BNL-224528-2023-COPA

LATTICE DESIGN FOR THE HADRON STORAGE RING OF THE ELECTRON-ION COLLIDER

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Submitted to the 14th International Particle Accelerator (IPAC23) Conference
to be held at Venice, Italy
May 07 - 12, 2023

Electron-Ion Collider
Brookhaven National Laboratory

U.S. Department of Energy
USDOE Office of Science (SC), Nuclear Physics (NP) (SC-26)

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LATTICE DESIGN FOR THE HADRON STORAGE RING OF THE ELECTRON-ION COLLIDER*

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Abstract

The electron-ion collider will utilize a major portion of the existing RHIC rings for its hadron storage ring (HSR). This paper describes the lattice design of the HSR. Presently, RHIC consists of two rings, each of which contains 6 straight sections, and between those straights are arcs, each consisting of 11 FODO cells. The HSR uses 7 of the existing RHIC arcs which are unmodified, other than powering changes to allow the beam to travel opposite to its direction in RHIC in selected arcs. We select the arc in one sextant to keep the orbit period of the HSR the same as that of the new electron storage ring, depending on whether we are operating at hadron energies around 41 GeV/u or in the range of 100 GeV/u to 275 GeV/u. We describe the purpose and lattice design of the 6 straight sections of the HSR.

INTRODUCTION

The hadron storage ring (HSR) of the Electron-Ion Collider (EIC) must circulate hadron beams with an energy range from 41 GeV/u to 275 GeV/u. It is a modification of the existing RHIC rings. RHIC consists of two hadron rings, denoted yellow and blue. Each ring has 6 arcs and 6 insertions (Fig. 1), the insertions (IRs) being designated by their positions on a clock (IR12, IR2, etc.). Each ring is 3-fold symmetric, with arcs alternating between inner and outer, such that in locations where one ring has an inner arc, the other has an outer arc. Both rings are identical but have particles circulating in opposite directions. Each insertion has antisymmetric focusing, such that if one side of the insertion has a focusing quadrupole, the other side has a defocusing quadrupole.

The HSR will retain the arcs from RHIC, but will modify the insertions. For higher-velocity particles (100–275 GeV/u), outer arcs will be used in 5, 9, and 11 o'clock regions, with inner arcs used in the remaining regions. Since the velocity of electrons in the electron storage ring (ESR) is essentially independent of energy, the velocity difference over the 100-275 GeV/u energy range must be compensated by moving the beam radially in the arcs [1]. For 41 GeV/u, the velocity difference cannot be compensated simply by shifting the orbit in the pipe, so instead we use an inner arc

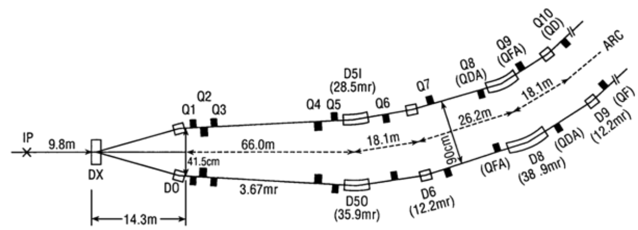

Figure 1: A RHIC half-insertion [3].

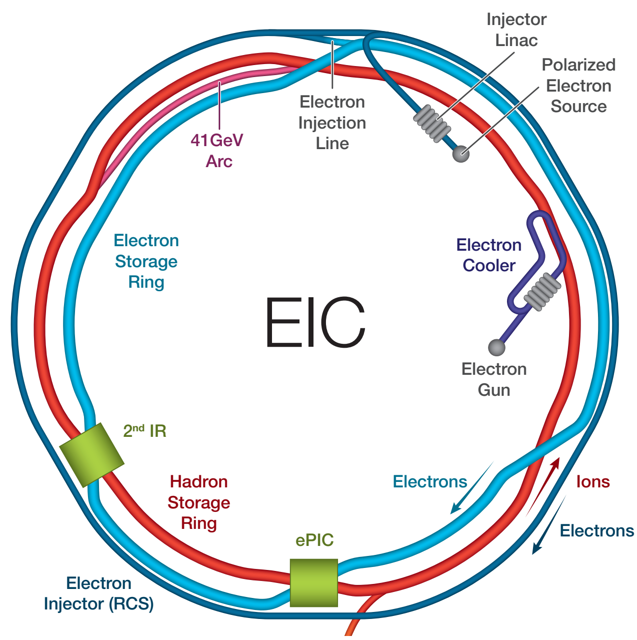

Figure 2: EIC overview. IR12 is at the top of the diagram.

in the 11 o'clock region (Fig. 2). The injected beam enters the tunnel near IR6, but because there is no free space for injection there, the beam is transported in the inner 5 o'clock arc to IR4 where injection occurs. The hadron beam travels in the counter-clockwise direction, in the same direction as in RHIC for the 3, 5, 7, and 9 o'clock RHIC arcs used in the HSR, as well as for the arc used at 11 o'clock for 41 GeV/u. The 1 o'clock arc, and the 11 o'clock arc used for higher energies in the HSR, are using magnets where in RHIC the beam would have been traveling in the opposite direction, and so dipole and quadrupole polarities will need to be reversed. While one might avoid the quadurpole polarity reversal by changing the focusing symmetry in the IRs, this not favorable because the configuration of correctors, transition jump quadrupoles [2], and skew quadrupoles would then be far from optimal.

