UPDATE ON INJECTION OPTICS INTO THE ELECTRON ION COLLIDER HADRON STORAGE RING*

H. Lovelace III†, V. Schoefer‡, J. S. Berg, E. Link, Ch. Liu, H. Oh, V. Ptitsyn, N. Tsoupas
Brookhaven National Laboratory, Upton, NY, United States

Abstract

The Electron Ion Collider Hadron Storage Ring (HSR) will be built on the campus of Brookhaven National Laboratory. The injection into the HSR will be vastly different from what is currently performed in the Relativistic Heavy Ion Collider. This paper will highlight the differences from RHIC, present the injection optics, and layout of the current design.

INTRODUCTION

The Electron Ion Collider (EIC) [1, 2] is currently being built on the campus of Brookhaven National Laboratory in the existing Relativistic Heavy Ion Collider (RHIC) [3] tunnel. The proton and heavy ion beams will circulate counterclockwise through the former RHIC yellow ring. The arcs of the RHIC lattice will be reused as the Hadron Storage Ring (HSR) arcs. The straight sections, with the exception of the experimental interaction region and the electron cooling section as a future upgrade, will keep the standard RHIC layout with the triplet optics of RHIC. The only changes to the the lattice geometry within the straight sections are the removal of the DX magnets which were the final bend into collisions for RHIC. The experimental hall, which houses the electron-Proton/Ion Collider (ePIC) detector, is upstream of the injection region in the denominated 6 o'clock region [4]. Upstream of the ePIC experimental hall is the 8 o'clock region where the Superconducting Radio Frequency (SRF) 591 MeV cavities reside. The 10 o'clock region is the dump location. The 12 o'clock region is designed with the ambition of a second detector possibly placed in the region as a future upgrade. The 2 o'clock region is the location of the hadron cooling system future upgrade where the injected beam will be pre-cooled prior to acceleration and cooled again, during the store.

INJECTION REGION LAYOUT

The layout of the injection region is shown in Fig. 2. The beam enters the HSR from the newly designed Alternating Gradient Synchrotron (AGS) to HSR (AtH) transfer line [5], through the two split DC current septa and an induction septum with a 15 mrad bend and a wall thickness of 4.9 mm. The beam is accelerated through the four 24.6 MHz normal conducting cavities. The eight 197 MHz normal conducting cavities are used at store. The 49.2 MHz cavities are split with two cavities immediately downstream of the 197 MHz system and the third cavity downstream of the triplet. The pair of warm dipoles follow with the 98.4 MHz system composed of 4 normal conducting cavities placed immediately after. The 49.2 MHz and the 98.4 MHz system are used for bunch splitting.

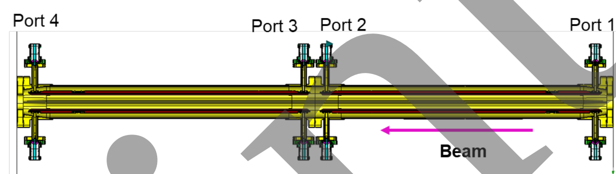

Figure 1: A simplified schematic of the two cell stripline injection kicker design

The 20 injection kickers, which have been updated from the previous discussions [6, 7] for a more compact design, are located ~65 m away from the from the induction septum. Figure 1 is a simplified schematic of the stripline kicker where each kicker module has two cells. A set of legacy triplet quadrupole magnets follows the injection kickers. The polarimetry instrumentation-proton-carbon (pC) coulomb nuclear interference (CNI) polarimeters [8], the helium-3 polarimeter [9, 10], and the hydrogen jet polarimeter (H-jet) [11]-is located directly downstream. The two plane pC polarimeter measures the instantaneous hadron beam polarization in the vertical and horizontal plane by rotating a thin carbon ribbon target through the accelerated beam. The jets measure the absolute polarization of the stored beam. Forward taggers are needed to reject the breakup products produced by the collision of the $^3He^{+2}$ with the jet beam. The dipoles downstream of the jets are then used to separate the protons, deuterons, and neutrons.

Between the warm dipoles used to separate the particles from the byproducts of the beam/jet collisions and the taggers is a longitudinal stochastic cooling pickup and the transverse stochastic cooling kickers. The stochastic cooling transversely cools the hadron beam by applying a RF kick to the off momentum particles based on the pickup signal amplified and processed [12,13]. Downstream of the taggers is a helical dipole snake [14], which is used to rotate the spin vector of the particles 180° vertically.

