DESIGN AND RECENT DEVELOPMENTS OF THE ELECTRON STORAGE RING FOR THE ELECTRON-ION COLLIDER*

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Abstract

The Electron-Ion Collider (EIC), which is currently being designed for construction at Brookhaven National Laboratory, will collide polarized electron beams (5-18 GeV) with polarized hadron beams (41-275 GeV for protons) at luminosities up to $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in a 3.8-kilometer ring. The EIC will be the only lepton-hadron collider since HERA at DESY and, in contrast to that earlier machine, will feature high polarization of both electrons and protons, a wide range of center-of-mass collision energies, a wide range of ion species, and much higher luminosities. These properties will make it an ideal machine for exploring the mass and spin dynamics of nucleons. The Electron Storage Ring (ESR) will be built in the existing 3.8-kilometer RHIC tunnel using normal-conducting magnets and a few superconducting magnets for the final-focus quadrupoles and spin-rotator solenoids. The wide range of energies, high polarization, high current, large beam-beam parameters, and stringent geometric constraints make the ESR a particularly challenging machine. Lately, the design of the ESR has advanced considerably with design alternatives and upgrade paths being considered to align with the key deliverables and funding profile of the project. This contribution highlights some of the important recent developments and design studies.

INTRODUCTION

The Electron-Ion Collider (EIC) [1] will collide spin-polarized electron beams with hadron beams (polarized protons and helium nuclei, as well as a broad range of unpolarized heavier atomic nuclei). Its scientific mission is to provide data from collisions that will support the exploration of the mass and spin dynamics of nucleons. The EIC will be built at Brookhaven National Laboratory, leveraging existing infrastructure from the Relativistic Heavy Ion Collider (RHIC) [2–4], including the 3.8-kilometer circular tunnel. One of the two existing RHIC hadron rings will be transformed into a new hadron storage ring (HSR) for the EIC, and a new electron storage ring (ESR) [5–8] will also be built in this tunnel for circulating electron beams for collisions. The electron and hadron beams will be brought into collision in the ePIC detector; a second interaction region and detector may be included in a future upgrade. The existing RHIC injector complex, including the 0.8-kilometer Alternating Gradient Synchrotron (AGS), will serve as the hadron injector for the EIC. A new electron-injector complex is being designed, including a polarized photoinjector, a Beam Accumulator Ring (BAR), and a 1.5-kilometer Rapid Cycling Synchrotron (RCS). Figure 1 shows a schematic of the EIC.

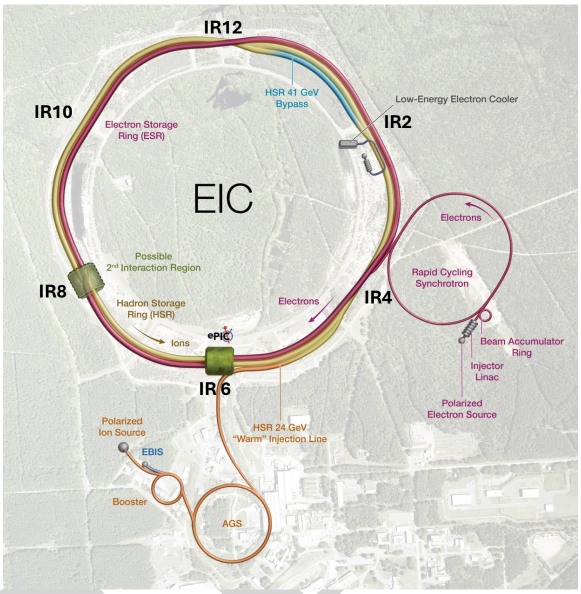

Figure 1: Schematic of EIC (not to scale).

The EIC will be the first collider to collide beams of electrons and ions, as well as the first collider to collide spin-polarized beams of electrons and protons. In contrast to the earlier collider HERA, which operated at DESY, Germany, the EIC will not only collide beams of protons but also a wide range of ion species, such as gold or uranium nuclei. The EIC will collide particles over a very wide range of center-of-mass energies, ranging from about 20 GeV to 100 GeV for electron-proton collisions initially, with a final planned energy of 140 GeV. High polarization and high luminosity are vital for the experimental program. The EIC will be able to produce beams of electrons, protons, and helium nuclei with polarization greater than 70% at collision, and the luminosity will extend to $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for certain working points.

The wide beam-energy range, high polarization, large beam-beam parameters, tight bunch spacing, and high beam current together make the ESR a challenging and unique storage ring. Novel solutions have been developed to fulfill these conditions, such as using super-bend triplets in the arc

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cells, an energy-dependent lattice design, compact solenoid-based spin rotators, and a crabbed crossing scheme.

The ESR will be composed of six arcs and six insertion regions (IRs), which fits the shape of the tunnel that housed the RHIC collider. The arcs will each consist of 16 FODO cells, with the dipoles arranged in super-bend configuration for emittance and damping-decrement control.

