ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPA049

DESIGN STATUS OF THE ELECTRON-ION COLLIDER*

C. Montag†, E. C. Aschenauer, B. Bhandari, P. Baxevanis, J. S. Berg, W. Bergan, M. Blaskiewicz, A. Blednykh, Z. Conway, K. A. Drees, A. V. Fedotov, W. Fischer, C. Folz, D. Gassner, X. Gu, R. Gupta, K. Hamdi, Y. Hao, C. Hetzel, D. Holmes, H. Huang, J. Jamilkowski, D. Kayran, J. Kewisch, Y. Li, C. Liu, H. Lovelace III, Y. Luo, G. Mahler, D. Marx, F. Meot, M. Minty, S. Nayak, B. Parker, S. Peggs, B. Podobedov, V. Ptitsyn, V. H. Ranjbar, G. Robert-Demolaize, M. Sangroula, S. Seletskiy, K. S. Smith, S. Tepikian, R. Than, P. Thieberger, N. Tsoupas, J. Tuozzolo, S. Verdu-Andres, E. Wang, D. Weiss, F. J. Willeke, H. Witte, Q. Wu, D. Xu, W. Xu, A. Zaltsman,
Brookhaven National Laboratory, Upton, NY, USA,
S. Benson, E. Daly, K. Deitrick, B. R. Gamage, T. Michalski, S. Nagaitsev, E. Nissen, R. Rimmer, T. Satogata, A. Seryi, M. Wiseman, TJNAF, Newport News, USA,
V. Morozov, F. Lin, Oak Ridge National Laboratory, TN, USA
E. Gianfelice-Wendt, Fermi National Accelerator Laboratory, Batavia, IL, USA,
Y. Cai, Y. Nosochkov, G. Stupakov, M. Sullivan, SLAC, Menlo Park, CA, USA
G. Hoffstaetter, D. Sagan, M. G. Signorelli, J. Unger, Cornell University, Ithaca, NY, USA

Abstract

The Electron-Ion Collider is gearing up for "Critical Decision 2", the project baseline with defined scope, cost and schedule. Lattice designs are being finalized, and preliminary component design is being carried out. Beam dynamics studies such as dynamic aperture optimization, instability and polarization studies, and beam-beam simulations are continuing in parallel. We report on the latest developments and the overall status of the project, and present the plans for future activities.

OVERVIEW

The Electron-Ion Collider (EIC) will be built at Brookhaven National Laboratory in a partnership between BNL and TJNAF. The project utilizes the existing infrastructure of the Relativistic Heavy Ion Collider (RHIC) accelerator complex. The Hadron Storage Ring (HSR) consists of a mix of arcs of the two superconducting RHIC storage rings that need to undergo some necessary modifications to make them suitable for the HSR beams. An electron storage ring (ESR) will be added in the existing RHIC tunnel, where it will provide collisions with the hadron beams stored in the HSR. Electron and hadron beams will collide in up to two interaction regions (IRs), located in the IR6 and IR8 straight sections of RHIC that currently house the STAR and sPHENIX detectors, respectively. While only the interaction region and corresponding detector in IR6 are within the scope of the EIC, a second interaction region is highly desirable. Therefore, it is mandatory to demonstrate that the EIC is indeed capable of supporting two interaction regions, both in terms of geometric layout and beam dynamics.

The highest luminosity of $1.0 \cdot 10^{34}$ cm^{-2} sec^{-1} is reached with 10 GeV electrons colliding with 275 GeV protons, which corresponds to a center-of-mass energy of 105 GeV.Higher center-of-mass energies are achieved by increasing the electron energy. To limit the total synchrotron radiation losses to 10 MW, the electron beam intensity has to be reduced accordingly, resulting in a corresponding reduction in luminosity.