LATTICE OPTICS

Injection

Figure 3 shows a comparison between the injection optics and the pre-ramp optics of the injection region. The asymmetric injection optics are driven by the placement of the kicker in comparison to the septum and the asymmetry of dipole placement in comparison to the triplet magnets. The

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy.
† hlovelace@bnl.gov
‡ schoefer@bnl.gov

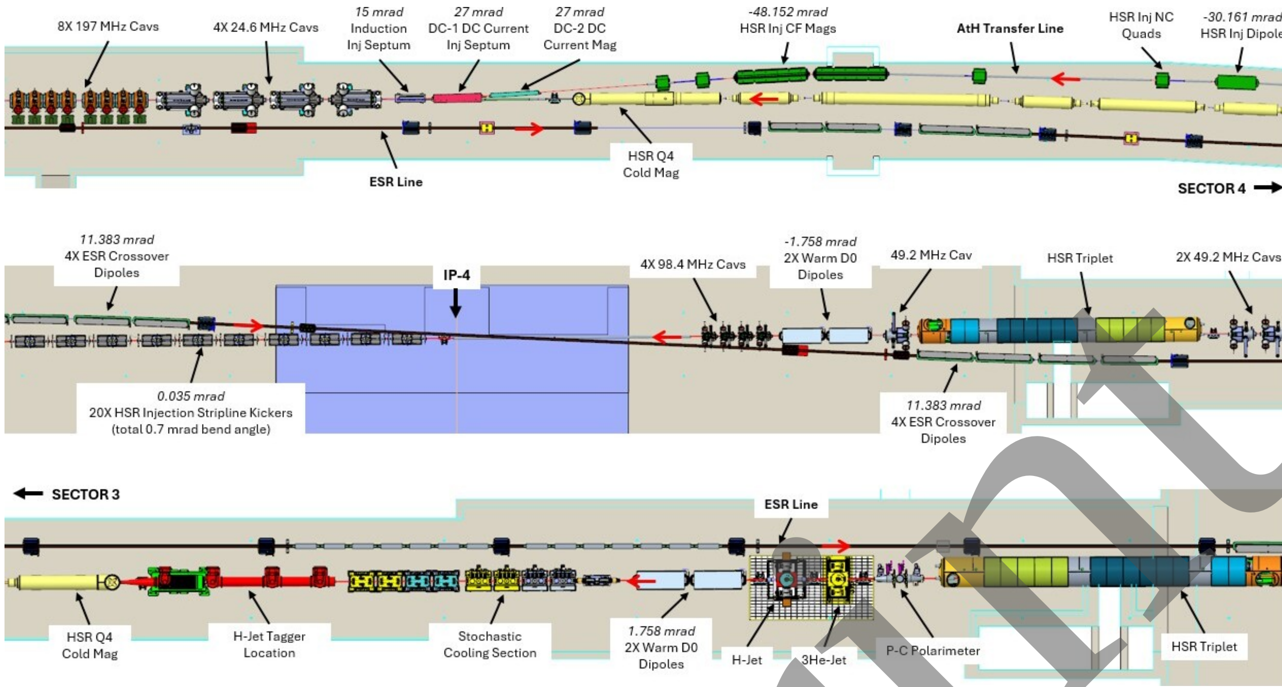

Figure 2: The plan view layout of the injection region. The top level is upstream of the injection kickers. The second level is the center in the kicker region. The third level is the polarimetry region.

kickers place the injected beam onto the closed orbit. To optimize to the minimal kick angle while maximizing the amplitude at the septum, the formula

$$\Delta x = \theta\sqrt{\beta_{x,septum}\beta_{x,kicker}}\cdot\sin(\phi_{x,septum}-\phi_{x,kicker}) \quad (1)$$

is used, where the horizontal Twiss function, β, is optimized at the exit end of the induction septum and the center of the kicker assembly with a deflection angle, θ = 0.7 mrad, which is within the maximum voltage limit of the kicker. The difference in horizontal phase advance, ϕ, between the induction septum and the kicker assembly is forced to be near $\pi/2$ to maximize displacement at the septum. Table 1 shows the displacement of the beam at the septum for various deflection angles.

