ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-MOPCO17

DESIGN STATUS OF THE ELECTRON-ION COLLIDER BEAM INSTRUMENTATION*

D. M. Gassner†, B. Bacha, G. Bassi, J. Bellon, A. Blednykh, L. Flader, R. Hulsart, C. Hetzel, K. Matsushima, C. Liu, R. Michnoff, F. Micolon, M. Oh, M. Paniccia, I. Pinayev, A. Pramberger, J. Pomaro, M. Sangroula, E. Skordis, M. Wendt
Brookhaven National Laboratory, Upton, NY, USA

Abstract

The Electron Ion Collider (EIC) is being built at Brookhaven National Laboratory (BNL). The system design phase efforts are underway. In addition to upgrading the existing RHIC instrumentation for the EIC hadron storage ring, new electron accelerator subsystems will include a 750 MeV Linac, accumulator ring, rapid-cycling synchrotron, electron storage ring, and a hadron cooling facility. The scope of the instrumentation includes devices to measure beam position, loss, current, charge, tune, transverse and longitudinal profiles, emittance, and crabbing angles. A description of the planned instruments and the present design status will be presented.

INTRODUCTION

The Electron-Ion Collider, designed in a partnership between BNL and TJNAF, aims at delivering an electron-proton luminosity of 10^{34} $cm^{-1}s^{-1}$. 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. An electron injector facility, that includes a Rapid-Cycling Synchrotron (RCS) that serves as a polarized electron injector for the ESR will be built adjacent to the RHIC tunnel. Electrons and hadrons will be brought into collision in a dedicated interaction region in the IR6 straight section [1]. The EIC project has been separated into subprojects, the first subproject covers the Hadron Storage Ring and Electron Storage Ring. The plan is to begin the construction phase of the first subproject next year. Subsequent subproject construction start dates will happen later.

EIC BEAM INSTRUMENTATION ELECTRONICS HARDWARE

The existing Collider-Accelerator Department (C-AD) hadron injector facility will be utilized as the hadron injector for the EIC Hadron Storage Ring (HSR). Progress has been made designing upgraded beam instrumentation electronics for use at C-AD which will also be used for all the future EIC beam instrumentation systems. The new BNL designed custom architecture will utilize a general-purpose carrier board based on the Xilinx Zynq Ultrascale+ System-on-Chip (SoC) that will interface with a family of application specific daughter cards to satisfy the requirements for each system [2].

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

ELECTRON INJECTOR FACILITY INSTRUMENTATION

The electron injector facility design includes a 310 kV polarized gun feeding a 750 MeV S-Band Linac, followed by a 51 m accumulator ring, which feeds a 1.4 km rapid cycling synchrotron that can accelerate the polarized electrons to 5, 10, and 18 GeV for injection into the ESR. The beam diagnostics systems will provide measurements to ensure bunch charges up to 28 nC, with 23 ps bunch lengths with 85 % polarization and normalized H/V emittance of 196/18 microns, and an energy spread of 0.68×10^{-3} dp/p can be delivered to the ESR. The electron injector facility EIC subproject is presently in a conceptual design phase, along with the beam diagnostics [3].

The electron pre-injector diagnostics systems are designed to provide a complete characterization of the beam, this includes bunch position, trajectory, orbit, beam energy, energy spread, transverse beam size, emittance, longitudinal bunch size, and beam polarization. The diagnostics must accommodate bunch intensities <1 nC during beam commissioning.

Electron Pre-Injector Diagnostics

The 65 m long pre-injector section includes a 310 kV DC polarized gun, Wein filters (spin rotators), a 197 MHz buncher, two 1.3 GHz NCRF cavities, fourteen 3 m long S-band cavity Linac modules to accelerate up to 750 MeV, a Mott polarimeter, and three diagnostics beamlines. The beam parameters include accelerating bunches up to 1 nC with an energy spread of <0.5 %, polarization of >88 %, transverse normalized emittance of <75 mm-mrad, and with a repetition rate up to 30 Hz. The planned beam diagnostics planned are shown in Table 1.

