BEAM COMMISSIONING OF THE 56 MHz QW CAVITY IN RHIC*

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Abstract

A 56 MHz superconducting RF cavity has been designed, fabricated and installed in the Relativistic Heavy Ion Collider (RHIC). The cavity operates at 4.4 K with a "quiet helium source" to isolate the cavity from environmental acoustic noise. The cavity is a beam driven quarter wave resonator. It is detuned and damped during injection and acceleration cycles and is brought to operation only at store energy. We have observed clear luminosity increase and bunch length reduction in the first operation of the cavity with Au + Au and Au + He3 collisions. The cavity voltage was limited by quenching in the Higher Order Mode coupler. This paper also discusses the cavity beam experiments with no higher order mode coupler in p + p and p + Au RHIC operation.

INTRODUCTION

The 56 MHz superconducting RF cavity has been manufactured and installed in RHIC in January 2014, and started beam operation later in the same year. The cavity is installed in the common section, 1.25λ away from the interaction point 4 (IP4), shown in Figure 1.

The purpose of the cavity is to provide sufficient RF acceptance to long bunches, thus reducing number of particles lost due to intra-beam scattering during rebucketing. Detailed studies have been discussed in previous papers [1][2].

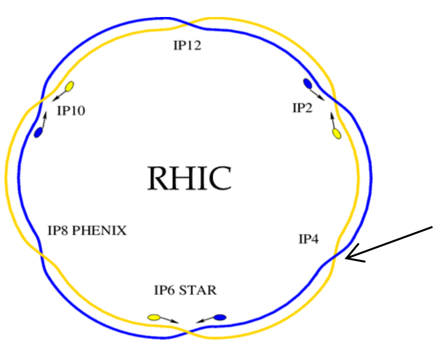

Figure 1: Location of the 56 MHz cavity in RHIC.

The helium supply for the cavity is provided via a quiet helium source, which exchanges the heat of a closed helium bath with the RHIC helium supply pipes. This system prevents big fluctuations of pressure brought by the main cooling pipes. The cryomodule of the cavity with the helium system is shown in Figure 2.

Figure 2: The 56 MHz cryomodule installed in the RHIC tunnel. Red arrow points to the quiet helium source tank.

CAVITY

The cavity is a quarter-wave resonator with beam traversing its axis. The diameter of the cavity is 50 cm. The acceleration gap is 8.5 cm with a flat end cap, as shown in Figure 3. Frequency tuning of the cavity is achieved via pushing and pulling the beam pipe on the gap side thus deforming the flat cap. The tuning range is listed in Table 1 for both stepper motor coarse tuning and piezo fine tuning. More details of the tuning study can be found in Ref. [3].

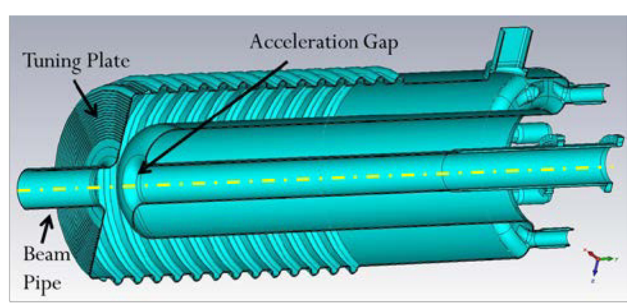

Figure 3: Cross-section view of the 56 MHz SRF cavity.

Table 1: Tuning Parameters of the Cavity

	Coarse tuning	**Fine tuning**
Frequency range	46.5 kHz	60 Hz
Travel distance	3 mm	3.5 μm
Tuning mechanism	Stepper motor	Piezo

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The cavity has thirteen corrugations on the outer shell for multipacting suppression [4]. The ripples are 2 cm in diameter with 4 cm spacing. Strong multipacting in coaxial structures is common. Location of multipacting would migrate along the structure as the RF field builds up. With this design, the field inside the cavity was increased to 2.3 MV with no hard multipacting barriers during conditioning. Multipacting was observed at low field levels, e.g. 1 kV, 50 kV, 70 kV, 80 kV, 120 kV, and 300 kV. All barriers are conditioned within 30 minutes. Simulation studies with GPU computing also predicted these field levels with multipacting, [5].

