ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPR06

PRELIMINARY DESIGN OF THE NORMAL CONDUCTING RF CAVITIES FOR ELECTRON ION COLLIDER HADRON STORAGE RING*

B. Xiao†, P. Berrutti, X. Gu, D. Holmes, D. Landwehrle, D. Lukach, P.D. Malendele, L. Panjoj
E. Polanco, S. Polizzo F. Severino, B. Vassallo, W. Xu, A. Zaltsman
Brookhaven National Laboratory, Upton, New York, USA
Z. Conway, J. Guo R. Rimmer, Jefferson Lab, Newport News, VA, USA

Abstract

The Normal-Conducting Radio-Frequency (NCRF) systems for the Electron-Ion Collider Hadron Storage Ring (EIC HSR) consist of 4 unique cavity resonators. The HSR NCRF systems are composed of 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. This paper presents the preliminary design of the HSR NCRF systems. We describe the unique approach taken to optimize HSR performance while limiting the total number NCRF systems, reducing the NCRF systems contributions to the total HSR impedance while reducing operating complexity.

INTRODUCTION

The Relativistic Heavy Ion Collider (RHIC) operating at Brookhaven National Lab (BNL) is comprised of 2 ion rings (referred to as blue that circulating clockwise, and yellow counterclockwise). Split evenly between the 2 rings there are 4 28 MHz Quarter-wave Resonator (QWR) NCRF cavities to accelerate and capture the beam, and 10 197 MHz NCRF cavities to store the beam [1-3].

The EIC HSR will reuse the 28 MHz systems and will modify them to 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 operate with a superconducting RF (SRF) 591 MHz system to both store the ion beam and provide bunch compression [4-6].

Converting RHIC to the EIC HSR is nontrivial. The EIC HSR will have 3x greater stored beam current, shorter bunch length (6 cm RMS, relative to RHIC's 75 cm), and more bunches (290, 580 or 1160, relative to RHIC's 110). The EIC HSR has the same challenging requirements for energy ramp and transition crossing of heavy ions.

Because of the above facts, 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 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 preliminary design of the EIC HSR NCRF systems and our solutions for the potential challenges of the EIC HSR.

REQUIREMENTS

Table 1 shows the RF parameters of the HSR NCRF systems. It is planned to modify all 4 RHIC 28 MHz cavities to 24.6 MHz for EIC, and to reuse 7 RHIC 197 MHz cavities. For the new RF systems, it is planned to use 3 49.2 MHz cavities, and 4 98.4 MHz cavities, to provide the voltage needed.

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. 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 loaded Q.

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 so that voltage can be built up when needed. For the 24.6 MHz RF system, since it is used to accelerate and capture the beam during energy ramp or during transition crossing of heavy ions, it 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, cavity voltage starts to ramp up right after transition crossing, an additional 240 kHz tuning range is needed, thus a total 320 kHz (-280 to +40 kHz) tuning range. For 98 & 197 MHz cavities, +/- 1.5 times revolution frequency is used, corresponding to 240 kHz (+/-120 kHz) tuning range.

Simulations have been done to determine the longitudinal HOM impedance threshold. A simplified conservative number of 90 kΩ-GHz has been used for the whole ring. Transverse HOM impedance threshold is 2.5 MΩ/m for the whole ring. EIC has a tighter threshold compared with RHIC.

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

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPR06

Table 1: RF Parameters of the HSR NCRF Systems

Freq [MHz]	24.6	49.2	98.4	197
Note	Mod from 28	New	New	Use current 197
Cavity Shape		QWR		Reentrant
Vtotal [kV]	600	500	600	6000
Number of cavities	4	3	4	7
Vacc/cavity [kV]	150	167	150	857
R/Q cir [Ω]	41.7	26.3	21.0	169.3
Q0	14000	12200	9500	52400
Power at Vacc/cavity [kW]	21.4	48.1	62.7	46.0
Amplifier Power [kW]		100.0	100.0*	
FPC Qext	7100	4600	3900	
Loaded Q	4711	3340	2765	
FMD	No	Yes	Yes	Yes
Mechancial tuner [kHz]	200	320	240	240
Fast tuner	20 kHz	No	No	No
Impedance budget, longitudinal [kΩ-GHz]				
whole ring	90	90	90	90
per cavity	22.50	30.00	22.50	12.86
Impedance budget, transverse [MΩ/m]				
whole ring	2.5	2.5	2.5	2.5
per cavity	0.63	0.83	0.63	0.36
Beampipe size [inch]	6	6	3	6