HADRON STORAGE RING

The hadron storage ring (HSR) consists of a mixture of the superconducting arcs of the existing RHIC facility, with some necessary modifications, both to the lattice and layout of the straight sections, and to technical systems [1, 2]. The new interaction region in the IR6 straight section requires lattice modifications that extend past the present transition jump quadrupoles in that area, thus requiring a different approach to transition crossing [3]. Dynamic aperture studies [4] are being carried out to ensure stable operation with sufficient beam lifetimes in the presence of the new interaction region as well as radial orbit shifts required to synchronize the electron and hadron beams over the entire hadron beam energy range [5]. To accommodate the large number of high intensity, short bunches, pre-coated, actively cooled beam screens will be inserted into the beam pipes. The copper coating of these sleeves will reduce the resistive wall heating to levels manageable by the cryogenic system, while an additional amorphous carbon coating will reduce the secondary electron yield to avoid electron cloud build-up. A dedicated probe [6] has been developed to survey the available aperture around the hadron ring to ensure safe insertion of the beam screens. The existing RHIC beam position monitors (BPMs) will need to be replaced by new button BPMs as a response to the higher beam current and shorter bunch length which would damage the existing system [7–9]. The collimation system will be relocated and upgraded with a momentum collimator to account for the more demanding background tolerances of the EIC detector. To facilitate the ramp and storage of polarized ^{3}He ions as well as to im-

* Work supported under Contract No. DE-SC0012704, Contract No. DE-AC05-06OR23177, Contract No. DE-AC05-00OR22725, and Contract No. DE-AC02-76SF00515 with the U.S. Department of Energy.
† montag@bnl.gov

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPA049

prove the polarization transmission for protons on the ramp, four additional Siberian snakes will be installed in the HSR, bringing the total number to six [10–12]. Spin tracking simulations have been performed to demonstrate the feasibility of accelerating polarized ^{3}He in this configuration [13]. The spin rotators around the interaction point will be relocated to accommodate the EIC interaction region [14]. While it is not in the EIC scope, a second interaction region [15] has been designed for installation in the IR8 straight section to ensure that the EIC can indeed support two interaction regions in the future, both in terms of geometric layout and beam dynamics.

ELECTRON STORAGE RING

The electron storage ring (ESR) is based on a regular FODO lattice structure with "super-bends" to enhance radiation damping at energies below 10 GeV [16]. In an effort to reduce cost, the existing quadrupoles, sextupoles and dual-plane dipole correctors of the Advanced Photon Source (APS) will be re-used throughout the arcs and most of the straight sections. Dipole magnets as well as a small number of special quadrupoles for installation in tight spaces are being designed. Dynamic aperture studies based on the measured multipoles of these magnets and realistic assumptions of the dipole field quality have been performed, and the minimum required dynamic aperture of 10σ in all three dimensions has been demonstrated [17–20]. Careful spin matching ensures polarization lifetimes that are sufficient to guarantee an average polarization of 70 percent, with single bunches replaced at a rate of one bunch per second [21, 22]. A particular challenge in this respect is the generation of a vertical emittance of about 3 nm (10 percent emittance coupling) without negatively affecting polarization [23]. Preliminary design of the components of the ESR is underway, like the SRF cavities [24], vacuum components [25], or collimators [26].

RAPID CYCLING SYNCHROTRON

Bunches circulating in the ESR are replaced on a regular basis in order to maintain high average polarization levels, using a rapid cycling synchrotron (RCS). The RCS needs to ramp over a wide energy range, from 400 MeV at injection to up to 18 GeV at extraction into the ESR. This raises concerns about the magnetic field quality at injection energy, when due to the low field values errors from remanent field effects can be particularly large. To raise the dipole field at injection to levels demonstrated at other facilities, each dipole is therefore split into three segments of equal length, and only the center dipole is powered to 190 G at injection while the two outer ones are at zero field after some de-gaussing process. Studies on the magnetic field tolerances are underway [27]. Bunches are supplied to the RCS from a 400 MeV S-band LINAC, operating at a repetition rate of 100 Hz. Four 7 nC LINAC bunches supplied by the gun [28, 29] are injected into the RCS and merged there into a single bunch at around 1 GeV [30].

