NORMAL CONDUCTING RF CAVITIES FOR ELECTRON ION COLLIDER HADRON STORAGE RING*

B. Xiao†[1], P. Berrutti[1], Z. Conway[2], M. Esposito[1], X. Gu[1], J. Guo[2], L. Guo[1], D. Holmes[1], V. Kaye[1]
G. Li[1], D. Lukach[1], P-D Malendele[1], L. Panjoj[1], E. Polanco[1], R. Rimmer[2], F. Severino[1]
K. S. Smith[1], B. Vassallo[1], S. Verdú-Andrés[1], S. Wang[2], Q. Wu[1], W. Xu[1], A. Zaltsman[1]
[1]Brookhaven National Laboratory, Upton, New York, USA
[2]Thomas Jefferson National Accelerator Facility, Newport News, VA, USA

Abstract

The Normal-Conducting Radiofrequency (NCRF) systems for the Electron-Ion Collider Hadron Storage Ring (EIC HSR) comprise four unique cavity systems. These systems include a 24.6 MHz capture and acceleration system, a combined 49.2 MHz and 98.4 MHz bunch splitting system, and a 197 MHz storage system for collider operations. All systems have successfully passed their final design reviews, and the detailed drawings are currently being completed for procurement. This paper reports on the recent progress achieved across these NCRF cavity systems.

INTRODUCTION

The Relativistic Heavy Ion Collider (RHIC) operating at Brookhaven National Lab (BNL) is comprised of 2 ion rings (referred to as blue that circulate clockwise, and yellow counterclockwise). Split evenly between the 2 rings there are four 28 MHz Quarter Wave Resonator (QWR) NCRF cavities to accelerate and capture the beam, and ten 197 MHz NCRF cavities to store the beam [1-4]. The EIC will reuse the modified 28 MHz system for the HSR 24.6 MHz. The 49.2 MHz and 98.4 MHz QWR for bunch splitting will be new QWR cavities. The HSR 197 MHz storage NCRF system will reuse the RHIC 197 MHz cavities and will operate with a superconducting RF (SRF) 591 MHz system to both store the ion beam and provide bunch compression [5-7].

Converting RHIC to the EIC HSR is nontrivial. The EIC HSR will have 3 times greater stored beam current, shorter bunch length (6 cm RMS, relative to RHIC's 60 cm), and more bunches (290 or 1160, relative to RHIC's 110). The EIC HSR has the same challenging requirements for energy ramp and transition crossing of heavy ions. The designs of the EIC HSR NCRF systems are significantly more challenging than those present in RHIC operations today. There are more RF systems in EIC HSR, two new systems with two modified systems from RHIC. It needs to deal with higher beam induced fundamental mode damper (FMD) and higher order mode (HOM) power, as well as broader fast tuning range and higher beam loading. It has tighter HOM impedance threshold. Combining all these together, the Multiphysics of these designs will be challenging. In this paper we show the design of the EIC HSR NCRF systems and our solutions for the challenges of the EIC HSR.

REQUIREMENTS

The typical RHIC collision store bunch pattern is currently 111 bunches in an h=120 bunch pattern. Bunches at store are compressed longitudinally to approximately a 1 ns (30 cm) RMS bunch length, using a non-adiabatic "rebucket" gymnastic [8]. For the EIC, 290 bunches in an h=315 bunch pattern will be injected, captured and accelerated using the upgraded 24.6 MHz NCRF cavity system. Several store scenarios are planned, involving 290 (h=315), 580 (h=630) or 1160 (h=1260) bunches. The 580 and 1160 bunch patterns will be produced via adiabatic bunch splitting using the new 49.2 MHz and 98.4 MHz NCRF QWR bunch splitting cavity systems, and the bunches will then be adiabatically compressed to their store length at 6 cm RMS using the upgraded 197 MHz NCRF cavity system, together with the new 591 MHz SRF cavity system that is not covered in this paper.