Couplers

The cavity has eight ports symmetrically distributed in the maximum magnetic field region, and one circular opening transitioned into rectangular on the side. All ports are designated for different RF purposes.

Four ports are reserved for higher-order mode (HOM) couplers with high pass filters. The locations of these ports are intentionally chosen for providing effective damping to all higher order modes in the cavity. Detailed study of the port selection for HOM couplers can be found in Ref. [6]. HOMs are coupled via a loop at the end of each coupler, which is fully penetrated into the cavity. The coupler's position and orientation is fixed once installed. Cooling of the coupler under high RF field is provided by liquid helium cooling channels connected to the coupler flange and the tip of one of the inductors. The cooled inductor and the center conductor of the loop was fabricated as Nb tubes with high RRR copper inserted inside for improving heat conduction from the tip of the inductor to the end of the loop.

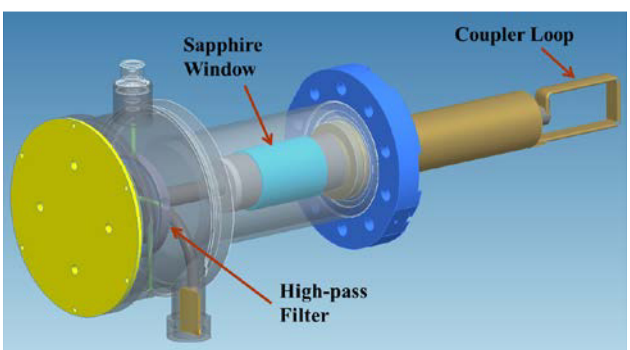

Figure 4: Prototype HOM coupler with high pass filter.

Figure 4 shows a 3D view of the HOM coupler prototype. The prototype coupler was fabricated at Jefferson Lab and installed into the cavity in January, 2014. Due to schedule reasons, there was only one HOM coupler installed in the cavity for RHIC operation in 2014.

Although the cavity is passively driven by beam, a fundamental power coupler (FPC) was installed and connected to a 1 kW amplifier. The purposes of providing a limited RF power include:

- Achieving required amplitude and phase stability;
- Providing conditioning capability.

A pick-up (PU) antenna is installed opposing the FPC in the cavity. Both couplers adopted a loop shape at the coupling end and are fabricated from copper. The FPC position can be changed over a range of 2.5 cm, which gives a continuous change of external Q from 2.2×10^6 to 7.1×10^7. A view of the FPC before installation is shown in Figure 5.

Figure 5: The Fundamental Power Coupler.

The port on the side of the cavity is used for fundamental mode damping (FMD) during beam acceleration period. The cavity tuning is not large enough to cover the entire frequency range when the beam builds up its energy. To prevent beam instability, the fundamental mode is damped to a loaded Q of 300 in addition to the full frequency detune by the tuning plate. The FMD couples to the fundamental mode with a loop shaped antenna. Location of the FMD along the cavity length is specifically chosen such that the cavity frequency change during the damper insertion detunes the cavity reasonably further, which in this case is 36.7 kHz. More detailed study of the FMD can be found in Ref. [7].

FIRST OPERATION

The first operation of the 56 MHz cavity was in June of 2014, with species Au + Au and He3 + Au. The RHIC operation parameters with the installed 56 MHz cavity are listed in Table 2.

The cavity voltage was limited at 330 kV by quench at the HOM coupler sapphire window. The cause of the quench was investigated and traced to RF heating of the braze alloy used during fabrication of the sapphire window. The HOM coupler was then removed during the 2014 RHIC summer shutdown. A redesigned new coupler is currently under fabrication.

Table 2: Parameters for RHIC Run14

	Unit	Au + Au	He3 + Au	
			He3 (b)	Au (y)
Peak Intensity	$\times 10^9$	180	5000	150
Energy	GeV	100	103	100
Bunch length	ns	2.5	2.2	2.5
beta*	cm	70	100	

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After the beams reached store energy, the FMD was extracted and tuning plate was moved slowly to bring the frequency toward the resonance. The tuning plate was parked when cavity voltage reached 300 kV. We observed 3% increase in the luminosity and 4.5% decrease of bunch length in both rings as shown in Figure 6.