*120.0 kW if the amplifier is outside the tunnel

Beam loading effect has been studied in detail. 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). 100 kW tetrode amplifiers in the tunnel can be used for both designs, while 120 kW solid state amplifier can be the backup plan for 98.4 MHz cavity.

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

RHIC 197 MHz NCRF cavity is shown in Fig. 1. It has one FPC with tetrode amplifier on top of it, one FMD, one mechanical tuner, two HOM dampers, two pickup couplers and one pumping port. For EIC, the coupling loop of one of the HOM dampers needs to be larger, while the other one could be the same as the RHIC one, and two pickup couplers need to be longer with tilted tips for both fundamental and HOM pickups, majorly to meet the impedance threshold of certain HOMs.

The 24.6 MHz cavity is shown in Fig. 2. The 0.9 m ID 1.5 m long cylinder of the RHIC 28 MHz cavity will be reused, two endplates will be redesigned together with the inner conductor of the QWR, with a total length of 2.8 m. Two new HOM dampers will replace the current Chebyshev type HOM dampers, shown in Fig. 3, while using the same ports on the cylinder so that tighter impedance threshold can be met, and higher HOM power can be handled. Additional two e-probe type 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 trying to avoid ceramic cracking. The mechanical tuner will be similar to the RHIC 28 MHz design. The vacuum pump for the RHIC 28 MHz will be 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. Table 2 shows the comparison of the ferrite fast tuner for RHIC 28 MHz cavity and EIC 24.6 MHz cavity. Here worst-case scenario with 1 24.6 MHz cavity not working is considered, in this case 3 cavities should provide the voltage needed, with 200 kV from each cavity, and 4 ferrite tuners per cavity is needed to provide the tuning range needed at 20 kHz.

The 49.2 and 98.4 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, one pumping port. The loop HOM damper and mechanical tuner will be similar to those in 24.6 MHz, the FPC and FMD will be similar to those in 197 MHz, shown in Fig. 1. Commercially available FPC window design rated at 120 kW is also under consideration. Thermal-mechanical coupled simulations have been done to the 98.4 MHz design,

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPR06

since the power dissipation on this cavity wall is the highest among all designs, while the cavity size is the smallest. With reasonable water-cooling design, maximum cavity wall temperature can be well below 70°C. Beam induced power has been calculated for these cavities. Table 3 shows the beam induced power on fully inserted FMD, majorly from the fundamental mode. Table 4 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.

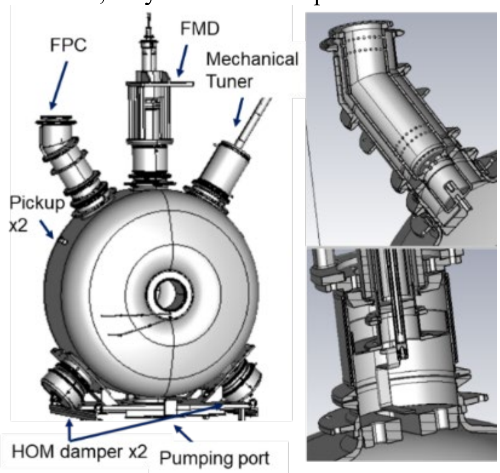

Figure 1: RHIC 197 MHz NCRF cavity (left), its FPC with ceramic window (top right), and its FMD (bottom right).