To deal with higher current and thus higher beam loading, and to regulate the voltage fluctuation, all QWRs are designed with relative low R/Q (circuit definition is used throughout the paper) and loaded Q Q_L. RHIC 28 MHz cavity has an R/Q of 67.6 Ω, the EIC 24.6 MHz cavity is designed to have a lower R/Q at 41.7 Ω, while for the new 49.2 and 98.4 MHz cavities, the R/Q are 26.3 and 21.0 Ω, respectively. The FPCs of the QWRs are set to have β at around 2 to lower the Q_L.

During energy ramp, the 49.2, 98.4 and 197 MHz RF cavities will be kept at zero voltage and should be transparent to the accelerating and transition crossing beam. FMDs will be used to lower the fundamental shunt impedance during ramp, and the FMD of each cavity will be extracted out of the cavity when voltage needs to be built up. The 24.6 MHz RF system is used to accelerate and capture the beam during energy ramp or during transition crossing of heavy ions, so needs fast tuners, while it does not need an FMD.

All these cavities need mechanical tuners. Each cavity needs a minimum of 78 kHz tuning range to cover +/- half of the revolution frequency. For 24.6 MHz cavities, an additional 120 kHz tuning range is needed to cover the frequency shift due to energy ramp, thus a total 200 kHz (- 160 to +40 kHz) tuning range. For 49.2 MHz cavities, it is needed for pre cooler for bunch lengthening, cavity voltage starts to ramp up right after transition crossing, an

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy.
† binping@bnl.gov

additional 240 kHz tuning range is needed, thus a total 320 kHz (-280 to +40 kHz) tuning range. For 98 and 197 MHz cavities, +/- 1.5 times revolution frequency is used, corresponding to 240 kHz (+/-120 kHz) tuning range.

Longitudinal HOM impedance threshold can be calculated using two methods [9,10], results showed a longitudinal impedance threshold of 220 kΩ-GHz.

For comparison, the following equation is normally used to calculate the longitudinal impedance threshold:

$$\Delta\Omega = i\frac{\bar{I}|\eta|}{4\pi Q_s E_T/q}\sum_{m=-\infty}^{\infty}\omega_m Z_{\parallel}(\omega_m)\exp\left(-\sigma_t^2\omega_m^2\right)$$

For HSR with sync tune of 0.0133, at 100 GeV, the longitudinal impedance threshold is 90 kΩ-GHz.

Transverse HOM impedance threshold is 2.5 MΩ/m for the whole ring. EIC has a tighter threshold compared with RHIC.

Beam loading is the phenomenon where a charged particle beam induces electromagnetic fields within an accelerating structure like an RF cavity, which then act back on the beam and the accelerating structure itself. This effect is critical for high beam current accelerators like EIC. If not addressed, it will cause excessive longitudinal emittance growth, uneven bunch splitting, and it will cause luminosity reduction. Mbtrack2 code is used to simulate the longitudinal bunch splitting procedure under beam loading conditions [11].

Cavity RF control has been studied in detail following the method shown in [12] using Matlab® code. Simulation shows that 49.2 MHz cavity needs 80 kW power in total, and 98.4 MHz cavity needs 80 kW with short (250 nS) delay or 90 kW with relatively long delay (1000 nS), to reach the phase slip suppression needed for even bunch splitting. 140 kW solid state amplifiers installed outside the tunnel will be used for 49 and 98 MHz cavities to deliver 100 kW power to each cavity interface. For 24.6 MHz cavities, 60 kW power with 78 kW power for abortion gap is needed for each cavity. Each cavity uses a transmitter with tetrode amplifier that can generate 60 kW RF power with 78 kW RF power for abortion gap to the cavity interface.

The cavity beampipe size is determined by the emittance and beta function. For Au ion with 200 nm emittance during injection and 200 m beta function, beampipe size equivalent of 12σ requires 3” ID. It is decided to use 6” ID beampipe for 24.6, 49.2 and 197 MHz cavities. 98.4 MHz cavity is the smallest one among the HSR NCRF cavities, while the power dissipation on the cavity wall is the highest and it needs excessive cooling on the inner conductor, thus a 3” ID beampipe is used.

