THE EIC ACCELERATOR: DESIGN HIGHLIGHTS AND PROJECT STATUS*

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Abstract

The design of the electron-ion collider (EIC) at Brookhaven National Laboratory is well underway, aiming at a peak electron-proton luminosity of 10^{34} cm^{-1} sec^{-1}. This high luminosity, the wide center-of-mass energy range from 29 to 141 GeV (e-p) and the high level of polarization require innovative solutions to maximize the performance of the machine, which makes the EIC one of the most challenging accelerator projects to date. The complexity of the EIC will be discussed, and the project status and plans will be presented.

INTRODUCTION

The Electron-Ion Collider, designed in a partnership between BNL and TJNAF, aims at an electron-proton luminosity of 10^{34} cm^{-1} sec^{-1}. The facility is based on the existing RHIC complex at BNL, taking advantage of the hadron injector complex and infrastructure. An electron storage ring (ESR) will be added in the RHIC tunnel, together with a rapid-cycling synchrotron (RCS) that serves as a polarized electron injector. Electrons and hadrons will be brought into collision in a dedicated interaction region in the IR6 straight section. Later addition of a second interaction region in IR8 is foreseen, but not part of the EIC project scope.

HADRON STRORAGE RING

The hadron storage ring will be composed of arcs from the RHIC facility [1]. After assessing the tunnel space and access/egress requirements, as well as the associated engineering challenges [2], it has recently been decided to use the entire "Yellow" RHIC ring as the HSR. Due to significant modifications for the interaction region in IR6 and for hadron cooling in IR2, a number of jump quadrupoles needed for the transition jump will have to be removed. Studies are underway to ensure transition crossing capability in the HSR [3–5]. The number of Siberian snakes will be increased from two in the present RHIC "Yellow" ring to six in the HSR in order to improve proton polarization preservation on the ramp and enable polarized ^{3}He operation [6, 7]. Additional, new normal-conducting RF cavities are being designed, together with a feedback system to suppress RF noise [8, 9]. Copper-clad stainless-steel sleeves will be inserted into the entire HSR beam pipes to improve conductivity for image currents and reduce the secondary electron yield to suppress electron cloud build-up [10–12]. The RHIC stripline BPMs will be replaced by button BPMs with lower beam coupling and impedance to the shorter bunch, higher current beams of the EIC [13]. To facilitate operation of the HSR with "flat" hadron beams with an emittance ratio of $\epsilon_y/\epsilon_x = 0.09$, the capabilities of the decoupling scheme are under study [14].

HADRON BEAM COOLING

Hadron cooling will be needed to first pre-cool the hadron beams at injection to the required emittances, and then to preserve these emittances during the store. While the pre-cooler design is based on "conventional" bunched beam electron cooling, two different options are being considered for high-energy cooling, namely a novel ERL-based coherent electron cooling [15–17] concept and conventional bunched beam electron cooling based on an electron cooler ring equipped with wigglers for enhanced synchrotron radiation damping [18, 19]. Beam dynamics and cooling performance of both approaches have been studied [20–22], and an appropriate insertion for the HSR IR2 lattice has been

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designed to accommodate the coolers. A high-intensity, low-emittance electron gun that is capable of generating the required beam parameters for the cooler has been developed [23].

