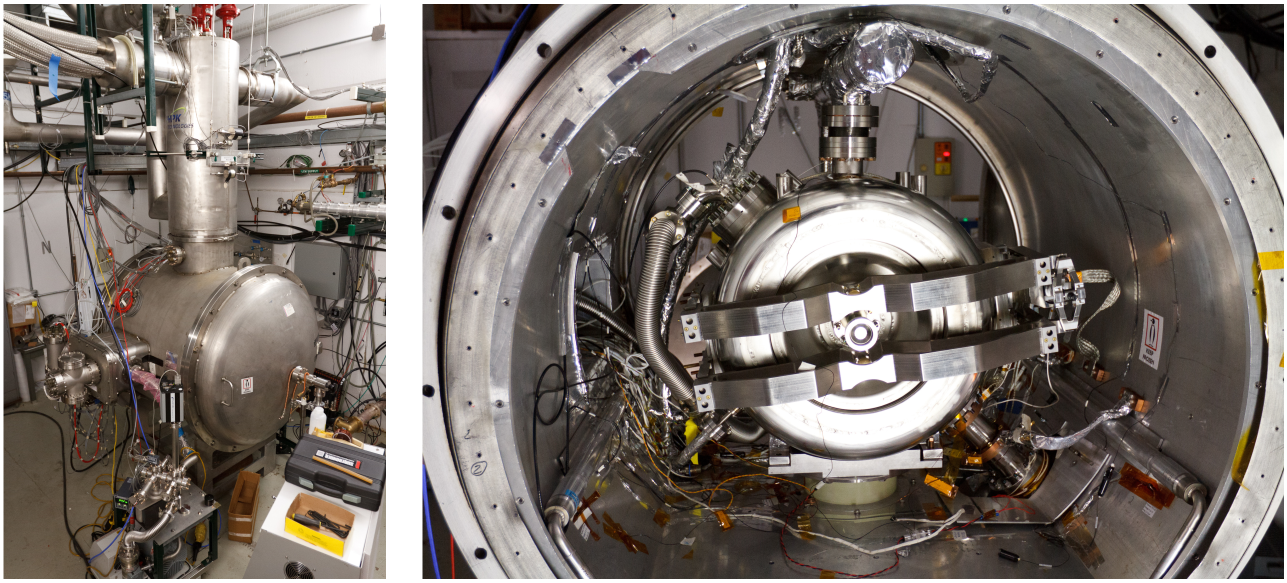

Figure 3: STC.

orders of magnitude, which helps to mitigate multipactor (MP) in subsequent RF testing.

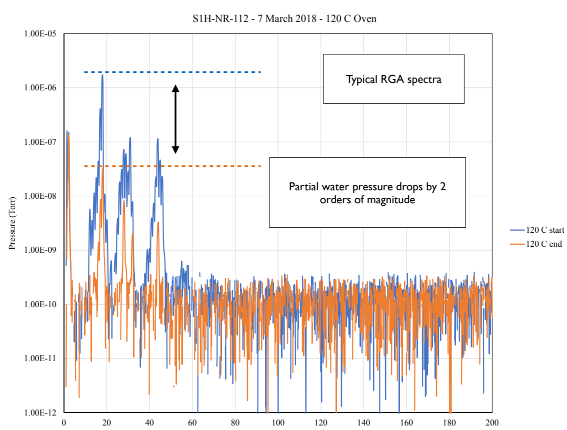

Figure 4: RGA.

STC Test Sequence

Typical SSR1 STC testing process includes cavity installation with removal of previous cavity (1–2 days), cool down (1 day), test (up to 7 days, depending duration of MP conditioning and additional studies beyond cavity characterization for CM assembly) and warm up (1 day). When cavity is cold at 2 K, we start tests with LLRF system calibration and measurement of the cavity resonance frequency f_0 and loaded quality factor, Q_L. We check coupler performance off resonance, gradually increasing forward power to the coupler up to 5 kW in pulsed mode with 2%, 4%, 8%, 15% and then in CW mode with 10–15 minutes dwelling time at maximum power at each timing settings. We then tune cavity on resonance at 325 MHz and begin multipactor conditioning, which takes from 3 up to 48 hours. After cavity is cleaned of MP, we perform baseline cavity performance characterization, which includes measurements of the maximum cavity field (administratively limited to 14.4 MV/m), maximum field limiting factors (quench, field emission radiation > 1500 mR/h), radiation onset field and radiation at maximum field (if present), Q_0 *vs* E_{acc} curve, cavity detuning sensitivity due to pressure variations (df/dp) and Lorentz force detuning coefficient. We conclude baseline testing with tuner qualification, measuring tuning ranges and sensitivity for coarse (stepper motor) and fine (piezo actuators) tuners. If time permits, we perform additional studies, including but not limited to development of resonance control procedures, effects of magnetic environment on cavity Q_0 and coupler thermal characteristics.