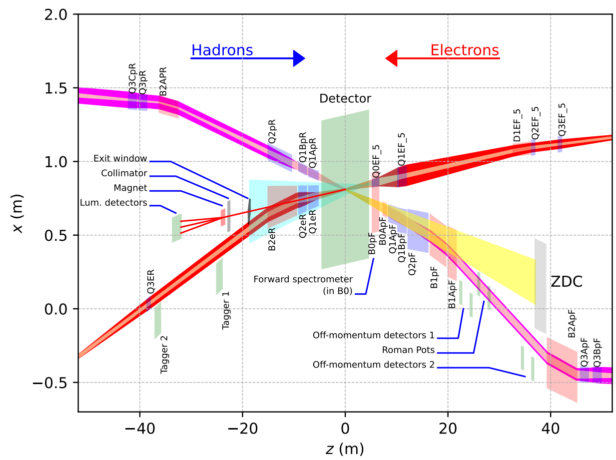

Figure 1: Layout of the EIC interaction region.

INTERACTION REGION

The interaction region (IR) [31] is based on a crossing angle of 25 mrad, compensated by crab cavities in both the electron and the hadron beam line [32–34], see Figure 1. Beams are focused to small cross sections with β-functions of typically 60 cm horizontally and 5 cm vertically, depending on the beam energies, by an arrangement of superconducting low-β quadrupoles around the interaction point. These magnets are placed about 5 m from the interaction point (IP) to provide sufficient space for the 9 m long detector. The outgoing, or "forward" hadron beam line is equipped with "Roman Pots" to detect scattered particles with transverse momenta as low as 200 MeV/c. To facilitate this, the forward hadron low-β quadrupoles need to have apertures that are much larger than required by the circulating beam alone. On the rear side of the detector, the electron low-β quadrupoles need large apertures to safely pass the synchrotron radiation photons generated by the upstream quadrupoles through the interaction region. These large apertures and the presence of the nearby beamlines for the electrons on the forward and the hadrons on the rear side, with their respective low-β magnets, make these magnets rather challenging [35]. The 2 T detector solenoid introduces significant coupling that needs to be compensated by skew quadrupoles that need to be integrated in the interaction region as well [31]. Placement of dipole correctors and beam position monitors is crucial to guide the beams as well as the synchrotron radiation fan safely through the interaction region [36, 37]

HADRON COOLING

To achieve the required design emittances of the hadron ring, a two-stage hadron cooling system is required. Hadron beams are first cooled by a bunched-beam electron cooler at injection energy to the normalized emittances required at store [38]. After ramping those beams to collision energy, these emittances are then maintained by a second cooler. This high energy cooler will be based either on microbunch

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPA049

coherent electron cooling [39, 40], or on bunched beam cooling by a high intensity racetrack ring [41–43]. A high intensity, low emittance electron gun for the hadron cooler is being designed and optimized [44–46].

BEAM DYNAMICS

Beam dynamics in the various accelerators that comprise the EIC have been extensively studied to ensure safe, successful operation of the facility [47]. Both weak-strong and strong-strong beam-beam simulations [48–50] have been carried out to study the effects of numerous imperfections on crab crossing, such as non-closure of the crab bump or transverse beam jitter [51–56]. The crab cavities themselves could have a negative impact on machine performance due to multipole field errors [57] or RF noise [58, 59], which needs to be studied carefully in order to determine the tolerances on these errors and to design the low level controls accordingly [60].

REFERENCES

[1] J. S. Berg *et al.,* "Lattice Design for the Hadron Storage Ring of the Electron-Ion Collider", presented at IPAC'23, Venice, Italy, May 2023, paper MOPL156, this conference.

[2] C. Liu *et al.,* "Lattice Optimization for Electron Ion Collider Hadron Storage Ring Injection", presented at IPAC'23, Venice, Italy, May 2023, paper MOPL008, this conference.

[3] H. Lovelace III *et al.,* "Transition Jump System of the Hadron Storage Ring of the Electron Ion Collider", presented at IPAC'23, Venice, Italy, May 2023, paper MOPA056, this conference.

