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# Operation of the 56 MHz Superconducting RF Cavity in RHIC during Run14

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## *Abstract*

A 56 MHz superconducting RF cavity was designed and installed in the Relativistic Heavy Ion Collider (RHIC). It is the first superconducting quarter wave resonator (QWR) operating in a high-energy storage ring. We discuss herein the cavity operation with Au+Au collisions, and with asymmetrical Au+He<sub>3</sub> collisions. The cavity is a storage cavity, meaning that it becomes active only at the energy of experiment, after the acceleration cycle is completed. With the cavity at 300 kV, an improvement in luminosity was detected from direct measurements, and the bunch length has been reduced. The uniqueness of the QWR demands an innovative design of the higher order mode dampers with high-pass filters, and a distinctive fundamental mode damper that enables the cavity to be bypassed during the acceleration stage.

## *Introduction*

RHIC was designed with accelerating and storage RF systems to operate at harmonic number  $h = 360$ , and  $h = 7 \times 360 = 2520$ , which correspond to frequencies of 28.15 MHz and 197.05 MHz respectively [1]. The five 197 MHz copper cavities installed in each ring are used to store bunches for up to 10 hours after they have been accelerated to the top energy. With the current RHIC operational settings, the typical full length of the 100 GeV Au beam is 9.7 ns with the 28 MHz acceleration RF system. The bucket length of the relatively high frequency storage cavities is 5.1 ns, which is not sufficient to accommodate the ion bunches without going through the RF gymnastics of bunch rotation, or re-bucketing. However, this re-bucketing process causes an increase in longitudinal emittance due to nonlinearity and hardware complications. The longitudinal emittance increase leads to 30% of the particles being spilled into neighboring buckets, which

hardly contribute to the luminosity at collision.

A storage cavity at a frequency of 56.3 MHz was proposed in 2007 to provide adequate RF acceptance to long bunches without re-bucketing [2]. The longitudinal acceptance using the 56 MHz cavity at RHIC is 6.4 eV·s/u for 100 GeV/u gold ions and 15.5 eV·s/u for 250 GeV protons, in both cases much larger than the beam emittance [3]. With the same longitudinal emittance, the full bunch length with the 56 MHz RF system may be suppressed to below the bucket size of the 197 MHz cavity [3]. As was shown from direct luminosity measurements during RHIC operation in 2014, the combination of the 56 MHz and 197 MHz RF systems raised the luminosity within the vertex of the detectors, which will be discussed in the later section of this paper. The 56 MHz RF cavity installed in RHIC is a superconducting resonator, which supports a high gap voltage to above 2 MV. With such an advantage, the number of cavities can be reduced to only one, which is shared

by both rings, and therefore has somewhat lowered the RHIC impedance. The cavity has a quarter-wave structure with the beam traversing it on axis. This design provides a compact size making feasible its installation in the existing tunnel.

The 56 MHz cavity is beam driven, although a maximum of 1 kW RF power is provided from an amplifier for controlling its amplitude. After the beam has been accelerated to top energy, the cavity is tuned towards the beam frequency from below. Since the cavity operates above the transition energy, Robinson instability [4, 5] is avoided. Nevertheless, external RF power is necessary to ensure stability of its amplitude against ponderomotive instabilities [6, 7, 8].

The instability of the coupled bunch of the ring-cavity system was studied [9], and damping is provided accordingly to the fundamental and higher order modes to the specified thresholds for passing through the transition energy and at store.

### Cavity

The 56 MHz SRF cavity is a quarter-wave resonator with beam passing along its axis of symmetry, as shown in Figure 1. The cavity is located in the common section of the RHIC, and shared by ion bunches from both rings. Serving both rings with one cavity provides costs benefits for construction and operation. To achieve identical longitudinal dynamic effects for both beams, the difference in RF phase must be equal to  $\pi$ . The two colliding beams are synchronized at the interaction point (IP). Thus the cavity should be installed such that the accelerating gap is located at  $(n + 1/4)\lambda$  away from the IP. The wavelength at a frequency of 56.3 MHz is  $\lambda = 5.33$  m. The available position in RHIC is located at  $1.25\lambda$ , which is 6.66 m from the IP. The parameters of the cavity operating at 2 MV are shown in Table 1.