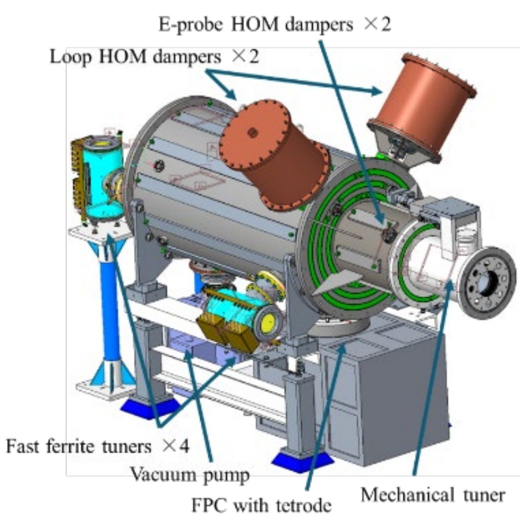

Figure 2: 24.6 MHz cavity.

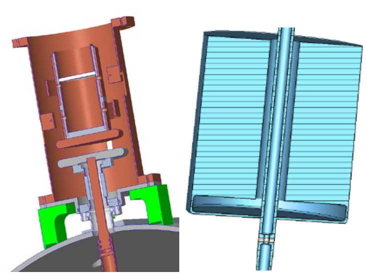

Figure 3: HOM damper for RHIC 28 MHz cavity (left, mechanical model), and for EIC 24.6 MHz cavity (right, vacuum model).

Table 2: Comparison of Ferrite Fast Tuner for RHIC 28 MHz Cavity and EIC 24.6 MHz Cavity

	RHIC 28 MHz	**EIC 24.6 MHz**
Beam current [A]	0.18	0.54
Voltage per cavity [kV]	300	200
R/Q per cavity [Ω in circuit definition]	64.0	41.7
Tuning range needed per cavity [kHz]	6	20
Tuning range provided per tuner [kHz]*	3.5	5.1
Number of tuners	1**	4
Tuning time [mS]	2	2
Power dissipation on tuners per cavity [kW]	0.8	3.2

*limited by 0.8 kW power dissipation per ferrite tuner
**Cavity out-of-regulation during transition

Table 3: Beam Induced Power on Fully Inserted FMD

RF Systems	**FMD Qext**	**FMD Power [kW]**	**Note**
197 MHz	100	34.3	<10 W with 75 cm bunch length
49 MHz	300	8.8	8.8 kW for both 6 cm & 75 cm bunch length
98 MHz	300	12.8	1.6 kW with 75 cm bunch length

Table 4: Beam Induced HOM Power [kW] with 6 cm Bunch Length

RF system	**290 bunches 0.74 A**	**1160 bunches 1 A**
197 MHz	2.20[a]	0.52
24.6 MHz	2.85[b]	1.58[c]
49 MHz	0.37	0.35
98 MHz	0.66	0.05

[a]0.70 from 1.351 GHz mode [b]1.60 from 0.937 GHz mode
[c]0.67 from 1.082 GHz mode

SUMMARY

Preliminary RF designs of the EIC HSR NCRF systems including all the components FPC, HOM dampers, mechanical tuner, fast tuner, FMD, etc., are finished and 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 preliminary thermal analysis has been done to the 98.4 MHz cavity. These preliminary designs are moving into the final design phase with greater Multiphysics detail to be included.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPR06

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., "The RHIC design overview," Nucl. Instrum. Methods Phys. Res., Sect. A, vol. 499, no. 2–3, pp. 245–263, Mar. 2003. doi:10.1016/s0168-9002(02)01938-1

[3] J. M. Brennan *et al.*, "RF Beam Control System for the Brookhaven Relativistic Heavy Ion Collider, RHIC", in *Proc. EPAC'98*, Stockholm, Sweden, Jun. 1998, paper WEP02G, pp. 1705-1707.

[4] 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

[5] R. Rimmer *et al.*, "2023 Cavity and Cryomodule Developments for EIC". In: Proceedings of the 65th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e+e- Colliders (eeFACT2022), INFN Frascati National Laboratories, Italy, p. 125, 2023.

[6] 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," Office of Scientific and Technical Information (OSTI), May 2023. doi:10.2172/1984791