Table 1: Electron Pre-Injector Diagnostics

Monitor	Beam Parameter	Qty
BPM	Beam position	21
BLM	Beam losses	5
FCT, WCM, ICT	Bunch charge	6
YAG Screens	Transverse profile	11
Bunch length	Longitudinal profile	1
Polarimeter	Polarization (Mott)	1

ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-MOPCO17

Electron Accumulator Ring and 750 MeV Beam Transport Diagnostics

The Beam Accumulator Ring's function is to accumulate 30 injections of 0.8 mm long, ~1 nC bunches, then extract a 20-70 mm long, 28 nC bunch for injection into the RCS. The beam diagnostics system will consist of components like those in the BNL NSLS VUV as well as NSLS-II systems developed for the transport lines. The planned beam diagnostics are shown in Table 2.

Table 2: Electron Accumulator Ring & 750 MeV Beam Transport Diagnostics

Monitor	Beam Parameter	Qty
BPM	Beam position	44
ICT	Bunch charge	6
YAG/OTR	Transverse profile	9
WCM	Longitudinal profile	2
Energy Slit	Beam energy spread	1
Faraday Cup	Dumped bunch charge	1

Rapid Cycling Synchrotron Ring and High Energy Beam Transport Diagnostics

The 1.4 km RCS ring will accelerate 85 % polarized electron bunches up to 28 nC, from 750 MeV to 5 and 10 GeV, over 75 ms, and accelerate bunches up to 11 nC to 18 GeV, over 100 ms. Acceleration to all 3 energies is planned to have 97 % polarization transmission. The circular RCS and extraction transport beampipe will be 36.3 mm diameter, made from 316L stainless steel. The synchrotron light monitors will be image light from separate dispersive and non-dispersive source points to improve energy spread measurements. See Table 3 for the planned diagnostics.

Table 3: Rapid Cycling Synchrotron Diagnostics

Monitor	Beam Parameter	Qty
BPM	Beam position	356
BBQ & kicker	Beam tune	2
BLM	Beam losses	~8
DCCT & FCT	Bunch current/charge	2
OTR Screens	Transverse profile	2
Synch Light	Longi & transv profile	2
Polarimeter	Polarization (Compton)	1
BBA (system)	Beam based alignment	1

The 133 m long RCS to ESR beam transport will use similar button BPMs as in the RCS. Several long segmented optical fiber (Cherenkov radiation) BLMs are planned along the transport beamline. OTR screen monitors in the non-dispersive section are used to measure the beam emittance, which can be challenging as the vertical beam size can be as small as 60 microns sigma. The planned beam diagnostics are shown in Table 4.

Table 4: RCS to ESR Transport Diagnostics

Monitor	Beam Parameter	Qty
BPM	Beam position	17
BLM (opt-fiber)	Beam loss	3
ICT, WCM	Bunch charge	2
OTR Screen	Transverse profile	2

ELECTRON STORAGE RING INSTRUMENTATION

The ESR is a 3.8 km warm ring designed to store 5, 10 and 18 GeV polarized electrons. At 5 and 10 GeV, 1,160 bunches spaced apart at ~10 ns, with 28 nC charge and 7 mm length will result in 2.5 Amps of beam current. At 18 GeV, 290 bunches spaced apart at ~40 ns with 10.1 nC and 9 mm length, will result in 227 mA of beam current. At 18 GeV, the stored beam current is set by the 10 MW synchrotron radiation power budget limitation.