The bunch profile changed with the 56 MHz cavity, which creates bigger potential well. The population of Au beam in the satellite buckets is squeezed toward the center as illustrated in Figure 7.

The cavity operated for 13 full stores of RHIC in 2014. The voltage fluctuation during the operation was controlled within 1 kV.

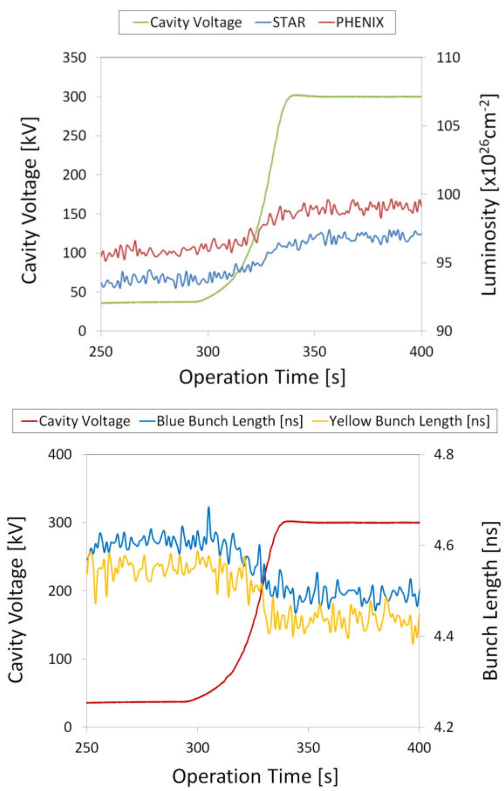

Figure 6: Luminosity increase (top) observed by the two RHIC detectors and bunch length decrease (bottom) due to the 56 MHz cavity turned on.

Despite the quench in the HOM coupler which limited the cavity voltage, HOM damping provided by a single coupler proved to be sufficient for the RHIC run. The output from the HOM coupler showed 8 excited modes, excluding the fundamental mode, which are all below 600 MHz. The beam did not experience measurable instability during tuning of the cavity, when the HOM frequencies are crossed multiple times by the beam spectrum lines.

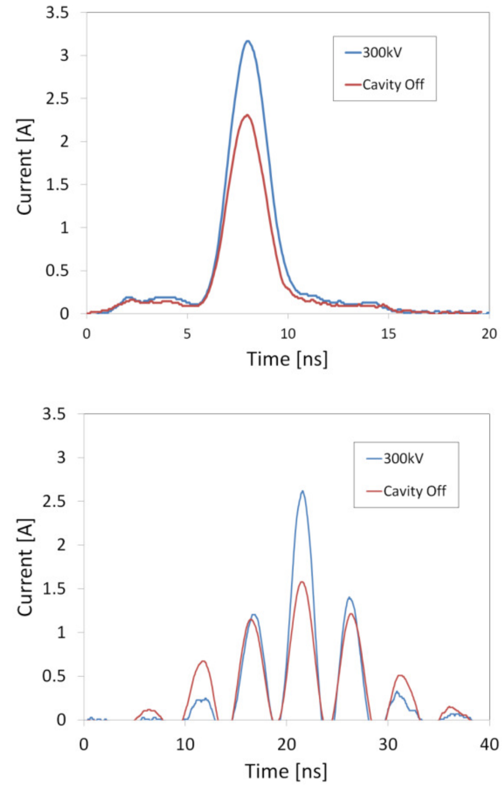

Figure 7: Beam profile comparison for 56 MHz cavity turned on and off. Top: Blue ring with He3 particles. Bottom: Yellow ring with Au particles.

HOM COUPLER REDESIGN

The prototype HOM coupler was removed from the cavity and a detail thermal study of the quench was carried out based on the thermal sensor data from the connection flange between the coupler and the cavity. ANSYS simulations showed the best match to the time constant of the temperature rise after the quench is local heating at the sapphire window braze joint to the Nb cuffs, as shown in Figure 8.

Figure 8: Braze joint at the end of the sapphire window.

With 330 kV in the cavity, the temperature of the Nb cuffs would reach 8.5 K, which is very close to critical temperature of the material (9.2 K).

The new design eliminates the sapphire window and uses only superconducting materials and sapphire rings in the filter section. New couplers are under fabrication at Jlab. Details of the design and fabrication can be found in Ref. [8].