ELECTRON STORAGE RING

The ESR is based on a rather conventional FODO lattice [24]. Due to many geometric and optical constraints imposed by the existing tunnel space, spin rotators, and dynamic aperture requirements, the ESR lattice design is very challenging. To reduce the cost of the facility and relieve the market pressure on the small magnet vendor base, quadrupoles and sextupoles from the decommissioned Advanced Photon Source at ANL will be used [25]. Dipoles, corrector magnets, as well as some additional quadrupoles and sextupoles, are currently being designed [26]. Dynamic aperture optimization has yielded a minimum dynamic aperture of 10σ in all three dimensions [27]. The polarization lifetime has been further maximized using the novel BAGELS (Best Adjustment Groups for ELectron Spin) method [28, 29], leading to self polarization anti-parallel to the main dipole field of up to 70%. BAGElS is also used to control the vertical electron beam emittance and to globally compensate coupling with minimal impact on polarization. Magnet power supply ripple requirements are determined based on beam-beam simulations, with the resulting hadron beam emittance growth rate defining the tolerances for beam jitter at the interaction point. These tolerances are then converted to power supply ripple amplitudes, taking into account the magnet impedances and eddy current shielding effects of the beam pipe [30]. Wakefields and their associated collective effects have been investigated to ensure stability of the 28 nC electron bunches [31–33]. The 591 MHz single-cell SRF cavity with its fundamental power coupler and higher-order mode absorber have been designed and tested [34–36].

ELECTRON INJECTOR SYSTEM

A rapid-cycling synchrotron [37] (RCS) accelerates the 400 MeV polarized electron beam from the LINAC to the corresponding collision energy of up to 18 GeV in the ESR. This machine is particularly challenging due to the low injection energy and the correspondingly low magnetic fields, which in the case of the main dipoles are only 56 G. Residual field measurements in the RHIC tunnel show levels as high as 5 to 10 G [38], which makes stable beam operation of the RCS questionable. Cycle-to-cycle reproducibility of the low magnetic fields is a concern that is being addressed by accurate modeling [39] as well as measurements on a dedicated test magnet [40]. A system of self-correction coils has been developed to compensate magnetic multipole fields induced by eddy currents in the beam pipe during acceleration [41]. A high charge, polarized electron gun has been developed and has exceeded the requirements for the EIC [42, 43].

Adding a polarized 3 GeV booster synchrotron [44] to the electron injector system is currently under consideration. The resulting higher injection energy for the RCS would significantly improve the performance of the RCS by increasing the RCS injection dipole field to some 400 G. In addition, the higher injection energy would also increase the stability thresholds for collective effects in the RCS. To partially offset the additional cost of the booster, the LINAC energy could be reduced to some 200 MeV [45].

INTERACTION REGION

The interaction region [46] has reached a high level of maturity, and the current focus is on the detailed design. Work on the second, off-project interaction region [47] is progressing as well. Superconducting magnets are being designed [48], and schemes to compensate the coupling effect introduced by the detector solenoid are being explored [49]. Effects of the imperfection of the crab crossing scheme [50], for instance the less-than-ideal betatron phase advance between crab cavities and the interaction point, and associated diagnostic methods are being investigated. The effect of the transverse RF field of the crab cavities on beam polarization is being studied [51], tolerances for the 197 MHz crab cavity prototype have been developed [52], and the higher-order mode power in the EIC crab cavity system has been investigated [53].

BEAM DYNAMICS

Detector backgrounds due to synchrotron radiation are a major concern for the EIC because of the high electron beam current of up to 2.5 A. The effect of component misalignment and orbit correction on detector backgrounds has been simulated to ensure safe operation of the detector [54]. Extensive beam-beam simulations as well as collective effects studies have been carried out to ensure reliable operation of the collider with its high beam currents, electron bunch intensities, and beam-beam parameters [55–60].

PROJECT STATUS AND SCHEDULE

The project was granted CD-3A status in early 2024, which entails approval of early procurement of long-lead items before start of construction, such as superconducting cables for IR magnets or lead-tungsten blocks for the detector. CD-2 baselining is envisioned to coincide with the end of RHIC operations at the end of FY25, with start of construction (CD-3) following shortly after.

REFERENCES

[1] J. S. Berg *et al.*, "The hadron storage ring lattice of the Electron-Ion Collider", presented at IPAC'24, Nashville, TN, May 2024, paper MOPC93, this conference.

[2] F. Micolon *et al.*, "From RHIC to EIC hadron storage ring – overview of the engineering challenges", presented at IPAC'24, Nashville, TN, May 2024, paper TUBD1, this conference.