The beam pipe is copper, the most common BPM aperture is octagonally shaped 36×80 mm, with a pair of 7 mm diameter molybdenum buttons spaced 22 mm apart, on the top and bottom of the chamber, in a planar configuration [4]. BPMs are planned to be installed near the vertically focusing quads. Dummy BPMs will be installed at the horizontally focusing quads, so there is an option to install buttons in the future if needed. Averaged position measurement resolutions down to 2 μm are required to ensure adequate beam-based alignment. To help preserve polarization and stabilize the beams at the interaction point, a slow orbit feedback system will be utilized to ensure an RMS orbit stability of less than 10 % of the RMS beam size at all locations in the storage ring. The planned beam diagnostics are shown in Table 5.

Table 5: Electron Storage Ring Diagnostics

Monitor	Beam Parameter	Qty
BPM	Beam position	220
BLM	Beam losses	50
DCCT & FCT	Bunch current/charge	2
OTR Screens	Transverse profile	2
Synch Light	Longi & transv profile	2
X-ray pinhole	Hi-res transv profile	1
Tune Monitor	Tune (H & V)	1
Trans BbB FB	Damp instabilities	1
Long BbB FB	Damp instabilities	1
Slow Orbit FB	Orbit corrections	1
Polarimeter	Polarization (Compton)	1
BBA (system)	Beam based alignment	1

HADRON BEAM INSTRUMENTATION

Hadron Injection Beam Transport Diagnostics

A new warm hadron injection beamline will be installed inside the RHIC tunnel to transport the beam from the

ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-MOPCO17

previous RHIC injection point in sector 6, to the new injection location for the yellow ring in sector 4. This new ~650 m transport will be an extension of the existing AGS to RHIC transfer beamline. Most of the instruments in the decommissioned RHIC injection X-arc (not needed for EIC) will be re-used in the new hadron injection beamline. The planned beam diagnostics are shown in Table 6.

Table 6: Hadron Injection Transport Diagnostics

Monitor	Beam Parameter	Qty
BPM	Beam position	41
BLM (ion chamber)	Beam loss	20
ICT	Bunch charge	2
Phosphor Screen	Transverse profile	2

Hadron Storage Ring Beam Diagnostics

The beam instrumentation in the HSR will primarily be upgraded versions of the existing similar systems presently in RHIC. Due to the factor of 3 increase in beam current (up to 1 A), and factor of 10 decrease in bunch length (to 6 cm), and operations with a large radial offset, planned at the HSR, the existing stripline BPMs will be shielded and new button BPMs will be installed nearby [5]. New SiO2 insulated BPM signal cables will be installed for all the cryogenic BPMs. The RHIC BLM ion chambers will be reused, and new diamond detector BLMs will be installed at strategic locations to measure bunch-by-bunch beam losses. See Table 7 for the planned IR Diagnostics.

Table 7: Hadron Storage Ring Diagnostics

Monitor	Beam Parameter	Qty
BPM	Beam position	279
BLM	Beam loss	350
IPM	H/V trans profile	2
DCCT	Beam current	1
WCM	Longi profile	2
Tune monitor	H & V tune	1
HF Schottky	Beam spectrum	1
LF Schottky	Beam spectrum	1
H-T monitor	Head-tail shape	1
Global Orb FB	Orbit corrections	1
BbB injection FB	Injection stability	1
Polarimeter (CNI/Hjet)	Polarization	2

Low Energy Cooling Beam Diagnostics

To meet the EIC luminosity goals when operating with proton beams, the vertical emittance of the HSR beam received from the AGS injector needs to be reduced from ~2 µm to 0.3-0.5 µm (rms normalized). This will be done at the HSR injection energy of 24 GeV, by cooling the hadron beam with a 13 MeV electron beam. The present design implements a stand-alone low energy electron cooling facility inside the existing RHIC tunnel at sector 2. The goal of cooling is to counteract the longitudinal and transverse emittance growth and maintain close to initial beam emittances. The experience gained developing the beam diagnostics used at the successful demonstration of low energy cooling at RHIC [6-8] will be leveraged for the HSR beam cooling. See Table 8 for the planned diagnostics.

