PROGRESS OF RF SYSTEMS FOR THE ELECTRON-ION COLLIDER*

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Abstract

The Electron-Ion Collider (EIC) under construction at Brookhaven National Laboratory (BNL) is being developed in partnership with DOE's Thomas Jefferson National Accelerator Facility (TJNAF). The EIC will deliver high-luminosity, variable center-of-mass energy collisions of highly polarized electron beams with highly polarized proton beams and ion beams. The EIC RF Systems provide a variety of functions and operate across a wide range of frequencies, utilizing multiple cavity types and technologies. We discuss challenges and proposed solutions for the EIC RF systems, provide high-level system parameters and main design choices, and review progress and plans for the RF Systems of the EIC Storage Rings.

THE ELECTRON-ION COLLIDER

The EIC will provide high-luminosity collisions of polarized electrons with polarized protons and light ions as well as with heavier stable nuclei in a center-of-mass energy range from 20 to 140 GeV. The EIC will reuse the hadron injection system, some components and infrastructure from the Relativistic Heavy-Ion Collider (RHIC) for the Hadron Storage Ring (HSR). The RHIC tunnel will host the HSR and a new Electron-Storage Ring (ESR). The electron injection system will consist of a preinjector (PRB), a Beam Accumulator Ring (BAR), and a Rapid Cycling Synchrotron (RCS). The collider will also have a Low Energy Cooler (LEC) in the RHIC tunnel. A sketch of the EIC accelerator complex is shown in Fig. 1 [1].

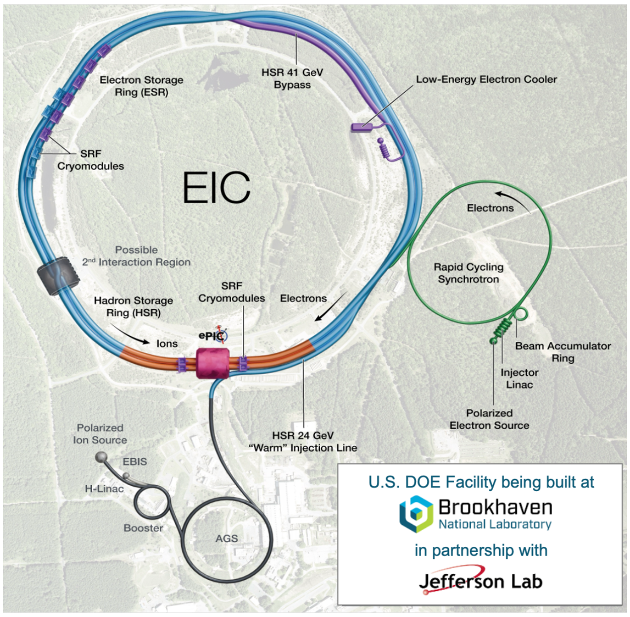

Figure 1: The EIC accelerator complex at BNL.

The HSR will host up to 1160 bunches, up to 1 A beam current of proton and ion beams, with an energy range from 40 to 275 GeV. A different beam scenario consists of 290 bunches, 0.69 A beam current of proton beams and presents the largest charge per bunch. The HSR is equipped with five different RF Systems to support injection, capture, acceleration, 4-way bunch splitting, compression, and store. For ion beams, the RF systems shall additionally enable transition crossing. The HSR will be a versatile machine as RHIC was, although operating with shorter bunches and higher current beams.

The ESR will store up to 1160 bunches with beam currents up to 2.5 A over an energy range of 5 to 18 GeV. Operation at the maximum energy of 18 GeV will be limited to 0.227 A to keep synchrotron radiation power within practical limits. The 9 GeV operating point will support the highest current, up to 2.5 A. The ESR employs a 591 MHz RF system to restore the energy lost to the beam.

To preserve polarization rates at collision, the electron injector system will deliver a fresh single bunch of up to 28 nC into the ESR every second at store energy. Highly polarized, 1 nC bunches at a 30 Hz repetition rate will be accelerated in the preinjector and accumulated in a single bunch of 750 MeV at BAR to deliver up to 28 nC bunches to the RCS at 1 Hz. The RCS will provide then fast acceleration to the different ESR store energies. The ramp to 18 GeV is only 120 ms.

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Achieving the required high luminosity demands not only Ampere-class beams, but also extremely small beam sizes – of a few tens (hundreds) of µm rms in the vertical (horizontal) dimension at the interaction point of the EIC. Combined with a large crossing angle of 25 µrad, this requires restoration of head-on collisions to recover geometric luminosity and preserve beam quality. Crab cavities will be installed on both sides of the interaction point to provide the necessary transverse beam rotation. Given the long hadron bunch lengths, second-harmonic crab cavities are required to produce a linear crabbing kick along the bunch.