Table 1: Kicker Strength and Separation at Septum for Various Kick Angles

Angle [mrad]	Strength [mTm]	Separation at Septum [mm]
0.6	2.43	0.461
0.7	2.84	6.862
0.8	3.24	13.264
0.9	3.65	19.666
1	4.06	26.067

Aperture Concerns

Figure 4 is of the injected Au^{+79} beam with an unnormalized emittance of 150 nm and the circulating beam with an unnormalized emittance of 200 nm. The circulating beam emittance reflects the intrabeam scattering growth after approximately 10 minutes. In the figure, the injected beam

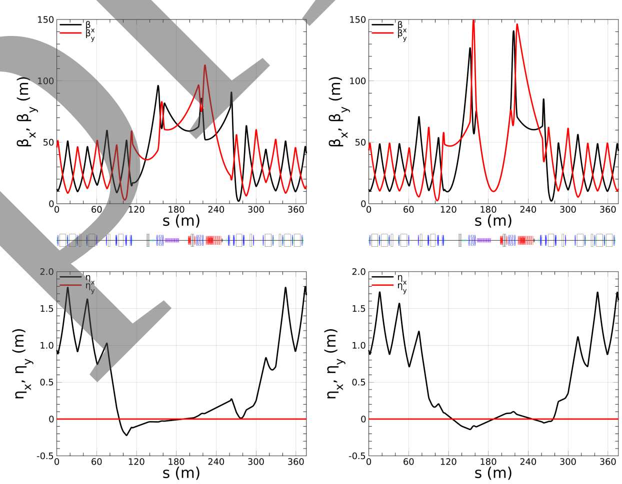

Figure 3: The injection and pre-ramp optics, left to right, respectively. Top: β-functions, middle:layout, and bottom: dispersion. The optics after injection smoothly ramps into the pre-ramp optics to prevent the shunt power supply currents exceeding current thesholds.

is deflected onto the closed orbit with a deflection angle of 0.7 mrad. The separation at the septum between the 5σ injected beam and the 6σ circulating beam is 6.862 mm. At the triplet, the 3 quadrupoles (blue xbox shapes) between the 49.2 MHz bunch splitting cavities (red xbox shapes) in Fig. 4, the focusing middle quadrupole deflects the beam horizontally placing the 5σ near quadrupole aperture with a clearance of 7 mm between the 5σ beam envelope and the vacuum chamber wall. The aperture of the quadrupole with the beam screen, used to reduce resistive-wall heating and to suppress e-clouds [15], is 105 mm for the major axis of the ellipse. Increases to the deflection angle, if not performed carefully, will cause beam scraping on the triplet quadrupole.

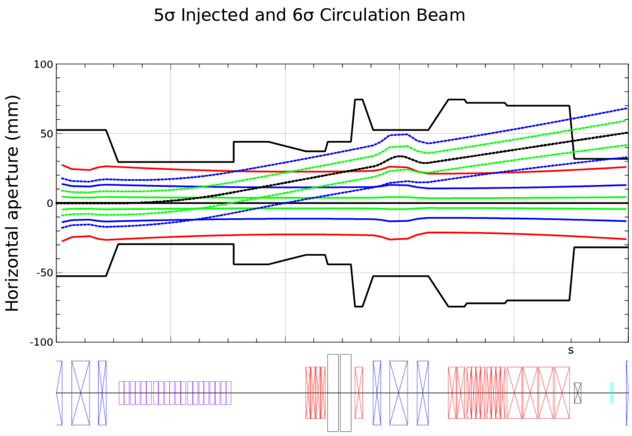

Figure 4: A schematic of injection into the HSR with a simplified aperture model. The injected beam envelope (blue dashed) is 5σ and the 6σ circulating beam envelope (red) both fit comfortably with the apertures of the beam pipe. The black curves, dashed and straight, are the injected beam trajectory and closed orbit, respectively. The black xbox on the right-hand side of the figure is the end of the injection septa. The red xbox indicates a normal conducting RF cavity, the blue xbox indicates a quadrupole, and the black box a dipole.

SUMMARY

The layout of the injection region of the HSR is presented. The polarimetry, RF, stochastic cooling, and injection located in the region forces the warm dipole layout asymmetry in the region. The injection optics allows for reduction of cost by preserving the RHIC power supply shunting scheme and accommodating the quadrupole triplet layout of the lattice. The beam screen inserted into the beam vacuum chamber reduces the aperture of the superconducting magnets limits range of the injection kicker deflection angle due to possible scraping.

