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AN OVERVIEW OF RF SYSTEMS FOR THE EIC*

R. A. Rimmer†, J. P. Preble, JLab, Newport News, USA
K. S. Smith, A. Zaltsman, BNL, Upton, New York, USA

Abstract

The Electron Ion Collider (EIC) to be constructed at Brookhaven National Laboratory in the USA will be a complex system of accelerators providing high luminosity, high polarization, variable center of mass energy collisions between electrons and protons or ions. To achieve this a variety of RF systems are required. They must provide for capture, formation and storage of Ampere-class beams in the electron and hadron storage rings (ESR and HSR), fast acceleration of high-charge polarized electron bunches in the rapid cycling synchrotron (RCS), provision of cold high current electron bunches in the strong hadron cooler (SHC) ERL and precise high-gradient crabbing of electrons and hadrons either side of the interaction point. The challenges include strong HOM damping in the storage ring cavities and cooler ERL, very high fundamental mode power in the ESR and cooler injector, extremely stable low-noise operation of the crab cavities, mitigation of transient beam loading from gaps, and operating over a wide range of energies and beam currents. We describe the high-level system parameters and principal design choices made and progress on the R&D plan to develop these state of the art systems.

INTRODUCTION

The EIC [1] is a challenging new project to build a high luminosity electron-hadron collider based on RHIC by adding a high current electron storage ring and injector chain. This unique machine shares many similar challenges with the high luminosity B-factories and LHC as well as new ones, such as high-energy electron cooling and very large crabbing angle at the IP. Wherever possible technical solutions are adopted that are based on proven technology.

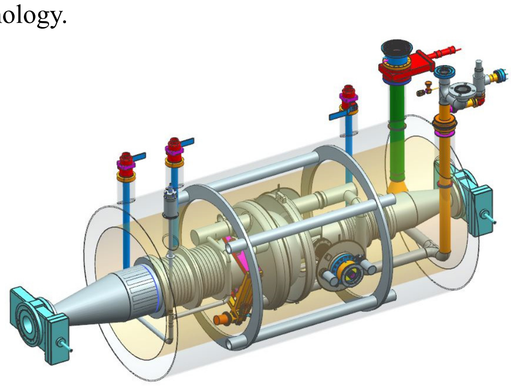

Figure 1: ESR 591 MHz 1-cell cavity.

Where new designs are needed a rigorous R&D program is being be conducted. The hadron storage ring will be based on the RHIC collider rings with updates for higher current and shorter bunches. Many existing RHIC RF systems will be refurbished or relocated, and a new 591 MHz SRF bunching system will be added to provide bunch lengths of ~1cm or less. The electron storage ring will use SRF single-cell cavities, see Fig. 1, with low R/Q and strong HOM damping to store up to 2.5 A of current. RF dipole (RFD) type crab cavities are used in both rings, see Fig. 2. Table 1 contains a summary of the RF systems.

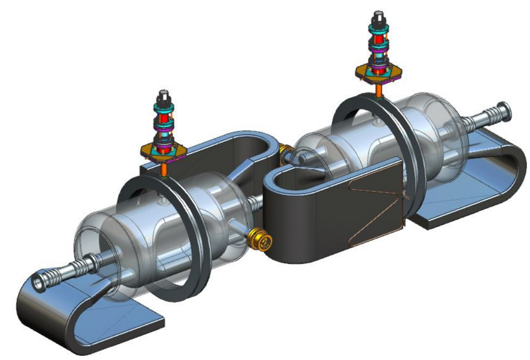

Figure 2: RFD crab cavity concept.

SRF DESIGN APPROACH

For all SRF systems, design limits on operating peak surface fields of 40 MV/m and 80 mT were adopted. The ESR 1-cell cavities are designed to operate at 3.6 MV, E_{acc} = 14.3 MV/m, E_{pk} = 39.2 MV/m, B_{pk} = 74.2 mT, but they will be qualified to at least 4 MV to provide operational margin.

The ESR cavity shape has been optimized for low R/Q (37 Ω), to reduce sensitivity to beam gap transients and to minimize HOM power. Cylindrical beam line absorbers will be used based on those developed by ANL [2]. The 5-cell 591 MHz SRF cavities for the HSR, RCS and ERL are based on the same cell shape but will have power couplers and HOM dampers optimized for each application. 1773 MHz third harmonic cavities will be needed in the ERL, which are similar in size to those used in CEBAF. The RFD crab cavities are similar to those developed for the high-luminosity upgrade of LHC [3] but with stronger HOM damping.