The EIC will also rely on a low-energy cooler (LEC) to counteract intrabeam scattering (IBS) and enable the formation and preservation of small beam emittances and ribbon-like (flat) beams. A cool, high current bunched electron beam will overlap with the hadron beam at injection energy. LEC is a scaled up version of the Low Energy RHIC electron Cooler (LEReC) which operated in RHIC [2].

THE RF SYSTEMS FOR THE EIC

Table 1 summarizes the high-level system parameters of the RF Systems for the EIC. The necessary RF systems to support operation with electron beams at 18 GeV and with 2.5 A electron beams at 9 GeV, as well as the 394 MHz crab cavities and the LEC system, are deferred scope to be executed outside of the EIC Project.

Main Challenges

The main challenges for the EIC RF Systems arise from the need to deliver high luminosity collisions over a broad range of energies and species while remaining within space constraints and practical cost.

Operation of high power beams in the ESR leads to high energy losses per turn mainly driven by synchrotron radiation but with also a significant contribution from beam-impedance interactions. The 10 MW of total power loss per turn requires significant installed power and, for a commensurate number of cryomodules that satisfy space and cost constrains, the adoption of MW-class continuous-wave (CW) fundamental power couplers (FPC). The high-current electron beam, in combination with short bunches of about 7 mm rms, also demands effective higher-order mode (HOM) power handling and proper damping for both the ESR 591 MHz and ESR 394 MHz RF systems. The ESR 591 MHz cryomodules are equipped with SiC beam line absorbers (BLA) designed to handle the 63 kW deposited by the beam [3].

The HSR RF systems will be equipped with high-gain, broad-band direct feedbacks to remain stable over the whole beam cycle. The long abort gaps in both ESR and HSR (about 1 µm long, or 100 empty buckets after a 1160 bunch train) result in heavy transient beam loading that demands large installed power and in some instances requires the implementation of active compensation (one-turn delay feedback or direct feedforward [4, 5]) or of adaptive voltage setpoints with modulated voltage phase. The need for a variable external Q in the ESR 591 MHz RF system as result of the wide range of beam scenarios is eliminated by the adoption of RF FODO or counter-phasing.

Beam-beam interactions are capable to transfer RF noise between beams and result in unmanageable emittance growth and beam loss. Since the EIC hadron beams do not have natural damping, tight RF noise requirements are imposed to the HSR RF systems in operation during collision [6]. For example, the HSR 591 MHz RF system phase stability integrated from 1 Hz to 10 kHz shall be not larger than 0.0588 degrees [7]. Much tighter RF noise requirements, of less than 2 µrad, are imposed to the crab cavities to limit transverse emittance growth [8].

Fast acceleration in the RCS has the potential to introduce significant dynamic Lorentz force detuning in the RCS 591 MHz RF System currently under design. Meanwhile, the LEC relies on precise overlapping of hadron and electron beams for effective cooling. Noise control is also critical here. Additional challenges are introduced by the series of RF gymnastics required to manipulate and form the bunches in the HSR, and include those already present in RHIC such transition crossing.

Overall Approach

The EIC will rely on about 20 types of RF systems, utilizing different cavity types and technologies to perform a wide variety of functions. Each RF system encompasses cavities (or cryomodules) and their ancillaries, high-level RF (RF power sources and distribution), and low-level RF controls. Given the vast number of RF systems needed across the EIC accelerator complex, the following strategies are pursued to reduce cost and effort:

Reuse or Modify Existing RHIC Equipment Drives the choice of harmonic numbers for the RF systems of the EIC Storage Rings and also motivates the conversion of the RHIC 28 MHz into the EIC HSR 24.6 MHz, as well as the RHIC 197 MHz into the EIC HSR 197 MHz.

Adopt Common Frequencies and Equipment Across Different RF Systems In this context, a MW-class broadband RF window has been developed for use in any of the EIC RF systems up to and including 591 MHz. The 98.5 and 197 MHz normal-conducting RF (NCRF) cavity systems will share a common cavity design but require custom ancillary components. The ESR and HSR 591 MHz RF systems will utilize the same superconducting RF (SRF) cryomodule design, with only minor variations in the FPC antenna. In addition, a common RF platform is being developed for low-level RF controls.

Leverage Designs from Other Facilities and Projects For example, the RF dipole (RFD) crab cavity for the luminosity upgrade of the CERN's Large Hadron Collider (HL-LHC) [9]; the L-band (1.3 GHz), standing-wave (SW), multi-cell, copper structure at Argonne Wakefield Accelerator (AWA) facility [10] and conventional S-band (2.8 GHz), traveling-wave (TW) structures for the EIC electron injector.