This paper presents some of the recent design studies that have been conducted, including studies of alternative designs. The following sections address the choice of energies, the location of the superconducting RF section, crossover sections, injection/extraction, collimation, and coupling correction.

CHOICE OF ENERGIES

In order to achieve the wide center-of-mass energy range, the ESR is designed to operate at three distinct energies. A minimum electron energy of approximately 5 GeV was chosen, in part because a lower energy would complicate the spin-rotator geometry. The spin rotators are composed of two solenoid modules – a long and a short. A higher ratio of maximum to minimum energy means that a larger bend angle is needed in between the two solenoid modules. With 5 GeV, this angle is already 97.8 mrad. Due to the strict geometric constraints of the existing tunnel, accommodating a larger angle would be very challenging. Furthermore, reducing the electron beam energy compresses the accessible y-range, making it difficult to detect scattered electrons at both high and low inelasticity due to energy resolution and angular acceptance constraints.

A maximum electron energy of approximately 18 GeV was chosen in order to maximize the center-of-mass energy. While the maximum strengths of the HSR magnets sets the maximum hadron energy, a tolerable synchrotron-radiation threshold of 10 MW sets a practical limit on the maximum electron energy. The RF and other components required to reach this full beam energy will not be available initially but will be installed in an upgrade.

A medium value for the electron energy of approximately 10 GeV was initially chosen, which corresponds to maximum-luminosity operation. The exact value of this energy is not so critical for the experimental program, however. Recently, it was decided to lower this energy to approximately 9 GeV in order to reduce the number of superconducting RF cavities that need to be installed in the initial phase, prior to the 18 GeV upgrade. Due to the fourth power scaling of energy loss due to the synchrotron radiation with energy, reducing the energy from 10 to 9 GeV results in a 34 % decrease in required voltage. This reduces the number of required two-cavity cryomodules for initial 800 mA operation to two, which not only leads to initial cost savings for the cavities but also provides more flexibility in their location in the ring. Additional cavities would be needed for operation at full current (2.5 A) or for the energy upgrade to 18 GeV.

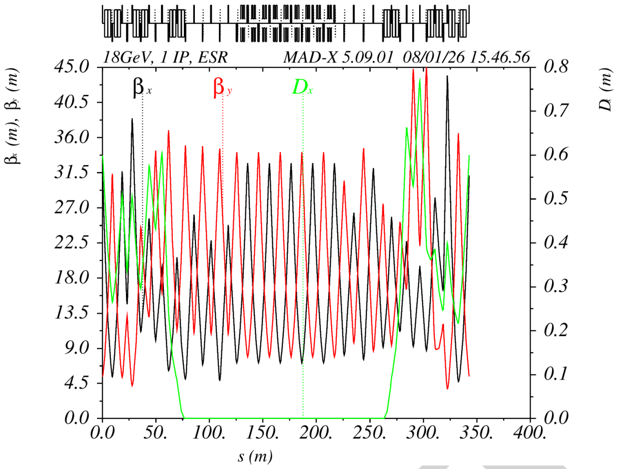

Figure 2: Optics through IR10 of the baseline configuration. The beam travels left to right. The RF cavities are located in the middle of this section.

SUPERCONDUCTING RF SECTION

In the baseline configuration, RF cavities for both the ESR and HSR are located in IR10, together with dedicated infrastructure at ground level. With a reduced number of RF cavities for the ESR, another option that is being considered is installing them in IR8, where there is an existing large hall that previously housed the sPHENIX experiment. In the baseline configuration, this location is reserved for a second interaction region as part of a potential future upgrade; while IR12 could be used as an alternative detector location, this would require upgrading the hall there. The hall in IR8, while much wider than that at IR10, is not as long – it can accommodate up to four two-cavity cryomodules instead of nine. To provide further voltage, additional locations would have to be found to house more cavities, or alternatively a four-cell cavity could be considered.

Regardless of the location of the superconducting RF section, special large-aperture quadrupoles located between each cryomodule with regular alternating polarities will be used. The dispersion will be matched to zero to avoid the unwanted effects of synchrobetatron coupling. Figure 2 shows matched optics for IR10 in the baseline configuration.

CROSSOVERS

In addition to the crossing at the interaction point in IR6, the ESR must cross the HSR in at least one more location. However, to ensure that the revolution times of electrons and hadrons are synchronized, the design must also ensure that half of the electron arcs are on the outside of the tunnel and half on the inside. With a second crossover at IR12 (at the direct opposite of the ring to IR6), only two crossovers in total would be needed. In the baseline design with a crossover at IR8 to accommodate a possible second interaction region, additional crossovers at IR12 and IR4 are needed to achieve synchronization. Figure 3 shows the geometry of the baseline and alternative designs in polar coordinates.

