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# CURRENT STATUS OF THE ELECTRON TRANSPORT LINE FROM RCS TO ESR: RTE LINE*

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*Abstract*

The electron injection system of the U.S. Electron-Ion Collider (EIC) is located outside of the RHIC tunnel. Electron beams accelerated by the Rapid Cycling Synchrotron (RCS) must be transported to the Electron Storage Ring (ESR), which resides within the RHIC tunnel. To accomplish this, a dedicated beam transport line, referred to as RTE (RCS-to-ESR) line is being designed. The proposed conceptual design comprises three main sections; RCS extraction, a vertical bend and dispersion suppression region, and ESR injection matching. The extraction section uses pulsed kickers and septum magnets to achieve a total deflection angle of 3°. To align the injection section with ESR, the beamline must provide a vertical elevation of 1.68 m, and an array of FODO cells is used to suppress the vertical dispersion. The total length of the RTE line is approximately 133 m, and this paper presents the current design status and considerations for this transport line.

## INTRODUCTION

The U.S. Electron-Ion Collider (EIC) complex is being designed to be built at Brookhaven National Lab (BNL), New York, as a collaborative effort in between BNL and Jefferson Lab (JLab). Figure 1 provides a bird eye view of the EIC complex. The Hadron Storage Ring (HSR) and Electron Storage Ring (ESR) are housed within the existing RHIC tunnel, while the electron injection system—consisting of an injector linac, Beam Accumulator Ring (BAR), and Rapid Cycling Synchrotron (RCS)—has been relocated to a dedicated tunnel outside the RHIC enclosure.

Polarized electrons are injected from the electron injector and pre-accelerated by the linac. The electron bunch charge exiting the linac is 1.1 nC with a repetition frequency of 30 Hz. The beam then enters the BAR ring, where the charge is accumulated to 28 nC at extraction [1–3]. These high charge electron bunches then are transported to the RCS, where the beam is accelerated to one of three different energies: 5 , 10 or 18 GeV, before being transported to and injected into the ESR ring at IP 4 [4].

Electron bunches are extracted from the RCS at a rate of up to 1 Hz for injection into the ESR. A single-bunch, on-axis extraction scheme is employed in the horizontal plane. The RTE line is divided into three sections: the RCS extraction segment, a vertical bend achromat to accommodate the elevation change, and the ESR injection segment [4].

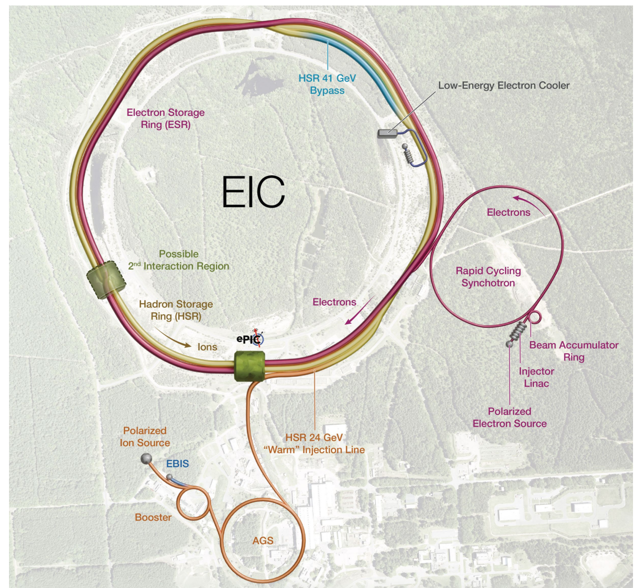


Figure 1: Layout of the current EIC design, HSR and ESR rings inside the RHIC tunnel, Electron and hadron injector complexes are outside of it.

In the conceptual design of the RTE line, three kicker magnets, each 0.8 m long, and two septum magnets—a thin septum (1.5 m) and a thick septum (2 m)—are used to achieve a net extraction angle of 52.36 mrad (3°) [4]. Since the two rings are located at different elevations, the RTE line incorporates a vertical drop of 1.68 m before ESR injection. The vertical bend section consists of two 3 m long vertical dipole magnets, and nine quadrupole magnets placed between them to suppress vertical dispersion, forming an achromatic bend. The matching quadrupoles are 0.3 m length with aperture 0.02 m radius, forming 4.5 FODO cells [4]. Figure 2 shows optics of this conceptual design.

The beta functions remain reasonable and well below 70 m. However, interference between the RTE beam pipe and the downstream RCS quadrupole (MQD21) magnet is observed, as shown in Fig. 3. To resolve this issue, the spacing between the MDQF21 and MQD21 quadrupole magnets must be increased. Therefore, the injection pulsed magnet beamline layout must be modified to accommodate the updated RCS lattice.