[3] H. Lovelace *et al.*, "An update on the transition crossing schemes for the EIC hadron storage ring", presented at IPAC'24, Nashville, TN, May 2024, paper TUPS03, this conference.

[4] H. Lovelace *et al.*, "Study of longitudinal effects during transition crossing of the EIC hadron storage ring", presented at IPAC'24, Nashville, TN, May 2024, paper TUPS01, this conference.

[5] S. Peggs *et al.*, "Crossing transition in the EIC HSR with a resonance island jump scheme", presented at IPAC'24, Nashville, TN, May 2024, paper THPC66, this conference.

[6] F. Meot *et al.*, "On proton beam polarization in the EIC HSR", presented at IPAC'24, Nashville, TN, May 2024, paper MOPC86, this conference.

[7] E. Hamwi *et al.*, "Snake matching in the EIC's hadron storage ring", presented at IPAC'24, Nashville, TN, May 2024, paper TUPS33, this conference.

[8] B. Xiao *et al.*, "Preliminary design of the normal conducting RF cavities for EIC hadron storage ring", presented at IPAC'24, Nashville, TN, May 2024, paper TUPR06, this conference.

[9] H. Huang *et al.*, "Simulation of the simple feedback system for the mitigation of the cavity RF noise effects in EIC HSR", presented at IPAC'24, Nashville, TN, May 2024, paper THPC79, this conference.

[10] M. Sangroula *et al.*, "Resistive wall heating and thermal analysis of the EIC HSR beam screen", presented at IPAC'24, Nashville, TN, May 2024, paper MOPS22, this conference.

[11] H. Lovelace *et al.*, "Impact of beam screen eddy currents on transition crossing in the EIC HSR", presented at IPAC'24, Nashville, TN, May 2024, paper TUPS02, this conference.

[12] M. Morrone *et al.*, "The mechanical behavior of the EIC beam screen during a magnet quench", presented at IPAC'24, Nashville, TN, May 2024, paper TUPR59, this conference.

[13] M. Sangroula *et al.*, "Design of the cryogenic BPM pick-ups for the EIC Hadron Storage Ring", presented at IPAC'24, Nashville, TN, May 2024, paper WEPG10, this conference.

[14] Y. Luo *et al.*, "Global betatron coupling compensation for the hadron storage ring of the Electron-Ion Collider", presented at IPAC'24, Nashville, TN, May 2024, paper MOPC90, this conference.

[15] K. Deitrick *et al.*, "Development of an ERL for coherent electron cooling at the Electron-Ion Collider", presented at IPAC'24, Nashville, TN, May 2024, paper THPC46, this conference.

[16] N. Wang *et al.*, "Optimization of cooling distribution of the EIC cooler ERL", presented at IPAC'24, Nashville, TN, May 2024, paper TUPC43, this conference.

[17] S. Setiniyaz *et al.*, "A preliminary feasibility study on dual cavity cryomodule integration for the Electron Ion Collider energy recovery linac cooler", presented at IPAC'24, Nashville, TN, May 2024, paper TUPC51, this conference.

[18] J. Unger *et al.*, "Dynamic aperture in a wiggler dominated ring electron cooler of the EIC", presented at IPAC'24, Nashville, TN, May 2024, paper TUPG60, this conference.

[19] A. Blednykh *et al.*, "Collective effects in the EIC SHC storage ring cooler", presented at IPAC'24, Nashville, TN, May 2024, paper THPC52, this conference.

[20] W. F. Bergan *et al.*, "Coherent electron cooling physics for the EIC", presented at IPAC'24, Nashville, TN, May 2024, paper THYD1, this conference.

[21] G. Wang *et al.*, "Estimates of the recombination rate for the strong hadron cooling system in the EIC", presented at IPAC'24, Nashville, TN, May 2024, paper TUPC16, this conference.

[22] O. Rahman *et al.*, "High average current DC electron gun for strong hadron cooling", presented at IPAC'24, Nashville, TN, May 2024, paper WEPC41, this conference.