[4] Y. Luo *et al.,* "Dynamic Aperture Evaluation of the EIC Hadron Storage Ring with Two Interaction Regions", presented at IPAC'23, Venice, Italy, May 2023, paper MOPA031, this conference.

[5] J. S. Berg *et al.,* "Synchronizing the Timing of the Electron and Hadron Storage Rings in the Electron-Ion Collider", presented at IPAC'23, Venice, Italy, May 2023, paper MOPL157, this conference.

[6] V. Ptitsyn *et al.,* "FELICIA – A probe to survey the RHIC magnet beampipe diameter for EIC beam screen insertion", presented at IPAC'23, Venice, Italy, May 2023, paper THPA184, this conference.

[7] D. Gassner *et al.,* "Design Status of the Electron-Ion Collider Beam Instrumentation", presented at IPAC'23, Venice, Italy, May 2023, paper THPL053, this conference.

[8] R. Michnoff *et al.,* "Beam Instrumentation Hardware Architecture for Upgrades at the BNL Collider-Accelerator Complex and the Future Electron Ion Collider", presented at IPAC'23, Venice, Italy, May 2023, paper THPL058, this conference.

[9] M. Sangroula *et al.,* "Design Study of button BPMs for the EIC Hadron Storage Ring", presented at IPAC'23, Venice, Italy, May 2023, paper THPL056, this conference.

[10] H. Huang *et al.,* "Strategy for Hadron Polarization in the Electron Ion Collider", presented at IPAC'23, Venice, Italy, May 2023, paper MOPL011, this conference.

[11] F. Meot *et al.,* "Multiple-Snake Schemes in the EIC Hadron Storage Ring", presented at IPAC'23, Venice, Italy, May 2023, paper MOPA026, this conference.

[12] F. Meot *et al.,* "Polarized bunch acceleration and store simulations in the EIC rings", presented at IPAC'23, Venice, Italy, May 2023, paper MOPA027, this conference.

[13] V. Ranjbar *et al.,* "Benchmarking Electron-Ion Collider's HSR HE3 polarization lifetime estimates against direct spin-orbit tracking", presented at IPAC'23, Venice, Italy, May 2023, paper MOPA034, this conference.

[14] K. Hock *et al.,* "An Overview of the Spin Rotator Configuration for Protons and Helions in the HSR", presented at IPAC'23, Venice, Italy, May 2023, paper MOPA030 this conference.

[15] D. Xu *et al.,* "Beam optics update for EIC HSR-IR2", presented at IPAC'23, Venice, Italy, May 2023, paper MOPA041, this conference.

[16] D. Marx *et al.,* "Designing the EIC Electron Storage Ring for Energies down to 5 GeV", presented at IPAC'23, Venice, Italy, May 2023, paper MOPA037, this conference.

[17] Y. Nosochkov *et al.,* "Dynamic Aperture Studies for the EIC Electron Storage Ring", presented at IPAC'23, Venice, Italy, May 2023, paper MOPA048, this conference.

[18] J. Unger *et al.,* "Interaction region effects on the EIC's Dynamic Aperture", presented at IPAC'23, Venice, Italy, May 2023, paper MOPA053, this conference.

[19] Y. Luo *et al.,* "Optimizing the Design Tunes of the Electron Storage Ring of the Electron-Ion Collider", presented at IPAC'23, Venice, Italy, May 2023, paper MOPA047, this conference.

[20] M. G. Signorelli *et al.,* "Nonlinear Coupling Resonances in the EIC Electron Storage Ring", presented at IPAC'23, Venice, Italy, May 2023, paper MOPA051, this conference.

[21] E. Gianfelice-Wendt, The polarization of the EIC electron beam", presented at XXIX Cracow Epiphany Conference, January 16-19, 2023, to be published in *Acta Physica Polonica B Proceedings Supplement*.