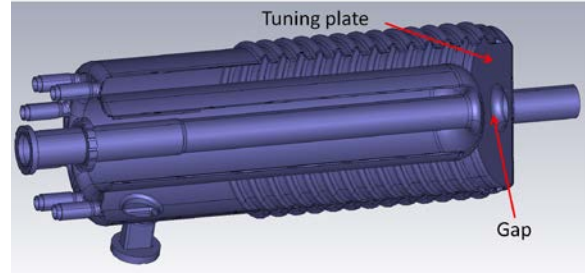


Figure 1: 56 MHz SRF cavity with a total length of 1.3 meters.

Table 1: Cavity parameters

Parameter	Unit	Value
Frequency	MHz	56.30
Length	cm	134.88
Gap	cm	8.45
Outer diameter	cm	50.5
Aperture	cm	10.0
Operating temp	K	4.5
$R/Q$	$\Omega$	80.5
$Q_0$		$1.95 \times 10^9$
$E_{acc}$	MV/m	23.5
$E_{peak}/E_{acc}$		1.77
$B_{peak}/E_{acc}$	mT/MV/m	3.81

As the cavity has traditional coaxial shape, multipacting is easily excited between the parallel walls of inner and outer conductors. For suppressing multipacting, thirteen corrugations were implemented on the outer wall [11]. When entering the corrugation region, the path of the secondary electrons deviates from their resonating condition, and therefore, there is no local accumulation of large quantities of electrons. The corrugation is 2 cm in diameter, with 6 cm spacing. Simulations showed that only the first 70 cm from cavity gap has an electric field strong enough for the resonance condition. Before operating the cavity, we encountered multipacting at 90 to 140 kV gap voltage. With the 1 kW amplifier running in the CW mode, the multipacting zone was conditioned away after 30 minutes. Following its conditioning, the cavity never

encountered multipacting during its operation with beam.

The cavity is tuned by pushing and pulling a flat tuning plate at the accelerating gap, as shown in Figure 1. The entire tuning range is 46.25 kHz, which corresponds to 1.5 mm motion of the tuning plate. During operation, the cavity is tuned 34 kHz below the beam resonance in order to minimize the beam excited cavity voltage to a negligible level. During operation, a piezo tuner is employed to minimize wear on the stepper tuner, and potentially compensate detuning due to microphonic noise.

### Couplers

The cavity does not have a sufficient tuning range to follow a large change in frequency during the RHIC energy ramp, so it is turned on only after reaching the store energy. In addition to fully detuning the cavity with the tuning plate, a fundamental mode damper (FMD) is inserted into the cavity from a rectangular port opened on the side. The fully inserted FMD is shown in Figure 2. A combination of the tuning plate and fully inserted FMD detunes the cavity frequency by 68.5 kHz. The loaded (by FMD)  $Q$  of the cavity is 309. This ensured that the cavity is 'invisible' to the beam.

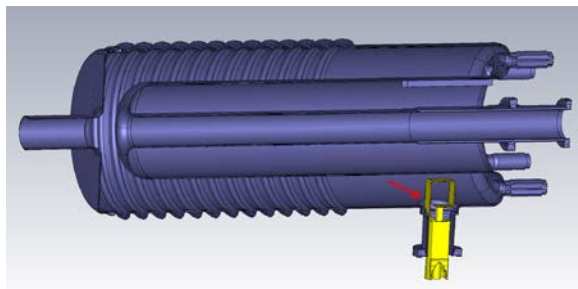


Figure 2: The fundamental mode damper fully inserted into the cavity.

Although RF power is mostly provided by the beam, an external amplifier with a maximum power of 1 kW is connected to the cavity via a fundamental power coupler

(FPC). The loop-shaped FPC, located in the maximum magnetic field region, is shown in Figure 3. Insertion of the FPC is variable via a stepper motor, and the external  $Q$  changes by two orders of magnitude. Due to small losses of the superconducting cavity, the amplifier power alone is sufficient for driving the cavity to above 2 MV on resonance and initial conditioning. During conditioning, the FPC is parked in its fully inserted position with an external  $Q$  of  $2.2 \times 10^6$  to maximize the transmitted RF power to the cavity.

During operation, the FPC couples RF power into the cavity to compensate the amplitude change in the gap voltage, which then is used as the real time correction of the voltage. Less than 10 watts from the amplifier is required to maintain the stability of the amplitude and the phase.