Table 8: Low Energy Cooling Diagnostics

Monitor	Beam Parameter	Qty
BPM	Beam position	48
BLM	Beam loss	32
DCCT & ICT	Current & Charge	7
Faraday Cups	Current & Charge	3
YAG Screen	Transverse profile	13
Wires/slits	Beam emittance	2
Thermal	Beam pipe temperature	80

INTERACTION REGION INSTRUMENTATION

The EIC interaction region (IR) is defined as the electron and hadron beamlines on both sides of the interaction point (IP), ±~150 meters. The majority of BPMs will be like the ones in the respective storage rings. There will be some BPMs with a variety of aperture sizes needed close to the IP, and near crab cavities, spin rotators, etc. due to non-standard beam apertures. To maintain luminosity, a local IR orbit feedback system with up to 500 Hz correction bandwidth (3 dB) will be needed to meet the beam-beam physics stability specifications at full design currents. BPMs used in the IR feedback system will need to provide measurement resolutions comparable to 1 % of the vertical beam size when operating with high bunch charges, which is ~100 nm. See Table 9 for the planned IR Diagnostics.

Table 9: Interaction Region Diagnostics

Monitor	Beam Parameter	Qty
BPM	Beam position	47
BLM	Beam loss	50
Orbit FB at IP	Optimize luminosity	2
Crab Monitor	Crab tilt measurement	1

CONCLUSION

Significant progress has been made on the overall design of the beam instrumentation systems planned for the EIC. The most advanced design maturity has been made on the ESR and HSR instrumentation systems, as these are included in the initial phase of the project. Key diagnostics challenges include achieving sub µm-level BPM resolution with stable two-beam IR orbit control, reliable tune/instability measurements and control during the fast RCS ramps. Having both storage rings in the same tunnel will result in all components being exposed to the high synchrotron radiation environment. This presents a challenge to the BLM system, and close attention needs to be given to the protection of instrumentation around the ring and at the interaction region.

ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-MOPCO17

REFERENCES

[1] C. Montag *et al.*, “The EIC accelerator: design highlights and project status”, in *Proc. IPAC'24*, Nashville, TN, USA, May 2024, pp. 214-217. doi:10.18429/JACoW-IPAC2024-MOPC67

[2] R. Michnoff *et al.*, “Beam Instrumentation Hardware Architecture for Upgrades at the BNL Collider-Accelerator Complex and the Future Electron-Ion Collider”, in *Proc. IBIC23*, Saskatoon, Canada, Sep. 2023, pp.308-311. doi.org/10.18429/JACoW-IBIC2023-WE2C03

[3] S. Peggs and T Satogata, Eds., “EIC Preliminary Design Report 2025”, unpublished draft, Sep. 2025.

[4] M. Sangroula *et al.*, "Design of a BPM pick-up for the EIC electron storage ring", in *Proc. NAPAC’25*, Sacramento, CA, USA, Aug. 2025, pp. 163-166. doi:10.18429/JACoW-NAPAC2025-MOP052

[5] F. Micolon *et al.*, “Status of the EIC HSR Cold BPM Mechanical Design and Integration”, presented at IBIC’25, Liverpool, UK, Sep. 2025, paper WEPMO21, this conference.

[6] D. M. Gassner *et al.*, “Instrumentation for the Proposed Low Energy RHIC Electron Cooling Project”, in *Proc. IBIC'13*, Oxford, UK, Sep. 2013, paper TUPF24, pp. 561-564.

[7] T. A. Miller *et al.*, “Overview of the Beam Instrumentation and Commissioning Results from the BNL Low Energy RHIC Electron Cooling Facility”, in *Proc. IBIC'19*, Malmö, Sweden, Sep. 2019, pp. 14-21. doi:10.18429/JACoW-IBIC2019-MOBO01

[8] S. Seletskiy *et al.*, “Operational Experience with Machine Protection System for High Current, High Brightness Accelerator”, presented at IBIC’25, Liverpool, UK, Sep. 2025, paper MOPMO25, this conference.