RESULTS

In duration of the SSR1 testing program at STC between May 1017 and November 2018 we perform 34 test cycles of 10 different SSR1 cavities in both LPC (17 cycles) and HPC (17 cycles) configurations, totalling 37 cool down/warm up cycles. These tests include development and prototyping for SSR1 tuner and coupler. In addition, few fully integrated production SSR1 cavities show strong field emission during test and require re-processing with BCP and HPR and re-testing to qualify for CM. Of the two untested cavities one has damage on the beam pipe flange and do not pass leak check. The other cavity develops strong corrosion spots at the surface of Helium vessel during US cleaning and is removed from processing sequence.

Baseline Performance

The main purpose of the STC testing is characterization and selection of 8 fully integrated SSR1 cavities for assembly of the 1st prototype SSR1 cryomodule. In this section we present results of these qualification tests.

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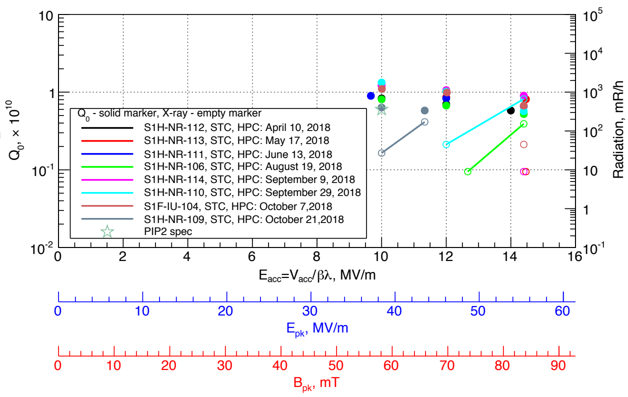

Figure 5: Q_0 and radiation *vs* E_{acc} for 8 SSR1 cavities qualified for prototype cryomodule assembly.

Figure 5 summarizes measurements of Q_0 and radiation as function of the cavity field for 8 SSR1 cavities qualified for cryomodule assembly. As one can see, performance of all selected cavities satisfy specification requirements for PIP-II linac. Three cavities are radiation free, while five other cavities have radiation onset at or above operating gradient (10 MV/m).

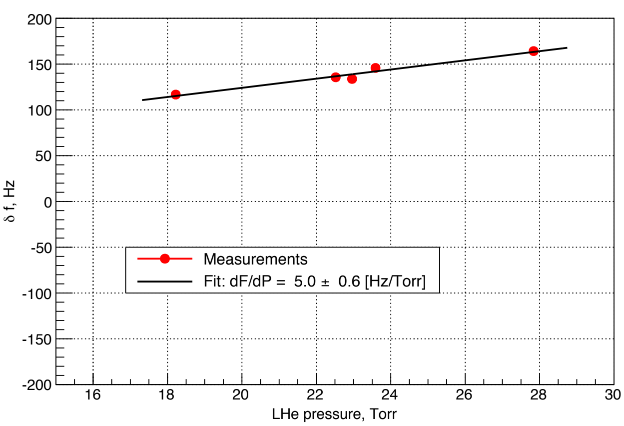

Figure 6: Typical df/dp of SSR1 cavity.

Sensitivity of SSR1 cavities detuning to pressure fluctuations df/dp are measured at STC by varying pressure of the liquid Helium bath within 18–28 Torr range. Typical results are shown in Fig. 6 for one of the cavities. In this particular case df/dp = 5 Hz/Torr. For 8 qualified cavities df/dp varies in the range 1.1–9.9 Hz/Torr, with the mean value of 6.4 Hz/Torr, which is lower than specified maximum value of 20 Hz/Torr.