ACKNOWLEDGEMENTS

We thank M. Sangroula, the EIC experimental, polarimetry, stochastic cooling, and RF groups for their continued patience in optimizing the design of the injection region.

REFERENCES

[1] EIC Collaboration, "Electron-Ion Collider at Brookhaven National Laboratory Conceptual Design Report", Brookhaven National Laboratory, Upton, NY, Rep. BNL-221006-2021-RPP, Feb. 2021. doi:10.2172/1765663

[2] C. Montag *et al.*, "Design status of the Electron-Ion Collider", in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 136–139. doi:10.18429/JACoW-IPAC2023-MOPA049

[3] RHIC: relativistic hadron ion collider configuration manual, Nov. 2006, https://www.bnl.gov/cad/accelerator/docs/pdf/rhicconfmanual.pdf

[4] J. Berg, R. Palmer, and H. Witte, "Lattice design for the interaction region of the electron-ion collider", in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 909–912, Sep. 2023. doi:10.18429/JACoW-IPAC2023-MOPL158

[5] H. Oh *et al.*, "Electron-Ion Collider (EIC) Hadron Storage Ring (HSR) Injection Transport Beamline (Y-Line Ext.) Lattice Design and Magnet Parameters", Brookhaven National Laboratory (BNL), Upton, NY, USA, Rep. BNL–228940-2025-TECH, Sep. 2025. doi:10.2172/2589365

[6] MP. Sangroula *et al.*, "Optimization of the Hadron Ring Stripline Injection Kicker for the EIC", in *Proc. IPAC'21*, Campinas, SP, Brazil, May 2021, pp. 3073–3076. doi:10.18429/JACoW-IPAC2021-WEPAB193

[7] H. Lovelace III *et al.*, "Lattice optimization for Electron Ion Collider Hadron storage ring injection", in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 519–522. doi:10.18429/JACoW-IPAC2023-MOPL008

[8] H. Huang and K. Kurita, "Fiddling carbon strings with polarized proton beams", *AIP Conf. Proc.*, vol. 868, no. 1, pp. 3–21, Nov. 2006. doi:10.1063/1.2401392

[9] Poblaguev, Andrei A., "Polarization Measurements of $p^\uparrow$ and $^3He^\uparrow$ Beams at RHIC and Future EIC Using the Polarized Atomic Hydrogen Gas Jet Target", *Universe*, vol. 10, no. 1, Jan. 2024. doi:10.3390/universe10010032

[10] F. Rathmann *et al.*, "Eliminating Beam-induced Depolarizing Effects in the Hydrogen Jet Target for High-precision Proton Beam Polarimetry at the Electron-Ion Collider", *Phys. Rev. Accel. Beams*, vol. 29, no. 2, p. 021001, 2026. doi:10.1103/8nh5-l63q

[11] A. Zelenski *et al.*, "Absolute Polarized H-jet Polarimeter Development, for RHIC", *Nucl. Instrum. Methods Phys. Res. A*, vol. 536, no. 3, pp. 248–254, 2005. doi:10.1016/j.nima.2004.08.080

[12] R. B. Palmer, "Stochastic Cooling in General and Its Application to $\bar{p}$ Storage in Particular", Brookhaven National Laboratory, Upton, NY, USA, Rep. BNL-18395, Oct. 1973. doi:10.2172/4374976

[13] M. Blaskiewicz, J. M. Brennan, and F. Severino, "Operational stochastic cooling in the relativistic heavy-ion collider", *Phys. Rev. Lett.*, vol. 100, no. 17, p. 174802, May 2008. doi:10.1103/PhysRevLett.100.174802

[14] W. W. MacKay, "Superconducting Helical Snake Magnets: Construction and Measurements", in *Proc. Particle Accelerator Conference 1999*, New York, NY, USA, Mar.–Apr. 1999, pp. 3179–3181. https://www.osti.gov/biblio/14642

[15] S. Verdú-Andrés *et al.*, "A Beam Screen to Prepare the RHIC Vacuum Chamber for EIC Hadron Beams: Conceptual Design and Requirements", in *Proceedings of the 12th International Particle Accelerator Conference (IPAC'21)*, Campinas, SP, Brazil, May 2021, pp. 366–369. doi:10.18429/JACoW-IPAC2021-MOPAB112