PRE-INSTALLATION PERFORMANCE OF THE RHIC 56 MHz SUPERCONDUCTING SYSTEM*

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Abstract

Pre-installation test results for the RHIC 56 MHz superconducting RF system are presented here. The 56 MHz quarter-wave resonator achieved a stable accelerating potential of 1.1 MV with 13 W of RF loss at 4.5 K demonstrating its viability for increasing the luminosity of sPHENIX collisions. The new 120 kW travelling wave fundamental mode damper and dual 6 kW combined-function fundamental power couplers perform as expected at 3 kW but remain to be operated with the expected ~40 times greater power achievable with the RHIC sPHENIX beams.

INTRODUCTION

The 56 MHz superconducting quarter-wave resonator (QWR) cryomodule first demonstrated during the 2016 RHIC run RHIC [1, 2] has undergone upgrades to the fundamental power coupling and fundamental mode damping systems. These upgrades are needed for higher intensity RHIC beams. These systems were identified for upgrade to meet future sPHENIX experimental program requirements and ease manipulation of the cavity fields during operations [2, 3]. This paper will review relevant aspects of the cryomodule assembly, and several measurements related to coupler performance prior to installation in RHIC.

As of this writing the 56 MHz superconducting quarter-wave cryomodule is installed in RHIC where it is fully damped. Work is ongoing to make the system ready and it is expected to start operations later this year.

CRYOMODULE RESULTS

Assembly

The 56 MHz QWR design was undertaken to provide 2-2.5 MV [4]. This was accomplished with an advanced design using a bellows-like outer conductor to prevent multipacting with straight cylinder inner and outer conductors [1].

The cryomodule assembly incorporated one unique aspect not typically employed for SRF cryomodules, horizontal HPR of components on the assembly tooling. The beam-line cold mass is comprised of 3 distinct assemblies: 2 end groups each weighing more than 300 pounds and the ~1,000 pound SRF resonator located in between. These 3 assemblies are joined in the clean room after alignment on the tooling and are very cumbersome to handle. While each of these components was high pressure rinsed with the rinse wand located beneath the device the 2 end-groups were also HPRed horizontally. Figure 1 shows a picture taken during this assembly. Due to the frequent "dirty" work ongoing around the end groups after the initial HPR and during alignment this extra HPR step was found to be necessary. After horizontal HPR water pooled inside the all metal RF gate valves and beam-line formed bellows which were subsequently dried with external radiant heaters.

Following clean assembly and leak check, no leaks found above a background of 1×10^{-11} mbar-l/s helium. The hermetic beam-line assembly was baked at 120 ^{0}C for 48 hours. The clean and baked assembly was then built into its cryomodule as was done in 2015. Minor changes were made to the system to improve cryogenic stability and will be discussed in a later paper.

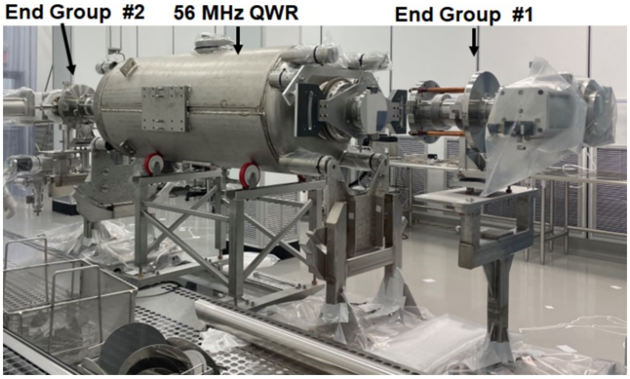

Figure 1: 56 MHz quarter-wave resonator cryomodule immediately before final clean assembly in the BNL class 10 clean room.

Table 1: 56 MHz QWR RF Parameters

Parameter	Value
Frequency	56.3 MHz
Beam Aperture	3.937 in
β	1
Effective Length (βλ/2)	2.7 m
E_{peak}/E_{acc}	56
B_{peak}/E_{acc}	121 mT/(MV/m)
$G = R_sQ$	20.2 Ω
R_{sh}/Q	80.5 Ω

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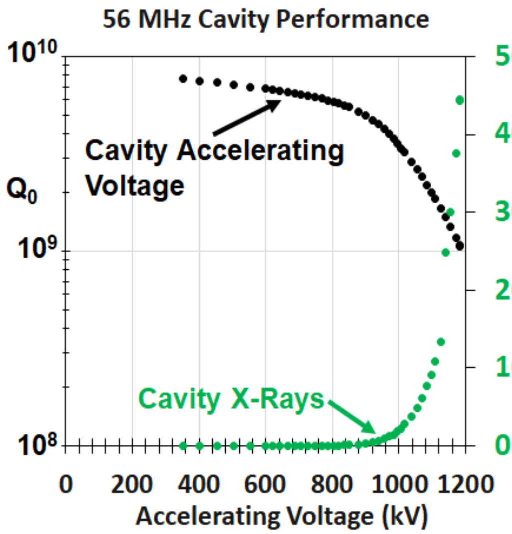