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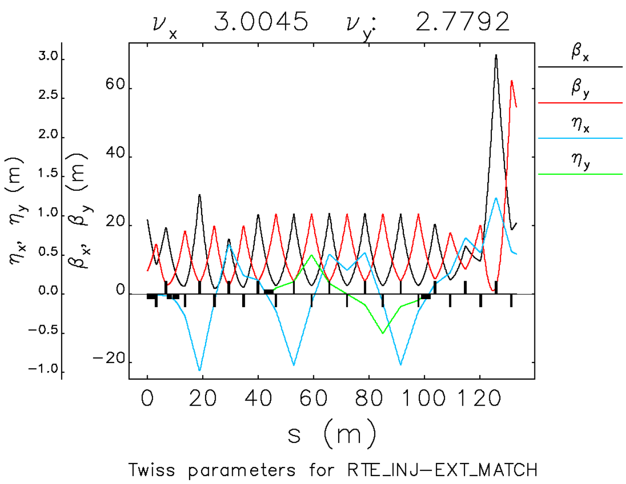


Figure 2: RCS to ESR transport line conceptual optics.

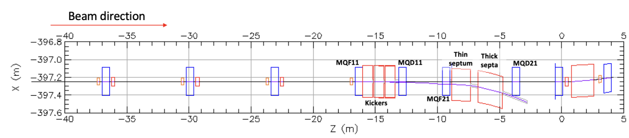


Figure 3: Pulsed-magnet layout in the RCS straight section. Three kicker magnets and two septum magnets from the RTE line are used for electron extraction.

## PRESENT STATUS OF RTE LINE

The RCS lattice has been revised to incorporate a longer drift section, necessitated by interference constraints. In the updated design, two distinct drift spaces have been introduced between the matching quadrupoles in the straight sections. Additionally, two separate quadrupole families are used for focusing and defocusing, with lengths of 0.71 m and 0.47 m, respectively. However, the placement of pulsed kickers had to be shifted downstream, closer to the next quadrupole magnet (MQD11), to accommodate the installation of an RF cold trap near to RCS cryomodule, as illustrated in Fig. 4. To ensure sufficient separation from the RCS beamline, RCS magnet layout require further adjustments-specifically, increasing the drift lengths between quadrupoles within the kickers and septum region.

The lengths of the first three kicker magnets have been reduced to 0.7 m length, due to space restriction in the drift sections. To compensate and provide the total required deflection, a fourth kicker has been added to achieve sufficient beam steering out of the 40 mm diameter beam pipe. The kick angle is 3.0 mrad for shorter kickers and 3.1 mrad for the longer one. New compact septum magnets have also been introduced, based on the designs used in the APS booster and APS injector systems.

The thin septum now follows the APS booster septum magnet design, with length 1.493 m and a maximum kick angle of 33 mrad, and shorten the length of thick septum to 1.75 m, to achieve an overall extraction angle of 3° [5]. The extraction lattice layout is shown in Fig. 4.

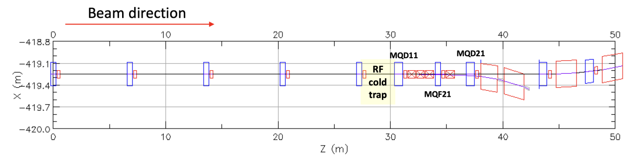


Figure 4: Placement of pulsed magnets in the updated RCS lattice, leaving space for the rf-cold trap.

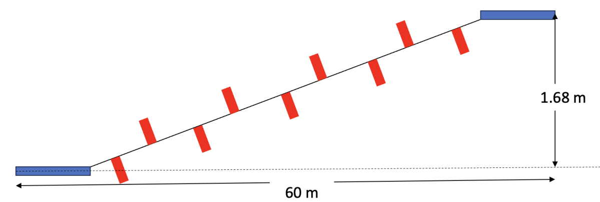


Figure 5: Vertical bend section with two 3 m dipoles and 9 quadrupole magnets.

### *Matching Section From RCS Extraction*

Control and matching Twiss functions downstream of the thick septum magnet are achieved using three FODO cells. The quadrupole magnets used in this section are identical to the long quadrupoles in the RCS lattice, each with a length of 0.71 m.

### *Vertical Bend Section*

The ESR and RCS rings are positioned at different elevations, necessitating a vertical bending section to accommodate an elevation of 1.68 m. To achieve this, vertical dogleg section with a total length of 60 m is designed using a 4.5-FODO-cell layout comprising nine quadrupole magnets, shown in Fig. 5. This configuration effectively suppresses the vertical dispersion, making this vertical bend section an achromat [6]. The two vertical bend dipoles are of length 3 m, provide a bend angle of 29.5 mrad.

This section uses 0.3 m long matching quadrupoles. However, the feasibility of reusing MIT-Bates quadrupole magnets [7] for the RTE line has been considered. Due to their larger aperture, these magnets exhibit significantly lower focusing strength than required. As a result, they must be grouped—three Bates magnets combined to function as a single effective quadrupole, as illustrated in Fig. 6. The total length of a quadrupole unit is 1.1 m; a drift of 0.1 m is used in between two magnets.