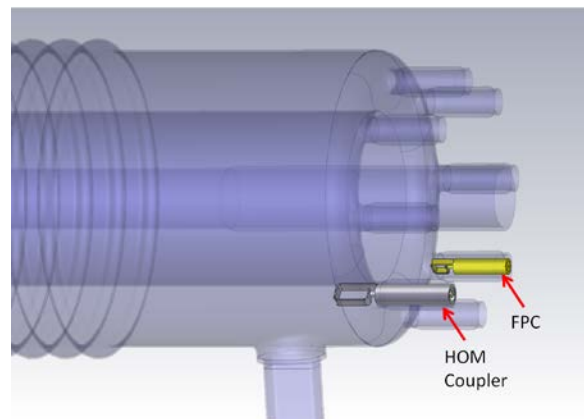


Figure 3: FPC (yellow) and HOM coupler (green) locations in the cavity.

Higher order modes (HOMs) of the cavity are damped through an HOM loop-shaped coupler, as shown in Figure 3. The FMD port breaks the symmetry of the cavity, therefore location of the HOM coupler is specifically chosen for attaining a balanced optimum damping of HOMs. For all HOMs below 700 MHz, we measured that the coupler damps power of all dipole modes by 5 orders of magnitude and of quadrupoles by 6 orders of magnitude.

The HOM coupler loop couples to all modes, including the fundamental mode. To avoid dangerously large amount of power from the fundamental mode being sent into the HOM coupler load, a Chebyshev high-pass filter was connected to the coupler loop. Frequency of the first HOM is 168 MHz. Thus the frequency difference between the fundamental mode and the first HOM is greater than 100 MHz, which simplified the filter design. An external  $Q$  of the fundamental mode measured at the filter output is  $3.46 \times 10^{10}$ , which corresponds to less than 1 W of power leakage. The fundamental mode's external  $Q$  would be 3,800 without filter. Attenuation by the filter of all HOMs is less than 10 dB.

During the RHIC 100 GeV Au + Au operations, all beam excited HOMs above 500 MHz were below -80 dBm with a full current of 0.4 A from both rings. No measurable affects on the beam stability were observed.

### RHIC Operation

The first operation of the 56 MHz cavity was during the RHIC run 2014, with the species Au + Au, and Au + He3. The cavity gap voltage was limited to 300 kV, due to the HOM coupler quench, compared with the planned operational voltage of 2 MV. Table 2 lists the typical beam parameters.

Table 2: RHIC operation parameters

	Au+Au	He3+Au	
	Au(b/y)	He(b)	Au(y)
Intensity ( $\times 10^9$ )	180	450	180
Energy (GeV)	100	103	100
Bunch length w/o 56MHz Cavity (ns)	4.5	6.0	4.5

Even with the six-fold lower voltage in the cavity during the Au + Au run, a reduction in bunch length and an increase in luminosity, reflected by the Zero Degree Calorimeter (ZDC) rate of the detectors, are observed clearly as the cavity is turned on, as illustrated in Figure 4. The bunch length of both beams shrinks by about 4.5%, when the 56 MHz cavity is turned on. The hourglass effect, which refers the increase of the betatron function and the size of the transverse beam away from the IP therefore, is reduced. Consequently, the luminosity is enhanced by about 3%, as measured by the ZDC coincidence rate. A similar observation was made in the He3 + Au run.

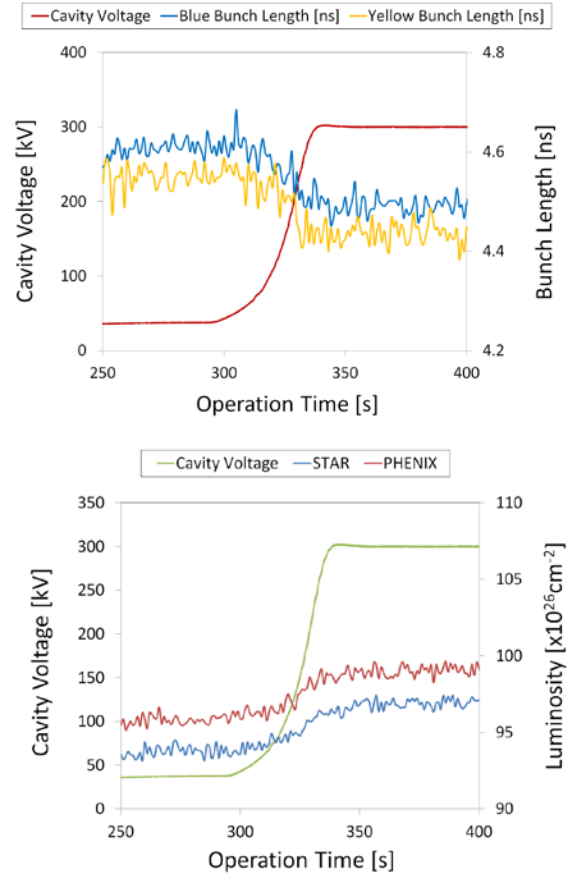


Figure 4: Reduction of the bunch length of both beams in RHIC (top) and the resulting improvement in luminosity (bottom) observed as the 56 MHz cavity voltage was slowly ramped up.