[22] M. G. Signorelli *et al.,* "Electron Polarization Preservation in the EIC", presented at IPAC'23, Venice, Italy, May 2023, paper MOPA052, this conference.

[23] F. Lin *et al.,* "Generation of Vertical Emittance through Transverse Coupling and its Impact on the Polarization in the EIC ESR", presented at IPAC'23, Venice, Italy, May 2023, paper MOPL087, this conference.

[24] J. Guo *et al.,* "Prototyping of the Electron Ion Collider Electron Storage Ring SRF cavity", presented at IPAC'23, Venice, Italy, May 2023, paper WEPA187, this conference.

[25] M. Sangroula *et al.,* "Localized Beam Induced Heating Analysis of the EIC Vacuum Chamber Components", `https://epaper.kek.jp/napac2022/papers/wepa85.pdf`

[26] M. Valette *et al.,* "Electron Storage Ring Collimation and Abort System design for the Electron Ion Collider", presented at IPAC'23, Venice, Italy, May 2023, paper MOPA050, this conference.

[27] V. Ranjbar *et al.,* "The Impact of Magnetic Errors on the Electron Ion Collider Rapid Cycling Synchrotron", presented at IPAC'23, Venice, Italy, May 2023, paper WEPL088, this conference.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPA049

[28] E. Wang *et al.,* “High voltage DC gun using Distributed Bragg Reflector Super Lattice GaAs Photocathode For EIC Polarized Electron Source”, presented at IPAC’23, Venice, Italy, May 2023, paper TUPA131, this conference.

[29] E. Wang *et al.,* “The design progress of a high charge, low energy spread polarized pre injector for electron ion collider”, presented at IPAC’23, Venice, Italy, May 2023, paper MOPL106, this conference.

[30] V. Ranjbar *et al.,* “Progress on the Electron Ion Collider’s RCS RF ramp development”, presented at IPAC’23, Venice, Italy, May 2023, paper MOPA035, this conference.

[31] J. S. Berg *et al.,* “Lattice Design for the Interaction Region of the Electron-Ion Collider”, presented at IPAC’23, Venice, Italy, May 2023, paper MOPL158, this conference.

[32] S. Da Silva *et al.,* “SRF cavities for crabbing at the Electron-Ion Collider”, presented at IPAC’23, Venice, Italy, May 2023, paper THYG1, this conference.

[33] B. Xiao *et al.,* “HOM power in the EIC crab cavity system”, presented at IPAC’23, Venice, Italy, May 2023, paper WEPA139, this conference.

[34] B. R. Gamage *et al.,*“Second interaction region design concept for the Electron Ion Collider”, presented at IPAC’23, Venice, Italy, May 2023, paper MOPA022, this conference.

[35] A. Zlobin *et al.,* “Large-aperture high-field Nb3Sn magnets for the 2nd EIC Interaction Region”, presented at IPAC’23, Venice, Italy, May 2023, paper WEPM063, this conference.

[36] C. Liu *et al.,* “Design and Simulation of EIC IR Orbit Control System”, presented at IPAC’23, Venice, Italy, May 2023, paper MOPL009, this conference.

[37] C. Liu *et al.,* “Study of Orbital Effects on EIC Detector Synchrotron Radiation Background”, presented at IPAC’23, Venice, Italy, May 2023, paper MOPL010, this conference.

[38] A. Fedotov, S. Benson et al., “Low-Energy Cooling for the Electron Ion Collider”, EIC-HDR-TN-012, 2020

[39] C. Gulliford *et al.,* “Design and Optimization of an ERL for Cooling EIC Hadron Beams”, presented at IPAC’23, Venice, Italy, May 2023, paper MOPA016, this conference.

[40] J. Qiang *et al.,* “Simulation of shot noise effects in the EIC strong hadron cooling accelerator using real number of electrons”, presented at IPAC’23, Venice, Italy, May 2023, paper WEPA041, this conference.