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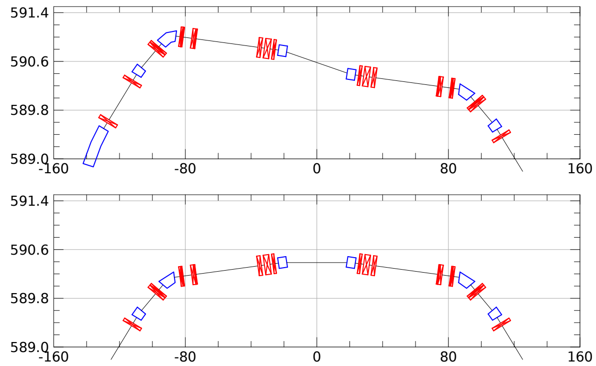

Figure 3: IR12 geometric configurations. Top: high-energy 11 o'clock arc. Bottom: 41 GeV/u 11 o'clock arc. Blue boxes are dipoles, central two dipoles are the new warm dipoles.

The IRs are utilized as follows:

- The detector will be in IR6 [4].
- At a later time, a second detector will be installed in IR8 [5]. Before then, IR8 will be nearly identical RHIC.
- IR10 will contain superconducting 591 MHz cavities for bunching and storage, the beam dump, and will allow switching beams between the two 11 o'clock arcs depending on the beam energy [6].
- IR12 will perform collimation, and will also allow switching beams between the two 11 o'clock arcs [7].
- The hadron beams will be cooled in IR2 [8]. This works best if there are inner RHIC arcs on both sides of this IR, driving our choice to switch arcs at 11 o'clock for adjusting path length.
- Injection occurs in IR4. IR4 also contains warm cavities used for acceleration, bunch splitting, and bunch compression, as well as instrumentation for polarimetry [9].

RHIC-LIKE INSERTIONS

Several IRs are RHIC-like: IRs 10 and 12, the non-colliding IR8 configuration, and to a lesser extent IR4. They are RHIC-like in the sense that they contain all magnets from the RHIC IRs shown in Fig. 1, with the exception of the DX and D0 dipoles. These dipoles will be replaced by 6 m long warm dipoles, placed near where the D0 diopoles are. In IRs 10 and 12, the beam will either cross from an outer to an inner arc, as in RHIC, or will go straight across, depending on which arc is being used in the 11 o'clock arc. This configuration of IRs 10 and 12 is an update from that given in [6, 7], see Fig. 3 to see the IR12 layout for the two configurations. When the beam goes straight across, the focusing configuration is symmetric (identical focusing/defocusing polarity on both sides), rather than anti-symmetric like in RHIC. In those IRs, only 2 warm dipoles will be used, and will be moved to the appropriate locations and re-oriented when the configuration of the 11 o'clock arc changes. In the 4 o'clock arc, the counter-clockwise warm dipole will be

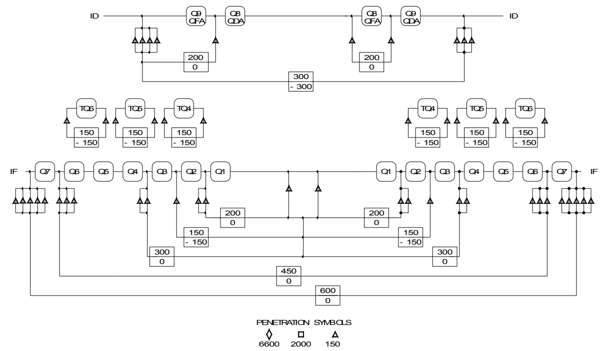

Figure 4: RHIC nested power supply scheme for the IR quadrupoles [3].

instead placed between Q3 and Q4 to assist with polarimetry layout [9].

Rather than individually powering magnets in the IRs, RHIC uses the nested power supply scheme shown in Fig. 4. The IR4 and IR10 configurations are slightly more flexible than this. In the RHIC-like IRs, we will retain this power supply configuration for the quadrupoles. The lattice files compute all RHIC-like IR quadrupole gradients from the power supply currents.

SNAKE CONFIGURATION

Siberian snakes will be used in the HSR to avoid spin resonance crossing during acceleration [10]. To enable polarization for all configurations, in particular ^{3}He, we will require 6 snakes. Particles must bend through an equal angle with spin up and spin down, and each snake switches the direction of the spin. A RHIC snake fits in the length between Q7 and Q8 (see Fig. 1) in a standard RHIC IR; our standard location for a snake will be in that slot on the counter-clockwise side of an IR. Ideally we would do this in every IR. Unfortunately, geometric constraints in a colliding IR8 [5] prevent that location from being usable. Instead, the optimal location would be as close to the arc on the clockwise side of IR8 as possible, likely at the angle of Q9 (see Fig. 1). This would require the snake in IR2 to be at that same angle. But for the initial RHIC-like IR8, we do not wish to modify it to place the Snake at that location (since the existing straight near Q9 is not long enough for a RHIC snake), so the snake would need to be at the Q7-Q8 angle as in the other IRs. This would require the snake in IR2 to be at the corresponding angle, and there would not be sufficient space to do so in IR2 if it is configured symmetrically.