Figure 2: Measured 4.5 K Q-curve for the 56 MHz quarter-wave resonator after cryomodule assembly with 7 W of RF losses at 1 MV. The Q-curve decay time for calibration is referenced to a weakly coupled decay time with the external Q ~$2x10^{12}$. The peak field achieved correspond to 25 MV/m and 53 mT, peak surface electric and magnetic field respectively.

Performance

In operation we are focused on achieving at least 1 MV of accelerating voltage in the 56 MHz QWR, offline testing of the cryomodule supports our operation at this level. Figure 1 shows the 56 MHz QWR voltage, quality factor and correlated x-rays during 4.5 K operation. Unlike previous tests, we were able to both critically and weakly couple during calibration of our electronics and measurement of the Q-curve. The Q-curve shown in Fig. 2 was measured critically coupled and the quality factor is referenced to a 400 kV weakly coupled decay curve with $\beta = 0.0035$ which agrees with the critically coupled decay time, decaying from the same field level, to 2%. It is useful to note that the cavity geometric factor was simulated at 20.2 Ω, Table 1, and the low-field residual surface resistance is calculated to be 1.5 nΩ at 4.5 K. Table 1 gives the RF performance parameters for the QWR

Previous operation of the 56 MHz superconducting system in RHIC relied upon the fundamental mode damper to both damp the fundamental mode and damp higher order modes (HOMs) excited by the RHIC beam. This system did not couple strongly to all of the HOMs excited by the RHIC beam and the new 56 MHz system has dual fundamental power couplers (FPCs) where only one FPC is required to excite the fundamental mode of the resonator and both FPCs can be used as supplemental HOM dampers while tuning the resonator.

Of note here is that both the FPCs and the FMD are loop type couplers which operate in the high magnetic field region of the 56 MHz quarter-wave resonator. To achieve the strong coupling and damping required for this application the coupling loop copper is immersed in the SRF magnetic field, not retracted within a port limiting the exposure of the copper to only evanescent fields. This is a location where copper cooling of any means cannot match the RF dissipation of the SRF fields. For this reason, the FPCs can only be used as dampers up to limited fields and the fundamental mode damper must be retracted from fully damping the cavity fields to not damping the cavity fields in a limited amount of time, limiting the copper temperature of the coupling loops < 100 ^{0}C.

With the increase in beam power the fundamental power coupling system was upgraded from a single 3 kW coupler to dual 6 kW couplers arranged to break the symmetry of and couple to HOMs up to quadrupole order, supplementing the role previous limited to the fundamental mode damper. This was done out of an overabundance of caution. In previous RHIC operation HOMs which lead to beam break-up were all longitudinal modes with suspected dipole mode excitation being weak. The fundamental power couplers can remain inside the superconducting resonator's field, strongly coupled, up to accelerating voltages initially estimated to be 400 kV. Above 400 kV the FPCs must be retracted to an external Q > $1x10^7$ to avoid heating the water-cooled copper couplers > 100 ^{0}C. This is expected to be sufficient for tuning the detuned 56 MHz resonator to the RHIC revolution frequency's 2520th harmonic because the fundamental mode frequency difference between 400 kV and 1 MV is only a few Hertz and no new HOMs should be excited while tuning through this small frequency range. If an HOM is damped by the FPCs at this transition the resonator voltage will be limited and unable to go higher. Figure 3 shows the FPC coupling loops prior to final welding of the assemblies installed on the 56 MHz resonator.

Figure 3: FPC coupling loops installed on the 56 MHz superconducting resonator.

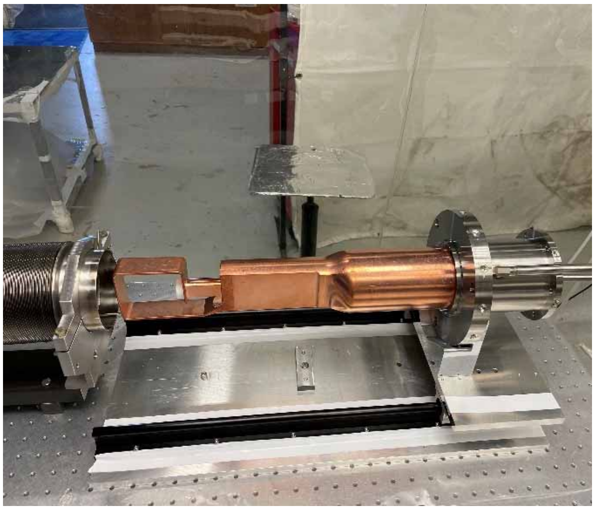

Figure 4: Fundamental mode damper prior to installation on the 56 MHz resonator and outer bellows welding. This picture was taken in the class 100 clean room in which the final welding was done because both the copper damper and bellows were previously high pressure rinsed.