SECOND OPERATION

During RHIC operation in 2015, the 56 MHz SRF cavity had no HOM couplers. It was detuned with the FMD inserted during routing operation, which made the cavity "invisible" to the beams.

A dedicated beam study with the cavity was designed with 11 bunches of protons in a 12 bunch pattern. The total intensity reached 2.39×10^{12}. As the cavity was slowly tuned to resonance with the beam, the bunch length doubled as the HOMs were excited successively, as shown in Figure 9. The signal from PU coupler showed that 4 monopole and 1 dipole HOMs were excited, all at frequencies under 500 MHz.

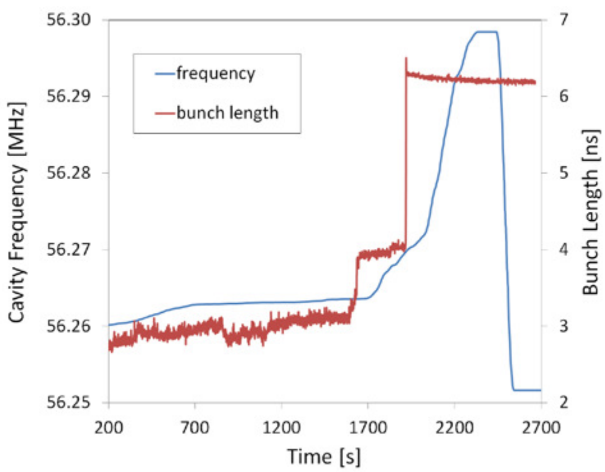

Figure 9: Bunch length doubled during the cavity frequency sweep without HOM damping.

To mitigate the affect from HOMs, we connected the FPC directly to a 1 kW RF load, bypassing the circulator. Due to the fact that the FPC is retracted into the port tube, coupling is limited. The cavity is not fully symmetric with the FMD port opening on the side, thus FPC, which is at a 45 degree angle from the FMD, can couple to all dipoles as they are being degenerated into specific directions. The loaded Q's of all excited HOMs below 500 MHz are in the range of 3×10^5 to 4×10^6, which is 3-4 orders of magnitude from the original setting for the beam experiment above. Beam study with limited HOM damping showed much smaller change in bunch length, Figure 10.

The beam profile at the end of two beam experiments discussed above showed clearly the difference between with and without HOM damping, as shown in Figure 11.

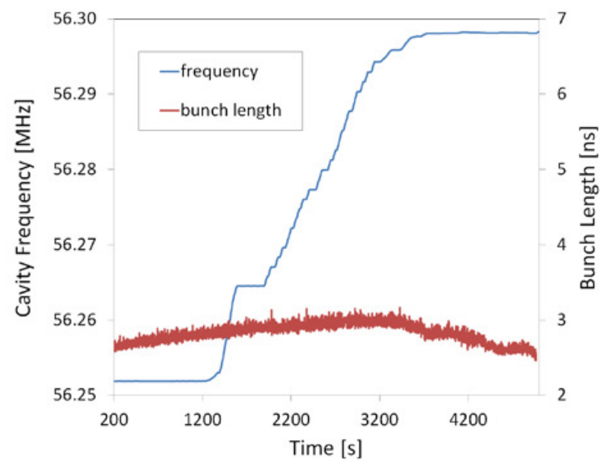

Figure 10: Less than 50% change during cavity frequency sweep with HOM damping from FPC.

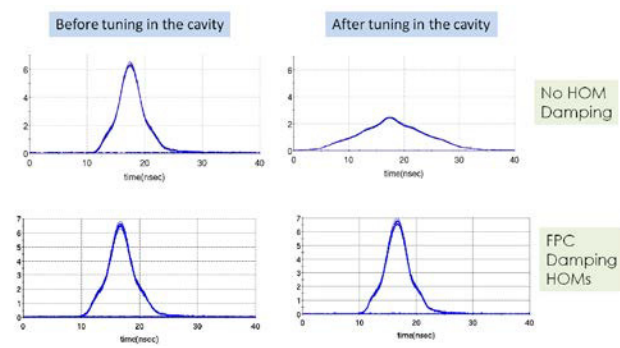

Figure 11: Beam profile comparison between without (top) and with (bottom) HOM damping from the FPC.