SYSTEM DESIGNS

The 24.6 MHz, 49 MHz and 98 MHz cavities are all QWR cavities that share design similarity. The 24.6 MHz cavity is repurposed from RHIC 28 MHz cavity, shown in Fig. 1. The large 0.9 m ID 1.5 m long outer cylinder of the RHIC 28 MHz cavity will be reused, two endplates, as well as the small outer cylinder, will be redesigned together with the inner conductor of the QWR, with a total length of 2.8 m. Two new triaxial HOM dampers that are similar to those for RHIC 197 MHz cavity will replace the current Chebyshev type HOM dampers, shown in Fig. 2, while using the same ports on the cylinder to meet the tighter impedance threshold, and to handle higher HOM power, with the difference that this HOM damper is in the air while the HOM damper for 197 MHz cavity is under vacuum. The HOM damper design is optimized so that the peak E field will be controlled be controlled below 3 MV/m. Rexolite® chips are used between two capacitive plates for mechanical support, and a knob is added to fine tune the rejection at 24.6 MHz. Additional two e-probe couplers will be used as HOM dampers on the end group close to the mechanical tuner. HOM window used in CERN crab cavities will be used here with some modifications to avoid ceramic cracking. The mechanical tuner for the RHIC 28 MHz cannot be used in EIC since it has a bellow on the beampipe, which is a concern on short range wake for EIC ion bunch with short bunch length. New mechanical tuners are designed to be installed on the small outer cylinder to provide the tuning range needed. The vacuum pump for the RHIC 28 MHz will be refurbished and reused. The RF power coupler for RHIC 28 MHz will also be reused while rotating the loop for better coupling. Tetrode amplifier will be modified to 24.6 MHz. Ferrite fast tuner for RHIC 28 MHz cavity will be used in EIC 24.6 MHz cavity for heavy ions transition crossing, 4 ferrite tuners per cavity are needed to provide the tuning range needed at 20 kHz. With the use of ferrite tuners, FMD is not needed for this cavity.

The 49 and 98 MHz designs are similar to the 24.6 MHz. Each of these cavities has two loop HOM dampers, two e-probe HOM dampers, one FPC, one FMD, and one pumping port. The loop HOM damper and mechanical tuner will be similar to those in 24.6 MHz. The FPC window designed for EIC Electron Storage Ring (ESR) 591 MHz SRF cavity that can handle 400 kW RF power will be used in these cavities and couple to the E field. For ESR coaxial to waveguide transition is used to provide water cooling to the center conductor of the FPC probe, which cannot be used here due to the size of the waveguides for 49 and 98 MHz. Quarter Wave (QW) stubs are designed to provide water cooling. 197 MHz FMD design cannot be used in these two cavities, that design has a QW structure resonating to 197 MHz, such a structure for 49 and 98 will be long, complex and cannot handle high power. RF Window for RHIC 56 MHz SRF QWR is used with a large loop coupler for FMDs of these two cavities.