Variations of the cavity resonance frequency as a function of the square of cavity field are characterized by Lorentz force detuning (LFD) coefficient. Figure 7 shows typical LFD behavior of one of the SSR1 cavities as measured during STC testing. Here LFD coefficient is −4.2 Hz/(MV/m)^2. Mean LFD for all qualified cavities is −5.7 Hz/(MV/m)^2.

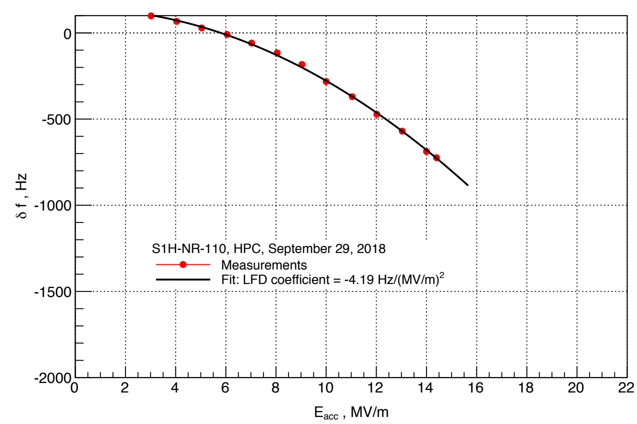

Figure 7: Typical Lorentz force detuning of SSR1 cavity.

Multipactor in SSR1 Cavities

We observe early during testing of bare SSR1 cavities at VTS, that multipactor may become a factor limiting performance of these cavities. We find that MP happens at certain values of the cavity filed, with the tree most prominent and strong MP barriers at approximately 5, 6.5 and 7 MV/m. When RF power is applied to cavity, the cavity field increases until MP barrier is reached. At this point increase of the cavity filed stops and excess of RF power is transfered to MP which heats cavity walls, effectively lowering cavity Q_0 and loading cryogenic system. MP barrier needs to be slowly condition away by gradual increase of RF power simultaneously keeping cryogenic system from overloading. Once conditioned, cavity remains clean of MP for the duration of cold test. If cavity warmed up and cooled down again MP may return but it usually takes less time to re-condition cavity. If cavity is exposed to air between consecutive tests, full strength of MP is observed and cavity require conditioning.

Two main contributing factors to MP formation in SRF cavities are cavity geometry and secondary electron yield (SEY) coefficient at the surface of cavity walls. We associate increase in SEY of SSR1 cavities with presence of molecular layers of water at the cavity surface. Long 48 hours bake of cavity at low temperature (120 C) reduces water content in cavity and decreases MP conditioning time.

While testing SSR1 cavities at STC, we accumulate large date set on MP conditioning. In this section we present preliminary results of analysis of these data.

Testing of SSR1 cavities in LPC configuration, when cavity is nearly critically coupler to the RF source allows for accurate measurement of the total power loss in cavity: $P_{loss} = P_f - P_r - P_t$, where $P_{f,r,t}$ are forward, reflected and transfered power. If MP is present, then the power loss associated with it is $P_{MP} = P_{loss} - P_0$, where $P_0 = V_{acc}^2/(R/Q)Q_0$ is power loss in cavity walls, V_{acc} is cavity voltage (energy gain). Time integral of P_{MP}, $\int P_{MP} dt$, represents energy deposition into MP during conditioning, E_{MP}, and allows for consistent analysis and comparison of MP conditioning between diffrent tests of the same or different cavities.

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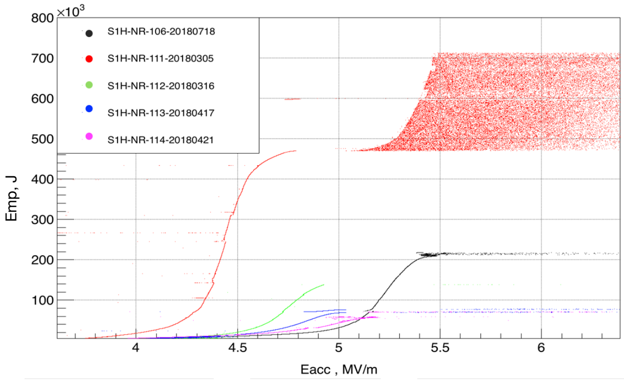

Figure 8: Energy deposition for MP type 1. No FE radiation, one barrier at 4.5–5 MV/m.