[23] E. Wang *et al.*, "Generating super-Gaussian distribution and uniform sliced energy spread bunch for EIC strong hadron cooling", presented at IPAC'24, Nashville, TN, May 2024, paper MOPC23, this conference.

[24] D. Marx *et al.*, "Design of the electron storage ring of the Electron-Ion Collider", presented at IPAC'24, Nashville, TN, May 2024, paper MOPC79, this conference.

[25] C. Montag *et al.*, "Recycling magnets for the EIC electron storage ring", presented at IPAC'24, Nashville, TN, May 2024, paper MOPC64, this conference.

[26] R. Lovelace *et al.*, "Progress on the normal conducting magnets for the Electron-Ion Collider", presented at IPAC'24, Nashville, TN, May 2024, paper TUPR42, this conference.

[27] Y. Nosochkov *et al.*, "Dynamic aperture of the EIC electron storage ring", presented at IPAC'24, Nashville, TN, May 2024, paper MOPC82, this conference.

[28] M. G. Signorelli *et al.*, "Polarization preservation methods for the electron storage ring of the EIC", presented at IPAC'24, Nashville, TN, May 2024, paper MOPC83, this conference.

[29] M. G. Signorelli *et al.*, "BAGELS: A general method for minimizing the rate of radiative depolarization in electron storage rings", presented at IPAC'24, Nashville, TN, May 2024, paper MOPC85, this conference.

[30] B. Podobedov *et al.*, "Eddy current shielding of the magnetic field ripple in the EIC electron storage ring vacuum chambers", presented at IPAC'24, Nashville, TN, May 2024, paper MOPC77, this conference.

[31] G. Wang *et al.*, "Updates on the wake potential calculation for the Electron-Ion Collider with ECHO3D", presented at IPAC'24, Nashville, TN, May 2024, paper THPC55, this conference.

[32] M. Sangroula *et al.*, "Beam induced heating analysis update for the EIC vacuum chamber components", presented at IPAC'24, Nashville, TN, May 2024, paper MOPS21, this conference.

[33] B. Podobedov *et al.*, "Transversely driven coherent beam oscillations in the EIC electron storage ring", presented at IPAC'24, Nashville, TN, May 2024, paper MOPC76, this conference.

[34] J. Guo *et al.*, "Design, prototyping and testing of the Electron Ion Collider electron storage ring SRF cavity", presented at IPAC'24, Nashville, TN, May 2024, paper WEPS58, this conference.

[35] W. Xu *et al.*, "Progress on high power FPC development for EIC", presented at IPAC'24, Nashville, TN, May 2024, paper WEPS14, this conference.

[36] W. Xu *et al.*, "Prototype and high power test of SiC HOM absorber for EIC", presented at IPAC'24, Nashville, TN, May 2024, paper WEPS13, this conference.

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[37] H. Lovelace *et al.*, "An update on EIC rapid cycling synchrotron optics", presented at IPAC'24, Nashville, TN, May 2024, paper MOPG02, this conference.

[38] P. Xu *et al.*, "Mapping the stray magnetic field at the Relativistic Heavy Ion Collider tunnel", presented at IPAC'24, Nashville, TN, May 2024, paper WEPS65, this conference.

[39] H. Singh *et al.*, "Extended Jiles-Atherton hysteresis model to accurately predict fields in a Rapid Cycling Synchrotron dipole magnet", presented at IPAC'24, Nashville, TN, May 2024, paper TUPR43, this conference.

[40] H. Witte *et al.*, "Test magnet for the EIC Rapid Cycling Synchrotron", presented at IPAC'24, Nashville, TN, May 2024, paper TUPR45, this conference.

[41] Q. Wu *et al.*, "Self-correction coil for RCS dipole in Electron Ion Collider", presented at IPAC'24, Nashville, TN, May 2024, paper TUPR51, this conference.