[41] H. Zhao et al., “Ring-based electron cooler for high energy beam cooling”, Phys Rev Acc and Beams 24, 043501 (2021)

[42] J. Kewisch *et al.,* “Optics for the EIC cooler based on an electron storage ring”, presented at IPAC’23, Venice, Italy, May 2023, paper MOPA043, this conference.

[43] S. Seletskiy *et al.,* “Parameters optimization for EIC Ring Cooler”, presented at IPAC’23, Venice, Italy, May 2023, paper TUPM021, this conference.

[44] W. Liu *et al.,* “The high voltage DC gun design progress for EIC strong hadron cooling”, presented at IPAC’23, Venice, Italy, May 2023, paper TUPA130, this conference.

[45] N. Wang *et al.,* “EIC Cooler Injector Space Charge Simulation Benchmarking”, presented at IPAC’23, Venice, Italy, May 2023, paper TUPL157, this conference.

[46] N. Wang *et al.,* “Optimization of cathode beam distributions at the EIC cooler”, presented at IPAC’23, Venice, Italy, May 2023, paper TUPL158, this conference.

[47] V. Ptitsyn *et al.,* “Accelerator physics challenges for EIC”, presented at IPAC’23, Venice, Italy, May 2023, paper WEZG1, this conference.

[48] D. Xu *et al.,* “Combining weak-strong and strong-strong simulation for EIC beam-beam study”, presented at IPAC’23, Venice, Italy, May 2023, paper MOPA042, this conference.

[49] Y. Hao *et al.,* “Haissinski distribution of electron beam in Electron-Ion Collider and its impact on the Hadron beam”, presented at IPAC’23, Venice, Italy, May 2023, paper MOPA032, this conference.

[50] H. Huang, “Analytical and numerical calculation of collider luminosity with crab dynamics”, presented at IPAC’23, Venice, Italy, May 2023, paper WEPA057, this conference.

[51] Y. Luo *et al.,* “Revisit the Effects of 10 Hz Orbit Oscillations in the Relativistic Heavy Ion Collider with Beam-beam Simulation”, presented at IPAC’23, Venice, Italy, May 2023, paper MOPA046, this conference.

[52] Y. Luo *et al.,* “Simulation Test of Various Crab Dispersion Closure Bumps for the Hadron Storage Ring of the Electron-Ion Collider”, presented at IPAC’23, Venice, Italy, May 2023, paper MOPA045, this conference.

[53] D. Xu *et al.,* “Closing crab dispersion by dispersive RF cavity in EIC HSR”, presented at IPAC’23, Venice, Italy, May 2023, paper MOPA040, this conference.

[54] D. Xu *et al.,* “Effect of electron orbit ripple on proton emittance growth in EIC”, presented at IPAC’23, Venice, Italy, May 2023, paper MOPA039, this conference.

[55] B. Podobedov *et al.,* “Eddy current shielding of the magnetic field ripple in the EIC Electron Storage Ring vacuum chambers”, presented at IPAC’23, Venice, Italy, May 2023, paper MOPL049, this conference.

[56] B. Podobedov *et al.,* “Transversely Driven Coherent Beam Oscillations in the EIC Electron Storage Ring”, presented at IPAC’23, Venice, Italy, May 2023, paper WEPL181, this conference.

[57] Q. Wu *et al.,* “EIC Crab Cavity Multipole Analysis and Their Effects on Dynamic Aperture”, presented at IPAC’23, Venice, Italy, May 2023, paper MOPL041, this conference.

[58] H. Huang *et al.,* “Quantifying Effects of Crab Cavity RF Phase Noise on Transverse Emittance in EIC-HSR”, presented at IPAC’23, Venice, Italy, May 2023, paper TUPM084, this conference.

[59] Y. Hao *et al.,* “Validation and countermeasures of vertical emittance growth due to crab cavity noise in a horizontal crab-crossing scheme”, presented at IPAC’23, Venice, Italy, May 2023, paper MOPA033, this conference.

[60] T. Mastoridis *et al.,* “EIC Crab Cavity LLRF Specifications”, presented at IPAC’23, Venice, Italy, May 2023, paper WEPM135, this conference.