Table 1: Summary of RF Cavity Systems for the EIC (☆: EIC Project scope)

System	Freq [MHz]	Function	Type	#Cavities	Vcav [MV]	#Couplers per cavity	Power per coupler [kW]
☆ PRB	197	Bunching	NCRF Reentrant	1	0.50	1	20
☆ PRB	1300	Capture	NCRF SW	1	2.8	2	1400
☆ PRB	1300	Capture/Accel	NCRF SW	1	11.7	2	6000
☆ PRB	2856	Acceleration	NCRF TW	14	60	1	35000
☆ BAR	98.5	Storage	NCRF QWR	1	0.1	1	120
☆ RCS	197	Acceleration	NCRF Reentrant	1	0.5	1	70
☆ RCS	591	Acceleration	SRF 5-cell	2	20.00	1	70
RCS	591	Acceleration	SRF 5-cell	4	20.00	1	70
☆ ESR	591	Storage	SRF 1-cell	4	3.64	2	400
ESR	591	Storage	SRF 1-cell	12	3.64	2	400
ESR	394	Crab Main	SRF RFD	2	2.90	1	35
☆ HSR	24.6	Capture/Accel	NCRF QWR	4	0.150	1	60
☆ HSR	49.2	Split	NCRF QWR	3	0.167	1	120
☆ HSR	98.5	Split	NCRF QWR	4	0.150	1	120
☆ HSR	197	Storage	NCRF Reentrant	8	0.750	1	60
☆ HSR	197	Crab Main	SRF RFD	8	8.45	1	75
HSR	394	Crab 2nd Har.	SRF RFD	4	-2.38	1	35
☆ HSR	591	Storage	SRF 1-cell	4	4.0	1	150
LEC	24.6	Compensation	NCRF QWR	2	0.005	1	160
LEC	197	Acceleration	NCRF Reentrant	17	0.80	2	140
LEC	591	Third harmonic	NCRF Reentrant	4	0.38	1	35
LEC	591	Deflecting	NCRF Deflecting	1	0.12	1	3

RF SYSTEMS FOR THE STORAGE RINGS: PROGRESS, STATUS, AND OUTLOOK

Over the past years, a series of critical components for the EIC Storage Rings have been prototyped and tested. A 591 MHz single-cell cavity prototype has been completed [11] and a 197 MHz RFD crab cavity prototype is being fabricated [12]. After the RHIC shutdown, tests conducted on the RHIC 28 and 197 MHz cavities confirmed that the components to be reused for the EIC will meet requirements [13]. RHIC has served as a bench to validate hardware, software, and firmware for low-level RF controls. A 24.6 MHz tetrode amplifier prototype demonstrated operation at 60 kW CW [14]. High power tests of a SiC beam line absorber [15] are ongoing and a pair of 400 kW CW input power FPC are being finalized to undergo RF conditioning and high power testing in the following months [16]. Figure 2 shows some of these design verification units (DVU).

The designs of the normal-conducting cavities [13, 17, 18] and the 197 MHz crab cavity [19] for the HSR are well advanced, and production of the first article ESR 591 MHz cryomodule has started. The design and lessons learned from this cryomodule will benefit the development of other EIC cryomodules. Figure 3 shows the string assembly design for the ESR 591 MHz RF system [3]. In parallel to the cavity and cryomodule developments, the high-level RF and low-level RF designs have also matured, and the contract for a couple of 400 kW 591 MHz solid-state amplifiers to support cryomodule testing has been awarded.

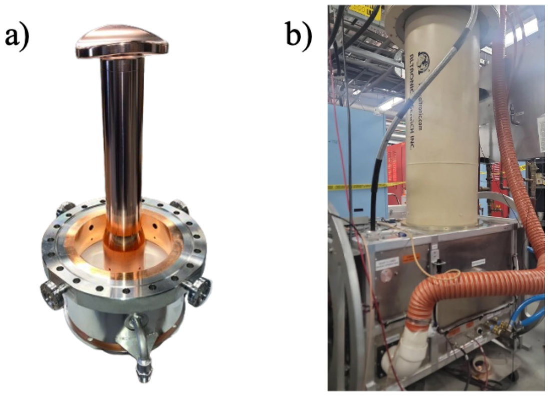

Figure 2: DVUs: a) 400 kW CW input power FPC, and b) 24.6 MHz tetrode amplifier connected to a dummy load.

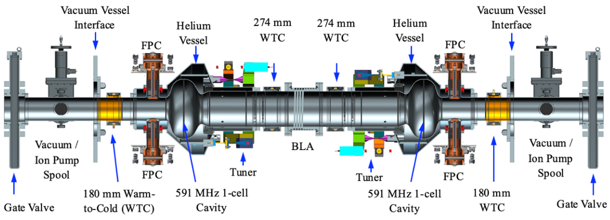

Figure 3: ESR 591 MHz 1-cell 2-cavity string assembly.

The team is now increasing their focus on advancing the RF systems for the electron injector system while maintaining steady progress on the RF systems for the storage rings. The work carried out up to date provides a solid foundation for these efforts.

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