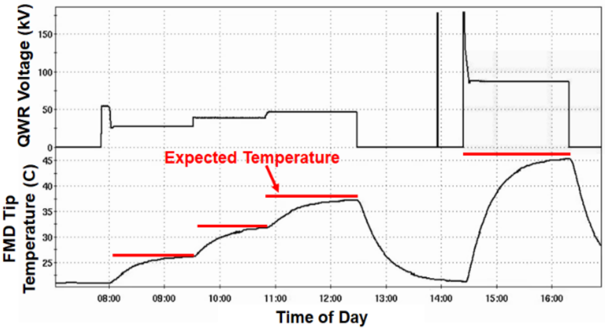

Figure 5: Measured FMD heating as the 56 MHz QWR field levels are raised. Top, the QWR voltage is plotted in units of kV. Bottom, the FMD tip temperature is plotted in degrees Celsius.

During offline testing the new dual FPCs were excited with a 3 kW RF power source and no anomalous heating was observed, giving good confidence that 6 kW operation will be achieved.

The FPC coupling loops are water cooled where the return water temperature is monitored to determine if the couplers are overheating. During offline testing, when the 56 MHz resonator fields exceeded 150 kV the return water temperature would steadily increase, clearly indicating that 150 kV is the upper operating limit for using the FPCs as strongly coupled HOM dampers and that our earlier calculations giving 400 kV for the upper operating limit were not overly conservative. Note that testing these conclusions with beam and high powers remains and results will be shared when available.

The fundamental mode damper (FMD) was upgraded from the previous 20 kW version to a 126 kW traveling wave coupler to support additional coupling loop cooling and enable higher power operation. Figure 4 shows the new FMD prior to installation on the 56 MHz resonator and outer bellows welding. This welding was done in a class 100 clean room as the parts being welded were previously degreased and high-pressure water rinsed.

During testing the FMD was equipped with a thermometer located at the base of the coupling loop inside the inner conductor. Figure 5 shows the FMD loop tip heating as the 56 MHz resonator fields increase with the cavity accelerating voltage plotted on the top graph and the correlated measured FMD loop heating shown on the lower graph. Red lines were added to the FMD heating graph showing the equilibrium temperature expected for the given cavity voltage at the location where the measuring thermometer location. Notice the difference in measured verse expected heating diverges as the FMD loop heats. This is due to the limited convective cooling in the channel internal to the FMD inner conductor through which the thermometer is routed. This cooling was not considered when estimating the loop heating and slow increased as the thermal gradient along the inner conductor increases. In the future this effect will be included in calculations to ensure greater accuracy of the results. This also shows that a possible future cooling scheme may be implemented with forced air cooling through this region of the FMD, possibly enabling higher field and longer periods of operation.

FUTURE PLANS

The 56 MHz superconducting quarter-wave resonator cryomodule was tested offline. Select results from this are presented here while all of the cryomodule subsystems were tested; e.g., slow and fast tuners, new cryogenic cooling capabilities, measurement of the 45 W static 4.5 K cryomodule heat load in addition to dynamic load measurements, etc. All tests indicate that the cryomodule is ready for installation in RHIC and future beam operations in support of sPHENIX.

In the past 1.5 months the cryomodule was installed in RHIC but has not been excited with beam present. This will be done in the coming months further improving our understanding of the system, evaluating the success of our designs and guiding future hardware upgrades.

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REFERENCES

[1] Q. Wu *et al.*, “Operation of the 56 MHz superconducting rf cavity in RHIC with higher order mode damper”, *Phys. Rev. Accel. Beams*, vol. 22, p. 102001, 2019. `doi:10.1103/PhysRevAccelBeams.22.102001`

[2] S. Polizzo, “56 MHz Project Overview and Status Update”, RHIC Machine Advisory Committee Review, 2016.

[3] M.M. Blaskiewicz, private communication, 2020.

[4] I. Ben-Zvi, “Superconducting Storage Cavity”, Technical Report C-A/AP/#33, Brookhaven National Laboratory, 2009.