### *Matching into ESR Injection*

After bending the beam trajectory downward to align with the ESR elevation, a set of quadrupole magnets is used to match the Twiss parameters at the ESR injection section. This matching section consists of four FODO cells, designed to accommodate the matching constraints imposed by the available quadrupole strengths. Similar in the extraction matching section, 0.71 m long quadrupoles are used in this section as well.

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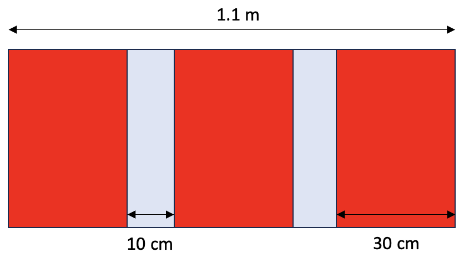


Figure 6: Layout of a single quadrupole unit re-using MIT-Bates magnets. Three magnets with 30 cm are used for a single quadrupole unit.

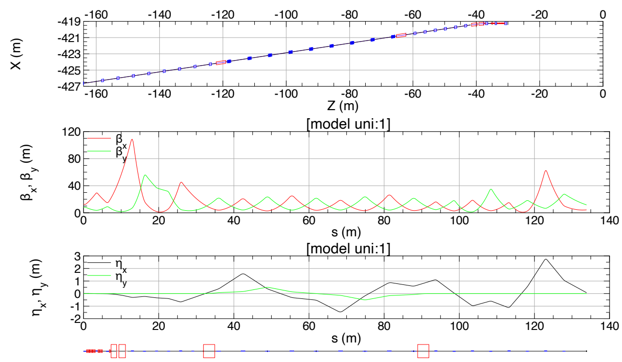


Figure 7: Lattice layout (top), lattice optics (middle), lattice dispersion (bottom) of the matched RTE line.

### *RTE Line Optics*

The RTE line must transport high intensity, vertically polarized electron bunches while minimizing polarization loss The lattice layout and optics are illustrated in Fig. 7. Vertical dispersion is zero except within the vertical bend section, while the horizontal dispersion is non-zero throughout the transport line, not exceeding 1.8 m limit. Beta functions are within the reasonable limits, with a maximum value ≈ 110 m. The optics are shown designed for the maximum electron energy of 18 GeV, which imposes more demanding requirements due to the larger beam rigidity.

## FUTURE WORK

The current RTE line is designed to provide 3° electron extraction from RCS and injection to ESR with an angle of 3°. However increasing the ESR angle to reduce the tunnel wall overlapping area between RHIC and transport line is preferred.

### *Alternate RTE Layout*

The increased injection angle into the RHIC tunnel will reduce the area of the tunnel that needs to be modified potentially reducing costs. Two options are being considered with ESR injection angles 6° and 9°, with adding additional horizontal bend dipoles as illustrated in Fig. 8. However, larger injection angle requires additional septum magnets, to provide a larger bend angle. Work is in progress designing a large-angle electron injection into the ESR.

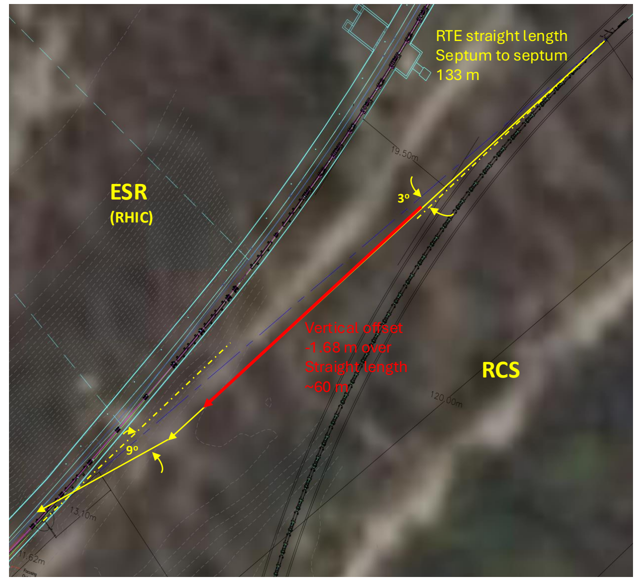


Figure 8: Alternate design layout for RTE line, with 3° electron extraction and 6° or 9° ESR injection angle, with using additional horizontal bending magnets.

Furthermore, there is a discussion on placing the both rings at same elevation, which then eliminates the use of two vertical bend dipoles. Design iterations with no vertical bends have performed, for the RTE line with straight line geometry.

## CONCLUSION

The design work of the electron transfer line with a total length 133 m from the RCS to ESR is in progress. Current design is based on 3° electron extraction and injection angles and utilize pulsed-power magnets for both cases. The design provides required downward elevation to inject the beam in to ESR horizontally, and provide a reasonable optics match with the current matching conditions from both RCS and ESR. This design accommodates reuse of existing magnets, reducing associated costs.

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