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† rarimmer@jlab.org .

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Table 1: Summary of Main RF Cavity Types for the EIC

Location	Freq (MHz)	Type	# Cavs	# Couplers	P/coup (kW)	Beam Current	HOM Power	Vcav / Pcav	Eacc MV/m
ESR	591	SRF, 1-Cell	17	2, Variable	400	2.5 A Max	(~34 kW) 2x20 kW	4 MV	15.8
RCS fundamental	591	SRF 5-cell	3	1	75	2x, 28 nC / bch	Small	20 MV / 60 kW	15.8
RCS merge 1	295.5	Cu 1-cell	2	1	40	4x, 14 nC	Small	0.65	
RCS merge 2	147.8	Cu 1-cell	1	1	40	2x, 28 nC	Small	0.7	
RCS injection 1	147.8/443.4	Cu QWR harmonic	1	1	5 (peak)	4.4 mA	Small	$V_\perp$ 200 kV	NA
RCS injection 2	295.5	Cu QWR	1	1	1.2 (peak)	4.4 mA	Small	$V_\perp$ 100 kV	NA
e injector Buncher 1	118	Cu λ/4	1	1	75 (peak)	8 x 7 nC	-	0.48 MV	
e injector Buncher 2	591	Cu 1-cell	2	1	34/26 (peak)	8 x 7 nC	-	0.32/0.28 MV	
e injector tapered buncher	2856	SLAC TWS	1	1		8 x 7 nC		15 MV	
e LINAC	2856	SLAC type	6	1	67 MW	8 x 7 nC	-	67 MV	16.7
De-chirper	1182	Cu LINAC	1	1	TBD	8 x 7 nC	-	33 MV	16.7
HSR capture	24.6	Cu λ/4	2	1	150	1 A	TBD	0.6	1.3
HSR bunch split 1	49.2	Cu λ/4	2	1	75	1 A	<20 kW	0.6	2.6
HSR bunch split 2	98.5	Cu λ/4	2	1	75	1 A	<20 kW	0.6	6
HSR bunch compress 1	197	Cu 1-cell	6	1	90	1 A		6	
HSR bunch compress 2	591	SRF 5-cell	1	1	75	1 A	~3 kW, 2x SiC loads	20	15.8
HSR Crab	197	RFD	8	1	<75	1 A	< 3.5 kW	8.5 MV /11.5 max	Crab cavity
HSR Crab	394	RFD	4	1	<75	1 A	< 3.5 kW	2.9 MV / 3.5 max	Crab cavity
ESR Crab	394	RFD	2	1	<75	2.5 A	<22 kW	2.9 MV / 3.5 max	Crab cavity
SHC buncher	197	Cu 1-cell	1	1	150	100 mA	TBD	0.6	
SHC booster	591	SRF 1.5 cell	1	2	360	100 mA	TBD	7	Graded beta
SHC linearizer	1773	SRF 1-cell	1	2	-40	100 mA	TBD	-2.3	Decel.
SHC ERL	591	SRF 5-cell	8	2	<75	100 mA	~200 W	21.2 MV	17
SHC ERL	1773	SRF 5-cell	3	2	20	100 mA	~600 W	-6.3 MV	14.8

NOTABLE CHALLENGES

High Currents

High luminosity is achieved through high currents in both the ESR (2.5 A), and HSR (1 A), in many bunches. This means HOM power is a significant concern both in the RF cavities and in the vacuum chamber. All bellows will have RF liners and all gate valves will be shielded. Special care is needed in the IR region where complex changes in cross section will inevitably trap modes. Impedances must meet tight constraints to avoid coupled-

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bunch instabilities during filling, store and in the HSR, ramping. Overall RF system stability is maintained by optimal detuning and maintaining sufficient RF overhead. In case of detuning to amplitudes comparable to the revolution frequency a 1-turn delay or comb filter may be needed.

High Bunch Charge

Despite using many bunches, the single bunch charge is high, leading to concerns about instabilities, wakefields, CSR, and prompt resistive wall (image current) heating. The ESR vacuum chamber will be designed for very low broad-band impedance, and will be actively cooled. The HSR magnet chambers will receive new low-impedance carbon-coated copper alloy liners to shield the stainless-steel beam pipe.