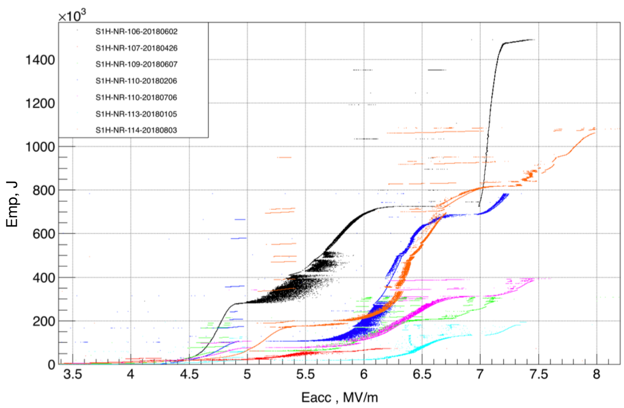

Figure 9: Energy deposition for MP type 2. FE radiation is present, three barriers at 4.5–5 MV/m, 6–6.5 MV/m and 7-7.5 MV/m.

Analyzing MP data, we find that cavities with or without radiation associated with filed emission, exhibit different behavior regarding MP conditioning. SSR1 cavities without FE radiation have only one strong barrier at 5 MV/m (we call this Type 1 MP), while cavities with radiation have three strong barriers at 5, 6.5 and 7 MV/m (Type 2 MP). This can be explained by abundance of primary electrons in FE emitting cavities which ignite MP at higher field levels.

Figures 8 and 9 show energy deposition during MP conditioning as function of cavity field for Type 1 and 2 MP, respectively. In these pictures, plots of different colors represent diffrent tests. MP barriers are evident as steep, almost vertical slopes in E_{MP}, while horizontal lines of little variations in E_{MP} show MP free zones. Total energy deposited in MP (the end points at the right edge of the plots) varies

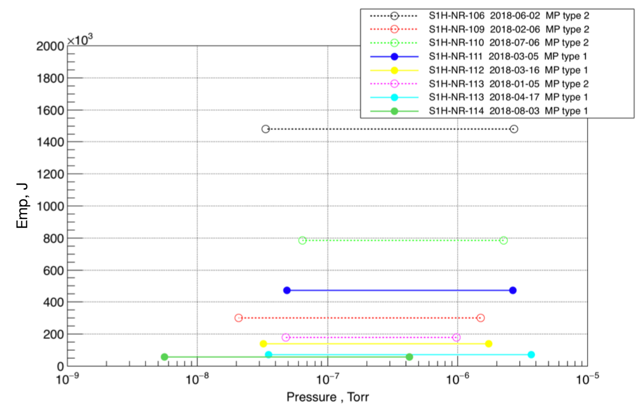

Figure 10: Total energy deposited in MP during conditioning *vs* partial pressure of water outgassing during 120 C bake.

from 100 to 400 kJ for Type 1, while in Type 2 it is few time larger in the range of 200–1400 kJ. Variations in location of MP barriers are due to small (few %) uncertainty in measurements of RF power signals and cavity field. Slight variations in geometry of cavities within mechanical tolerances during manufacturing can also lead to small displacement of MP barriers.

In Fig. 10 we compare total energy deposited in MP during conditioning to partial water pressure variations during 120 C bake of cavities. Right and left end points in horizontal lines correspond to beginning and end of bake. In agreement with our initial observation we can see, that there is very strong correlation between water content at the cavity walls and strength of multipactor.

CONCLUSION

We test and characterize ten jacketed SSR1 cavities at STC. We successfully qualified and selected eight fully integrated cavities with high power coupler and tuner for assembly in the 1st Fermilab prototype SSR1 cryomodule for PIP-II linac. We analyse multipactor conditioning using total energy deposition. We observe effect of suppression of MP barriers at higher cavity fields in radiation free cavities. We confirm strong correlation between water content at cavity walls and strength of MP.

REFERENCES

[1] V. Lebedev *et al.*, "PIP-II Reference Design Report", http://pxie.fnal.gov/PIP-II_RDR