EIC 197 MHz NCRF cavity is repurposed from RHIC 197 MHz NCRF reentrant shape cavity, with RHIC 197 MHz NCRF cavity shown on left of Fig. 3. The RHIC design has one FPC with tetrode amplifier on top of it, one FMD, one mechanical tuner, two loop coupler HOM (h-HOM) dampers, two pickup couplers and one pumping port. For EIC, the FPC with tetrode amplifier, the FMD, the mechanical tuner, the pumping system (with refurbished components), as well as one of the pickup couplers and one of the h-HOM dampers will be reused from RHIC 197 MHz cavity system. While for another h-HOM damper, its coupling loop needs to be larger, this change brought higher power dissipation on the center conductor of the triaxial design, which leads to a temperature much higher than 100°C. A simple modification of the existing h-HOM damper does not work, and a new design is needed. An e-HOM damper will be inserted into a port that was originally designed for pickup coupler. Simulation shows that with air cooling, the e-HOM probe will be around 130°C, a QW stub is needed on the e-HOM damper so that the center conductor can be water cooled. The 90 kΩ-GHz longitudinal impedance threshold cannot be met with these modifications. Detailed simulation with 197 MHz HOM spectrum showed that it will not cause beam breakup, thus is acceptable for EIC. Tuning ranges of the RHIC 197 MHz cavities were measured, only one cavity could provide +/- 120 kHz tuning range with nominal frequency at 197.0508 MHz, the other cavities' nominal frequency are shifted to higher frequency end thus cannot provide tuning range required for EIC. The insertion of the modified h-HOM damper is optimized so that the nominal frequency is shifted to the middle of tuning range to meet the EIC requirement. With these changes, the longitudinal and transverse impedance spectrum are suppressed to thresholds that can be tolerated by EIC beam.

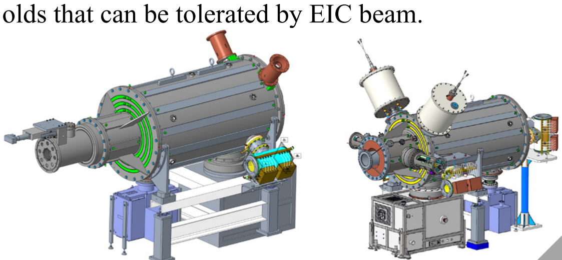

Figure 1: RHIC 28 MHz cavity, left; EIC 24.6 MHz cavity, right.

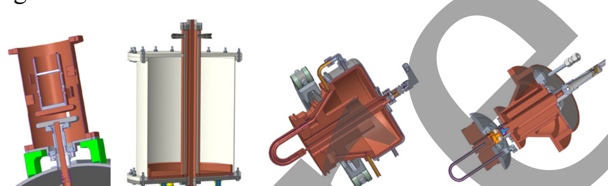

Figure 2: HOM dampers: for RHIC 28 MHz cavity, left; for EIC 24.6 MHz cavity, left-middle; for RHIC 197 MHz cavity, right-middle; and modified for EIC 197 MHz cavity, right.

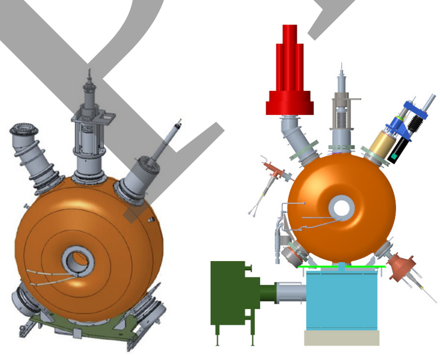

Figure 3: RHIC (left) and EIC (right) 197 MHz NCRF cavities.

Beam induced power has been calculated for these cavities. Table 1 shows the beam induced power on fully inserted FMD, majorly from the fundamental mode, for 49, 98 and 197 MHz cavities. HOM power is calculated considering worst case scenario, considering 0.6 mm transverse beam shift and each HOM frequency. Table 2 shows the beam induced HOM power for different bunch pattern with 6 cm bunch length. HOM powers with 75 cm bunch length are not shown here, they are small compared with 6 cm. The distribution of HOM power on each component is also calculated for all cavities and is fed into the Multiphysics simulations where needed.

Detailed multipacting simulations have been done to ensure there is no multipacting at voltages > 30 kV, while for operation the voltage will be > 50 kV. Thermal-mechanical coupled simulations have been done to all new cavities and components. With reasonable water-cooling design, maximum cavity wall temperature can be well below 70°C.