High Beam Power

The synchrotron radiation power in the ESR will be up to 10 MW, with 2.5 A of beam up to 10 GeV, falling to 230 mA at 18 GeV. This power must be replenished by the RF system, leading to very high RF power per cavity. Two coaxial couplers per cavity are adopted to keep the power per-coupler to a reasonable level.

Beam gaps in the rings give rise to phase transients in the RF systems, leading to variations in bunch arrival time at the IP. The low R/Q and high stored energy of the SRF cavities, and the option of counter-phasing [4] at low energy can minimize this effect in the ESR, while the lower current and number of cavities in the HSR make it less of a concern. Initial estimates are that luminosity loss from these effects is small, however the effect on the crabbing system has yet to be studied in detail.

Crabbing

The 25 mRad crossing angle requires high crabbing voltage especially in the HSR. The crab cavities must be strongly HOM damped. Even at 197 MHz in the HSR curvature of the RF waveform over the bunch length can lead to problems. A second-harmonic, 394 MHz, crabbing system will be used to linearize the kick. With the short bunches in the ESR a single 394 MHz system can be used. Other challenges include synchronization, emittance growth from noise and alignment tolerances.

Strong Hadron Cooling

To minimize luminosity loss some form of high energy cooling is needed. For heavy ions microwave stochastic cooling may be sufficient, but for protons something stronger is needed. High energy electron cooling will be used in the EIC, using ~100 mA CW beam from an ERL using 5-cell cavities similar to the HSR ones.

R&D PLAN

R&D has begun on these challenging systems, starting with the ESR 1-cell cavity and the 197 MHz crab cavity. Early R&D on the power couplers and HOM absorbers is also under way. In the first 3 years of the project both cavity types will be prototyped and ready for horizontal test. The 5-cell 591 MHz cavity, 394 MHz crab cavity and other cavities will follow soon afterwards.

CONCLUSION

The EIC is an exciting new project that is pushing the state of art on many frontiers. We are fortunate to have the examples of the LHC [5] and the B-factories [6, 7] to learn from and welcome new collaborations. The RF systems are being developed as an integrated set with a high degree of commonality and modularity in design and execution.

ACKNOWLEDGEMENTS

This paper summarises the work of a large team of people including the RF design groups at BNL and JLab as well as external collaborators. We thank them all for their contributions and look forward to working together to construct this ambitious machine.

REFERENCES

[1] EIC Conceptual Design Report, 2021, https://www.bnl.gov/ec/files/EIC_CDR_Final.pdf

[2] S.-H. Kim *et al.*, "Higher Order Mode Damping in a Higher Harmonic Cavity for the Advanced Photon Source Upgrade," in *Proc. 17th Int. Conf. RF Superconductivity (SRF'15)*, Whistler, Canada, Sep. 2015, paper THPB072, pp. 1293-1296.

[3] S. U. D. Silva, J. R. Delayen, H. Park, and Z. Li, "Cryogenic test results of the SPS prototype RF-dipole crabbing cavity with higher order mode couplers," in *Proc. 29th Linear Accelerator Conference (LINAC'18)*, Beijing, China, Sep. 2018, pp. 402-404. doi:10.18429/JACoW-LINAC2018-TUPO033

[4] T. Abe *et al.*, "Performance and Operation Results of the RF Systems for the KEK B-Factory," *Progress of Theoretical and Experimental Physics*, vol. 2013, no. 03, Mar. 2013. doi:10.1093/ptep/ptt020

[5] O. S. Brüning *et al.*, "LHC Design Report Vol.1: The LHC Main Ring", CERN, Switzerland, Rep. CERN-2004-003-V-1, 2004.

[6] J. Seeman *et al.*, "Performance of the PEP-II B-Factory collider at SLAC," in *Proc. 21st Particle Accelerator Conf. (PAC'05)*, Knoxville, TN, USA, May 2005, paper TPPP035, p. 2369.

[7] K. Oide, "KEKB B-factory, the luminosity frontier," *Prog. Theor. Phys.*, vol. 122, no. 1, pp. 69–80, Jul. 2009. doi: 10.1143/ptp.122.69