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UPGRADE OF THE RHIC 56 MHz SUPERCONDCUTING QUARTER-WAVE RESONATOR CRYOMODULE*

Z.A. Conway†, R. Anderson, D. Holmes, K. Mernick, S. Polizzo, S.K. Seberg, F. Severino, K.S. Smith, Q. Wu, B. Xiao, W. Xu, A. Zaltsman
Brookhaven National Laboratory, Upton, NY

Abstract

In preparation for the 2023 RHIC sPHENIX experimental program the superconducting 56 MHz quarter-wave resonator cryomodule, used operationally for longitudinal bunch compression with up to 1 MV RF voltage, is being refit to accommodate an expected beam current of 418 mA per ring, an increase of ~1.5 relative to previous operation. The upgrades to the system include an improved fundamental mode damper, and dual function fundamental power and higher-order mode damper couplers. This paper will describe the preliminary testing, select subsystem changes and plans for testing the cryomodule prior to installation in the RHIC beam line in 2022.

INTRODUCTION

Brookhaven National Laboratory (BNL) finished and used a 4.4 K 56 MHz superconducting Quarter-Wave Resonator (QWR) cryomodule in RHIC to reduce particle losses during transfer of the accelerated 28 MHz bunches to the 197 MHz storage system [1]. During several RHIC runs finishing in 2016 the 56 MHz QWR system was made operable with up to 1 MV RF voltage while avoiding several high-order mode driven beam instabilities, successfully demonstrating improved RHIC experimental luminosities [2]. During this effort several cryomodule subsystems were identified for upgrade to meet future sPHENIX experimental program requirements and ease manipulation of the cavity fields during operation.

Three areas dominate the improvements being made to the 56 MHz QWR's performance: RF voltage, higher power fundamental mode damping (FMD) and dual function power couplers capable of both fundamental power coupling and higher-order mode (HOM) damping. This paper briefly reviews the cryomodule geometry, the status of work in these areas and concludes with comments on our future work.

56 MHz QWR PERFORMANCE

The target RHIC operating voltage is 2-2.5 MV [3] and reaching this voltage is advantageous for sPHENIX, possibly increasing the total luminosity by >2 [4]. Previous experience with the 56 MHz QWR was limited to ~1 MV peak RF voltage at 4.4 K while operating in RHIC [2]. To measure the upper threshold of cavity operation and define the level all couplers need to operate the 56 MHz QWR was vertically tested at BNL in a 4.4 K bath dewar with

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† zconway@bnl.gov

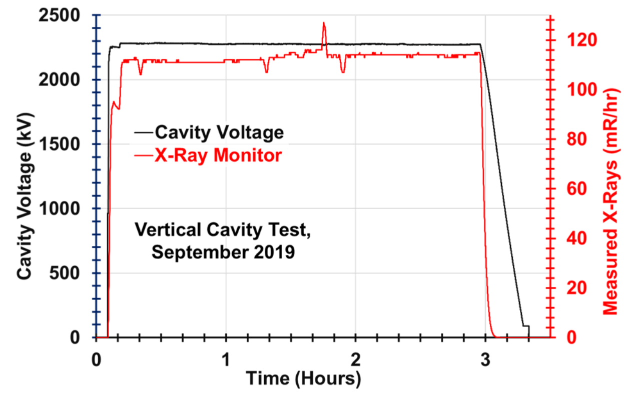

Figure 1: 56 MHz QWR operating at 4.4 K.

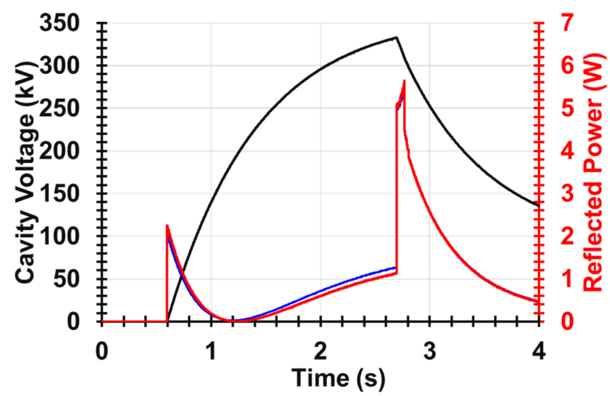

Figure 2: Pulsed 56 MHz QWR response showing uncertainty in coupling strength.

a beam-line mounted fixed power coupler and a pick-up probe located on the toroid end of the resonator, details of the BNL bath dewar and the 56 MHz QWR arrangement during testing are in [5].