Beam simulations were performed for the 56 MHz cavity voltages of 300 kV and 2 MV. The simulated luminosity and bunch pattern are shown in Figure 5. Effects included in simulations are intra-beam scattering, cavity's wake-fields, and stochastic cooling. Parameters used in these simulations reflect those during the normal operation of RHIC. The results indicate a 5% luminosity increase when the 300 kV is applied to the beam. This agrees well with our experimental observations. The same simulation tool also predicts that the luminosity will be ~30% higher if the full 2 MV gap voltage is reached.

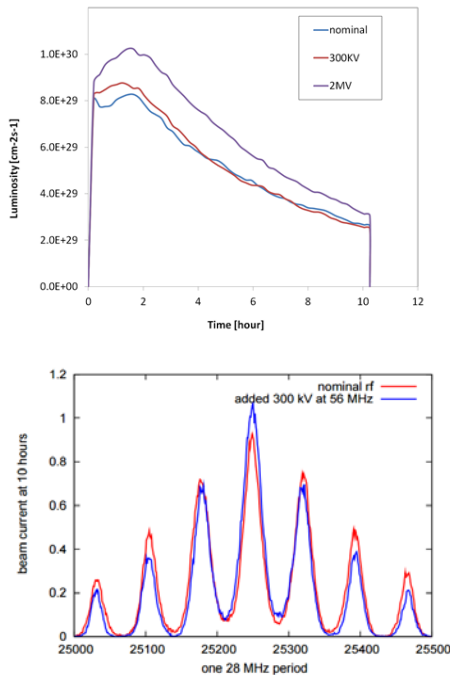


Figure 5: Simulations of the RHIC luminosity (top) and bunch pattern (bottom) at different voltages of the 56 MHz cavity.

The simulations also predict change of the population of ions in different 197 MHz RF buckets when Au beam is re-bucketed. Population of the particles in the satellite buckets is reduced because the bunch length is squeezed by the 56 MHz cavity. We also observed this population difference, between

turning on/off the 56 MHz cavity at the end of the store time (about ten hours), using a wall current monitor, as shown in bottom of Figure 6. A decrease in the bunch length is 4%.

With full current beam in RHIC, a total power extracted from the single HOM coupler was measured as 4.1 W. An extracted power at the fundamental frequency was 2.5 W, corresponding to an external  $Q$  of  $4.1 \times 10^{10}$ . All HOMs under 600 MHz with a power of 0.8 mW or higher were identified using a spectrum analyzer; the HOMs at higher frequencies were below the measurement resolution. No measurable degradation of the RHIC beam due to the HOMs from the 56 MHz cavity was observed.

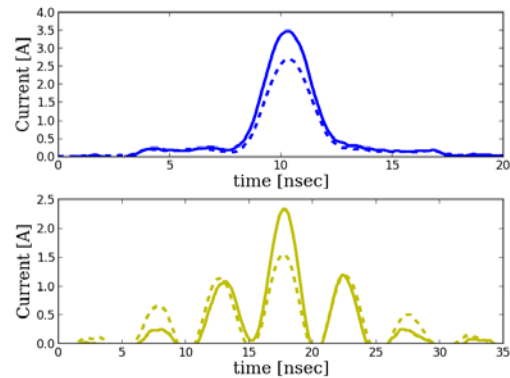


Figure 6: The longitudinal profile of the He3 beam (in blue ring, top) and the Au beam (in yellow ring, bottom). The solid lines and dashed lines correspond to operation with the 56 MHz cavity on and off, respectively.

### Conclusion

We successfully designed, installed, and commissioned the first QWR SRF cavity in RHIC. The initial beam tests showed a luminosity boosting of 3%, and a bunch length shrinking of 4% at 1/6 of the design cavity voltage. The HOMs were very efficiently damped under full beam current. The higher order mode coupler will be



redesigned to ensure that full voltage can be achieved in RHIC during run 2016, and so experiments can realize a 30% boost in luminosity as expected from theoretical studies.

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