Table 1: Beam Induced Power on Fully Inserted FMD

RF Systems	FMD Qext	FMD Power [kW]	Note
49 MHz	228	2.26	
98 MHz	112	3.63	
197 MHz	150	0.01	FMD cannot be inserted into the cavity when the beam is short

Table 2: Beam Induced HOM Power in kW with 6 cm Bunch Length

RF system	290 bunches 0.74 A	1160 bunches 1 A
24.6 MHz	1.06	0.78
49 MHz	0.89	0.09
98 MHz	0.52	0.62
197 MHz	5.81[a]	1.18

[a]3.00 from 812.7 MHz mode

SUMMARY

RF designs of the EIC HSR NCRF systems including all the components FPC, HOM dampers, mechanical tuner, fast tuner, FMD, etc., are finished and are able to provide the required voltages, while meeting the requirements intrinsic to handling 3× higher current, shorter bunch lengths, more and varied bunch fill patterns, with tighter HOM impedance thresholds relative to RHIC designs, while the challenges of RHIC remain, i.e. energy ramp, and transition crossing of heavy ions. FMD and HOM powers have been calculated, and thermal analysis has been done to all new designs. Final design reviews have been completed for these cavities. Efforts currently are focused on addressing the review recommendations and towards procurement readiness.

REFERENCES

[1] J. Rose, J. M. Brennan, A. Campbell, S. Kwiatkowski, W. Pirkl, and A. Ratti, "RHIC 28 MHz Accelerating Cavity System", in *Proc. PAC'01*, Chicago, IL, USA, Jun. 2001, paper MPPH031, pp. 840-842.

[2] H. Hahn *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. A,* vol. 499, no. 245, 2003.

[3] J. Brennan, A. Campbell, J. DeLong, T. Hayes, E. Onillon, J. Rose, and K. Vetter, RF beam control system for the Brookhaven Relativistic Heavy Ion Collider, RHIC, 1998.

[4] B. Xiao and Z. Li, "A wide-open-waveguide cavity for the International Linear Collider crabbing system", in *Proc. IPAC'24*, Nashville, TN, USA, May 2024, pp. 985-988. doi:10.18429/JACoW-IPAC2024-TUPC01

[5] J. Berg *et al.*, "Lattice design for the hadron storage ring of the Electron-Ion Collider", in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 903-905. doi:10.18429/JACoW-IPAC2023-MOPL156

[6] R. Rimmer *et al.*, in *Proceedings of the 65th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e+e- Colliders (eeFACT2022)* INFN Frascati National Laboratories, Italy, 2023), pp. 125. doi:10.18429/JACoW-eeFACT2022

[7] W. Xu, J. Guo, R. Rimmer, A. Zaltsman, K. Smith, and E. Daly, "Evaluation of baseline 5-cell cavity for EIC RCS, HSR and SHC ERL", 2023. doi:10.2172/1984791

[8] J. M. Brennan, M. Blaskiewicz, J. Butler, J. DeLong, W. Fischer, and T. Hayes, "RF Techniques for Improved Luminosity at RHIC", in *Proc. EPAC'04*, Lucerne, Switzerland, Jul. 2004, paper MOPLT159, pp. 905-907. https://proceedings.jacow.org/e04/PAPERS/MOPLT159.PDF

[9] V. I. Balbekov and S. V. Ivanov, *Soviet Atomic Energy* vol. 60, no. 5, 1986.

[10] I. Karpov and E. Shaposhnikova, Generalized threshold of longitudinal multibunch instability in synchrotrons", *Physical Review Accelerators and Beams,* vol. 27, p. 074401 2024. doi:10.1103/PhysRevAccelBeams.27.074401

[11] X. Gu, M. Blaskiewicz, B. Xiao, and T. Satogata, :MBTRACK2 - Application on HSR 275GeV Bunch Split with Beam Loading:, 2026.

[12] J. Tückmantel, "Adaptive RF transient reduction for high intensity beams with gaps" , *10th European Particle Accelerator Conference* Edinburgh, UK, 2006. https://proceedings.jacow.org/e06/PAPERS/MOPLS006.pdf