The 56 MHz QWR attained an RF voltage of 2.3 MV at which point the cavity quenched. After quenching the cavity operated stably at 2.25 MV and 4.4 K, at this level Fig. 1 shows the 56 MHz QWR voltage and correlated x-rays during a run of several hours. The fixed power coupler was over-coupled to the resonator with $\beta \sim 33$ and $Q_{ext} = 1.52\text{x}10^8$ complicating cavity field and Q measurements. To calibrate the RF electronics and measure the cavity Q_0 a weakly coupled decay time was measured. A single pole double throw switch was installed in the RF transmission line at a location where it did not present a large impedance to the power coupler. The cavity was excited, and the switch was opened decoupling the RF drive amplifier and allowing the cavity fields to decay. The weakly coupled and coupling-strength corrected Q_0's were measured many

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times with typical valves ranging from 4 $x10^9$ to $5x10^9$ at 4.4 K. It is useful to note that the cavity geometric factor was simulated at 20.2 Ω and the residual surface resistance is calculated to be 4 nΩ at 4.4 K. Several decay curves were measured at decreasing temperatures down to ~2.3 K where the BCS contributions to the cavity surface resistance are 0. These measurements resulted in extremely low residual resistance measurements, < 1 nΩ, and these results will be checked in our upcoming cryomodule tests where we will have a pair of variable couplers capable of weakly coupling to the 56 MHz QWR with $Q_{ext} = 1.4x10^{11}$. Figure 2 shows a measure of the coupling strength of the cavity at 4.4 K during testing.

FUNDAMENTAL MODE DAMPER

The 56 MHz QWR system is designed to be detuned and decoupled from the RHIC beams during energy ramp up. A tuner and fundamental mode damper accomplish this in operation. While the tuner detunes the cavity resonant frequency the fundamental mode damper (FMD) reduces the fundamental mode and several HOM resonance Q's to effectively decouple the modes from the beam; e.g., the fundamental mode Q_L ~ 300. After the RHIC beams are at storage energy the FMD is gradually removed from the resonator as the frequency tuner tunes the cavity to the desired operating frequency/voltage. The FMD removal procedure is determined by balancing the needs to use the FMD as an HOM damper with the increasing fundamental mode RF power coupling inherent to increasing the resonator Q and fields.

At 416 mA per RHIC ring the maximum power handling requirement for the 56 MHz QWR FMD increased from 26 kW to 125 kW during the final stages of coupling the system to the RHIC beams. This has 2 immediate consequences: (1) the process of coupling the 56 MHz QWR to the RHIC beams must be executed quickly to avoid overheating of the FMD copper loop and (2) the FMD must survive the higher RF fields and thermal loads of 120 kW RF travelling wave.

Estimates of the new FMD loop tip heating find that this coupler can sustain operation at 125 kW within the 4.4 K 56 MHz QWR for ~ 8 minutes before the loop tip exceeds 100^0C. During previous operation in RHIC the FMD removal step which corresponds to this power level lasted minutes and this threshold indicates that the FMD will survive. The cost of exceeding 100^0C for short times is not expected to impede performance after completion of a 2-day 120^0C high vacuum bake-out of the system. This bakeout will include the entire 56 MHz QWR beam-line assembly and will take place after finishing clean assembly.

The previous fundamental mode damper was comprised of an 1-5/8" rigid coaxial line with a demountable coupling loop, where the demountable joint's screws and lock-washers were located inside the low-particulate SRF assembly. To reduce the coaxial line RF losses, improve conductive cooling and reduce the chances of particulate contamination inside the resonator the fundamental mode damper is now based on a 3-1/8" rigid coaxial line fabricated from 2 pieces of copper and no compression joints, to facilitate cooling of the loop via thermal conduction. The previous FMD coupling loop area was 54 cm^2 fixed by the cavity port dimensions and tolerances on the loop's fabrication. With improved fabrication and linear motion system the loop area has been increased by 10 cm^2 to 64 cm^2. Figure 3 shows a model cross section of the new FMD and Fig. 4 shows the copper inner and outer conductors before final brazing. FMD fabrication is expected to conclude in July 2021.