The solution to this is to configure IR2 asymmetrically, with a drifts long enough for a snake at the Q9 angle on the clockwise side and the Q7-Q8 angle on the counter-clockwise side [8]. The corresponding snake configurations are shown in Fig. 5. Allowing IR2 to be asymmetric also improves the dipole configuration and aperture usage, since the RHIC dipoles can be used at their design currents and angles.

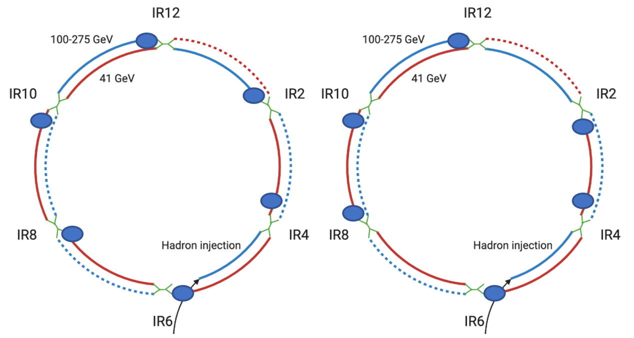

Figure 5: HSR snake configurations. Left: RHIC-like IR8. Right: colliding IR8.

MATCHING AND TUNING

The process of setting the ring tune is to create a function that maps arc quadrupole currents to the tune. This is done by setting the arc quadrupole currents, individually matching each IR to to the arc cells, then computing the ring tune. A systematic matching process is developed for each IR, so that this function is well-defined. In the case of the RHIC-like IRs, the beta functions at the center are somewhat arbitrarily chosen to be 5 m (since that is near the middle of the range of capabilities for a RHIC IR [11]) and at a minimum, reasonable choices are made regarding dispersion, and remaining degrees of freedom to achieve a systematic solution are chosen so that the power supplies that are closest to their limits are all equidistant in current from those limits. Fractional tunes are chosen based on beam-beam simulation results [12], and the horizontal and vertical tunes should have different integer components. The tunes used for 275 GeV protons are (28.228,27.210). Increasing the quadrupole currents will not increase the machine tune without limit; the ring tunes reach a maximum as the arc tunes increase, because the increase in the arc phase advance is compensated by a reduction in the phase advance in the IRs.

For transition crossing, these tunes result in vertical phase advance in the arc that is lower than desired [2]. We will investigate raising the arc phase advance, either by finding a different set of solutions for the IR matches, or possibly by allowing the global tune to drop as the vertical arc phase advance increases.

REFERENCES

[1] S. Peggs *et al.*, "Large Radial Shifts in the EIC Hadron Storage Ring," in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 1443–1446. doi:10.18429/JACoW-IPAC2021-TUPAB042

[2] H. Lovelace III, J. S. Berg, S. Polizzo, S. Peggs, V. Ptitsyn, and G. Robert-Demolaize, "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.

[3] *RHIC Configuration Manual*, called the RHIC Design Manual on the website, 2006. https://www.bnl.gov/cad/accelerator/

[4] J. S. Berg, R. Palmer, and H. Witte, "Lattice Design for the Interaction Region of the Electron-Ion Collider," presented at IPAC'23, Venice, Italy, May 2023, paper MOPL158, this conference.

[5] B. R. Gamage *et al.*, "Design Concept for a Second Interaction Region for the Electron-Ion Collider," in *Proc. IPAC'22*, Bangkok, Thailand, 2022, pp. 564–567. doi:10.18429/JACoW-IPAC2022-MOPOTK046

[6] H. Lovelace III *et al.*, "The Electron-Ion Collider Hadron Storage Ring 10 O'clock Switchyard Design," in *Proc. IPAC'22*, Bangkok, Thailand, 2022, pp. 2071–2073. doi:10.18429/JACoW-IPAC2022-WEPOTK015

[7] G. Robert-Demolaize *et al.*, "Layout of the 12 O'clock Collimation Straight Section for the EIC Hadron Storage Ring," in *Proc. IPAC'22*, Bangkok, Thailand, 2022, pp. 2142–2145. doi:10.18429/JACoW-IPAC2022-WEPOTK035

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

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

[10] V. Ptitsyn and J. S. Berg, "EIC Hadron Spin Rotators," in *Proc. IPAC'22*, Bangkok, Thailand, 2022, pp. 1734–1736. doi:10.18429/JACoW-IPAC2022-WEPOST020

[11] S. Tepikian, V. Mane, and S. Peggs, "Tuning Curves," Brookhaven National Laboratory, Tech. Rep. BNL-102134-2013-IR, 1994, origninal note RHIC/AP/23. doi:10.2172/1119419

[12] F. Willeke and J. Beebe-Wang, "Electron Ion Collider Conceptual Design Report 2021," Tech. Rep. BNL-221006-2021-FORE, 2021. doi:10.2172/1765663