Cavity Conditioning

The cavity was conditioned during maintenance period and after the RHIC operation.

The voltage reached 1.18 MV in pulse mode and 1.05 in CW mode after all maintenance day conditioning. The RF power into the cavity was limited by the 1 kW amplifier and 3 dB loss in the over 400 feet long cable. Figure 12 shows that the cavity reached 80% of its maximum voltage within the first 5 hours of conditioning at the end of the last maintenance day. The process became very inefficient for the rest of the 26 hours.

After RHIC summer shutdown 2015 began, we kept the 56 MHz cavity at 4.5 K for four days allowing a dedicated conditioning period. The cavity was conditioned for more than 74 hours over this period. To improve the process, a 4 kW amplifier was connected to the FPC inside the tunnel. The input RF power was ensured to be more than 3.5 kW. Helium gas was also introduced into the cavity during the process.

With the large amplifier only, the cavity reached 1.65 MV in pulsed mode within the first 10 hours of conditioning. For the rest of the conditioning, the cavity was filled with helium gas periodically with a pressure controlled in a range from 1×10^{-5} to 5×10^{-4} Torr.

As shown in Figure 13, the cavity voltage reached 2.30 MV in pulsed mode and 1.93 MV in CW mode. The

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cavity can operate at 1.65 MV in CW mode without substantial cryogenic consumption (~40W dynamic loss). The peak voltage was limited by cryogenic capacity, but there was no hard limit. Further conditioning can be done as needed, to improve the RF surface and reach the designed voltage of 2 MV.

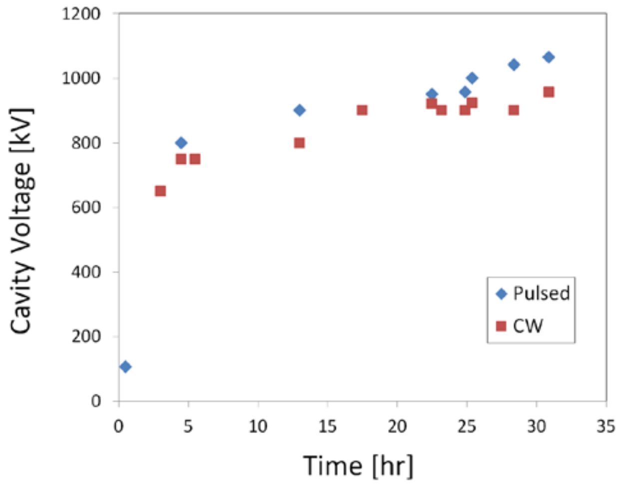

Figure 12: Cavity voltage change with conditioning at 500 W.

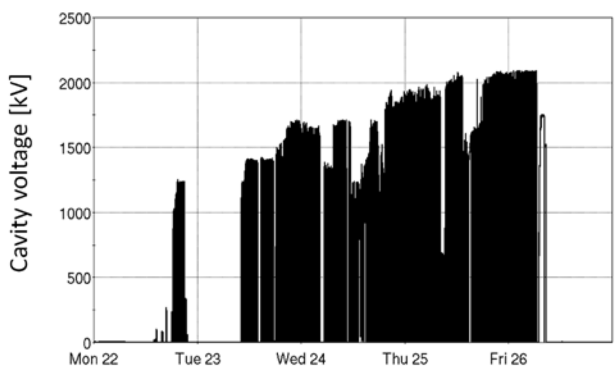

Figure 13: Cavity voltage increase during continuous conditioning after RHIC operation.

CONCLUSION

With the prototype HOM coupler, the 56 MHz SRF cavity has successfully operated with RHIC beam up to 330 kV, which is 16.5% of the design voltage. We observed a few percent of luminosity increase and bunch length reduction under this voltage. The changes in the luminosity and bunch length occurred simultaneously with the cavity tuning into resonance.

Beam experiments showed that the cavity would cause significant bunch lengthening if no HOM couplers are installed. After thermal analysis of the quench, the HOM coupler was re-designed to eliminate heating caused by the brazing material. New couplers will be installed for the RHIC run of 2016.

The cavity reached 1.93 MV in CW after helium conditioning with high power amplifier, limited by the cryogenic system capacity.

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