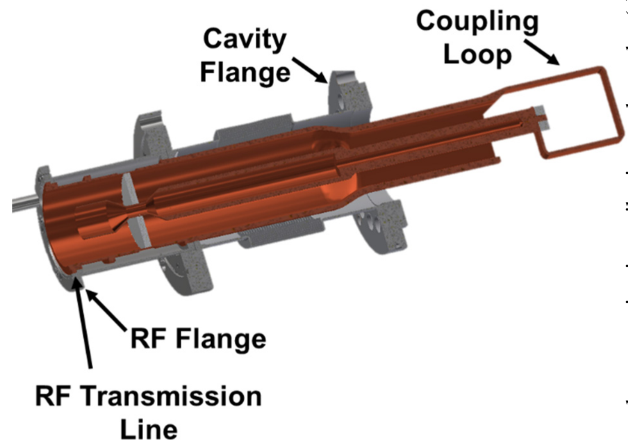

Figure 3: Cross section of the new fundamental mode damper.

Figure 4: FMD copper outer and inner conductors before brazing. The outer conductors with coupling loop are 22.43" long and were bent from a continuously machined assembly which was 30" long with a 3.5" diameter.

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POWER COUPLERS/HOM DAMPERS

A pair of room temperature copper couplers are in the final stages of fabrication for use with the 56 MHz QWR. These couplers have many unique design features such as water cooling the entire coupling loop inside the 4.4 K resonator, water cooling of the RF ceramic window inside the cryomodule ~45 K thermal shielding and no braze joints between water and the RHIC beamline vacuum. A very useful feature is these couplers doubling as HOM dampers during QWR tuning. Operation at resonator peak surface field levels above ~5 mT results in excessive RF heating of the copper loops for $Q_{ext} < 1x10^6$. For example, the 167 MHz 3λ/4 HOM mode's external-Q can be varied with a Q_{ext} as low as $4x10^4$ with one loop coupler providing some defense against beam break-up instabilities during energy ramp-up in RHIC but these couplers, like the FMD, must be removed as the resonator fields increase.

Figure 5 shows 2 coupler braze assemblies. After brazing, the couplers are welded to a bellows spool terminated with a flange for attachment to the QWR. The coupler outer diameter of 1.5" was chosen to maximize loop area in the 1.6" diameter niobium coupling ports.

Figure 5: 2 coupler braze assemblies prior to final welding of the stainless-steel bellows and flanges necessary for cavity attachment.

The low-particulate requirements for the SRF system assembly require cleaning these couples prior to installation on the 56 MHz QWR. To this end we built fixtures to weld the couplers in a quasi-clean environment, and high-pressure rinse tooling for the coupler components before they are welded onto the copper braze assemblies and after all welding is finished. Welding in a low-particulate laminar airflow was cumbersome. The clean air flow disrupts the argon cover gas distribution leading to undesirable oxidation of the components which, on a test-part, created an infinite particle source in an oxidized region. This problem is mitigated during final welding by cleaning and high pressure rinsing all parts prior to weld set-up in a clean work area and then welding with the clean air handling system turned off. A similar approach was adopted for the FMD preparation.

The 2 couplers are now assembled and mounted in a test apparatus to measure the RF heating. Results from this and cavity measurements will be shared once finished.

FUTURE PLANS

Fabrication of the new FPC/HOM couplers and FMD is progressing well and expected to finish soon. Our immediate plans are to assembly the 56 MHz QWR with all couplers and perform room temperature measurements characterizing the full coupling range of all 3 couplers and then progress to final cleaning and assembly. A 4.4 K cryomodule test is planned for winter 2021-2022 in BNL's ERL Test Facility. Results from all work will be reported on in the future.

During the BNL Min-Safe SARS-CoV-19 operating mode the BNL high pressure rinse system was contaminated with an array of microorganisms. In parallel with the work described here we have rebuilt the HPR system and processed a single cell cavity supplied and tested by FNAL. The single cell cavity processed at BNL field emitted heavily and indicates that our HPR system is not ready to process the 56 MHz QWR. We are working to improve this and implement a new system in time to meet the future plan outlined here.

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