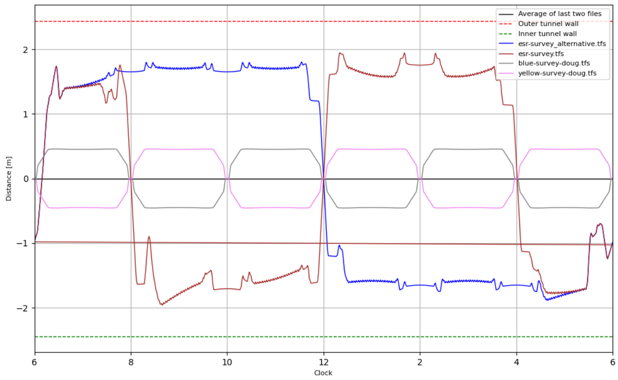

Figure 3: Geometry of the ESR beamline for the baseline configuration (in brown) and the alternative configuration (in blue), shown alongside the two existing RHIC rings (in gray and pink). The HSR will follow the trajectory of the pink line in the arcs. The plot shows radial distance from the center of the ring, normalized to the center of tunnel, on the vertical axis and angular distance around the ring (in terms of the numbers on a clock face) on the horizontal axis. The ESR beam will travel clockwise, i.e. left to right on this plot. The green and red dashed lines indicate the approximate locations of the inner and outer tunnel walls respectively.

The simplest design approach for a crossover, a vertical chicane, is not desirable due to the complexities of implementing this while ensuring spin preservation. Another approach that was adopted for the baseline design is to tilt the ESR by 200 µrad about the line joining the interaction point in IR6 and IR8 so that there is a separation of about 0.2 m at IR12 and 0.1 m at IR4. Alternatively, the path lengths can be set appropriately so that electron bunches and hadron bunches miss each other. This was adopted in the baseline for IR8 since the ESR and HSR must be in the same plane at that location in case of a future upgrade to include a second interaction region.

The design of a crossover includes a set of four dipoles upstream and downstream with opposite polarities to bend the electron beamline across the HSR beamline. These dipoles have been designed to have the same bending angle as others in the IRs so they can be connected together in series. Due to the presence of these dipoles, the dispersion cannot be brought down to zero through the central section of the IR. These dipoles also prevent a FODO-like pattern in the central IR section, so quadrupoles need to be independently powered. Figure 4 shows an example of the optics through a crossover section, corresponding to IR12 of the baseline configuration.

INJECTION/EXTRACTION

A swap-out bunch-replacement scheme is planned for the ESR. Bunches will be replaced at a maximum rate of one bunch per second in order to maintain high polarization. This will be located in IR4 (baseline design), with IR8 currently under consideration as a possible alternative in case it is decided to reconfigure the ESR so that it is on the inside of the HSR in IR4. The injection/extraction scheme is detailed in Ref. [9].

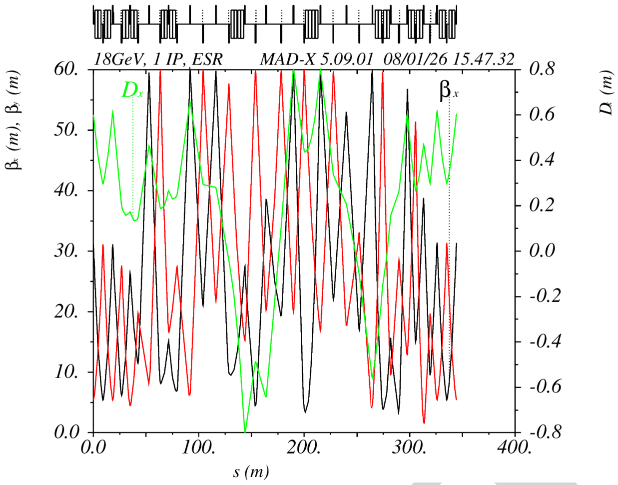

Figure 4: Optics through IR12 of the baseline configuration. The beam travels left to right. The two sets of four dipoles near the center bend in opposite directions to create the crossover.

COLLIMATION

Collimators will be situated downstream of the injection point to protect against injection malfunctions and to reduce particle losses in the interaction region. The configuration has been studied to optimize the locations and apertures of the collimators to ensure that they do not significantly impact the machine acceptance or beam lifetime [10]. Possible collimator locations in IR4 have been found for the baseline lattice, with multiple locations needed to cover the three energies. In case the alternative injection in IR8 is pursued, there is a lot more flexibility for the collimator location due to the much greater distance between the injection point and the interaction region.

COUPLING CORRECTION

A local coupling-correction scheme, using 14 skew quadrupoles, will be implemented in the ESR interaction region. This will correct coupling caused by the detector solenoid, which will have a field strength of up to 2 T, as well as field errors in the machine. The skew quadrupoles are individually powered and may be operated up to 2 T integrated field strength. They have been set to correct the coupling, crab dispersion, and optics functions at the interaction point.

CONCLUSION

Recently, the ESR design has advanced to align more closely with the key deliverables and funding profile of the project. Some of the recent studies and design alternatives have been detailed in this paper. These studies will inform design decisions that will be taken soon to bring the ESR to a high maturity level.

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