[42] J. Biswas *et al.*, "Quest for an optimal spin-polarized electron source for the Electron Ion Collider", presented at IPAC'24, Nashville, TN, May 2024, paper MOPR79, this conference.

[43] E. Wang *et al.*, "DBR-SL-GaAs surface charge limit observation and suppressing for EIC high charge polarized source", presented at IPAC'24, Nashville, TN, May 2024, paper WEPC45, this conference.

[44] V. Ranjbar, "Polarization performance of a 3 GeV electron booster", presented at IPAC'24, Nashville, TN, May 2024, paper MOPG03, this conference.

[45] E. Wang *et al.*, "The design progress of a high charge, low energy spread polarized pre injector for Electron Ion Collider", presented at IPAC'24, Nashville, TN, May 2024, paper MOPC27, this conference.

[46] H. Witte *et al.*, "Progress on the design of the interaction region of the Electron-Ion Collider EIC", presented at IPAC'24, Nashville, TN, May 2024, paper MOPC75, this conference.

[47] B. Gamage *et al.*, "Status of the second interaction region for Electron Ion Collider", presented at IPAC'24, Nashville, TN, May 2024, paper MOPC97, this conference.

[48] H. Witte *et al.*, "Design of dipole magnets for luminosity pair spectrometer subsystem at the detectors of Electron Ion Collider", presented at IPAC'24, Nashville, TN, May 2024, paper TUPR46, this conference.

[49] V. Morozov *et al.*, "Correction of the detector solenoid effect in the hadron storage ring of the Electron-Ion Collider", presented at IPAC'24, Nashville, TN, May 2024, paper MOPC48, this conference.

[50] D. Xu *et al.*, "Assessing global crabbing scheme feasibility for Electron-Ion Collider", presented at IPAC'24, Nashville, TN, May 2024, paper MOPC77, this conference.

[51] V. Shmakova *et al.*, "Impact of the crab cavities on polarization in EIC", presented at IPAC'24, Nashville, TN, May 2024, paper MOPC71, this conference.

[52] S. De Silva *et al.*, "Tolerance calculations for 197 MHz prototype crab cavity for EIC", presented at IPAC'24, Nashville, TN, May 2024, paper WEPS36, this conference.

[53] B. Xiao *et al.*, "HOM power in the EIC crab cavity system", presented at IPAC'24, Nashville, TN, May 2024, paper WEPS12, this conference.

[54] C. Liu *et al.*, "Study of orbital effects on EIC detector synchrotron radiation background", presented at IPAC'24, Nashville, TN, May 2024, paper MOPC04, this conference.

[55] J. Qiang *et al.*, "Combined wakefield and beam-beam effects in the EIC design", presented at IPAC'24, Nashville, TN, May 2024, paper THPC73, this conference.

[56] A. Blednykh *et al.*, "EIC impedance and beam dynamics", presented at IPAC'24, Nashville, TN, May 2024, paper THPC45, this conference.

[57] Y. Hao *et al.*, "Haissinski distribution of electron beam in Electron-Ion Collider and its impact on the hadron beam", presented at IPAC'24, Nashville, TN, May 2024, paper MOPC92, this conference.

[58] Y. Luo *et al.*, "Weak-strong beam-beam simulation with crab cavity noises for the hadron storage ring of the Electron-Ion Collider", presented at IPAC'24, Nashville, TN, May 2024, paper MOPC88, this conference.

[59] Y. Luo *et al.*, "Wide range tune scan for the hadron storage ring of the Electron-Ion Collider", presented at IPAC'24, Nashville, TN, May 2024, paper MOPC89, this conference.

[60] D. Xu *et al.*, "Advancing electron injection dynamics and mitigation approaches in the Electron-Ion Collider's swap-out injection scheme", presented at IPAC'24, Nashville, TN, May 2024, paper MOPC80, this conference.

[61] A.Blednykh *et al.*, "Beam commissioning of the EIC with detector", presented at IPAC'24, Nashville, TN, May 2024, paper MOPC66, this conference.