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Status of the Electron-Ion Collider

Christoph Montag[a,*]

[a] *Brookhaven National Laboratory,*
PO Box 5000, Upton, NY 11973, USA

E-mail: montagc@bnl.gov

The Electron-Ion Collider is gearing up for "Critical Decision 2", the project baseline with defined scope, cost and schedule. Lattice designs are being finalized, and preliminary component design is being carried out. Beam dynamics studies such as dynamic aperture optimization, instability and polarization studies, and beam-beam simulations are continuing in parallel. We report on the latest developments and the overall status of the project, and present the plans for future activities.

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[*] Speaker

1. Introduction

The Electron-Ion Collider (EIC) [1], to be built at Brookhaven National Laboratory, will be the next major research facility for nuclear physics in the US. Its key performance requirements are formulated in the White Paper [2]:

- An electron-proton luminosity of 10^{33} to 10^{34} $\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ - two to three orders of magnitude higher than HERA [3];
- A large electron-proton center-of-mass energy range from 29 to 140 GeV;
- Favorable conditions for detector acceptance, such as a transverse momentum acceptance down to $p_\perp > 200$ MeV;
- A large variety of hadron species, from protons all the way to uranium;
- Highly polarized proton and light ion beams such as deuterium ot ^{3}He.

The EIC design meets or even exceeds all of these requirements.

The EIC will be based on the existing Relativistic Heavy Ion Collider (RHIC) [4] at Brookhaven National Laboratory. RHIC consists of two superconducting storage rings, “Blue” and “Yellow”, with a circumference of 3.8 km that intersect at six equidistantly spaced locations around the perimeter, as schematically shown in Figure 1. In the arcs, the two rings lay side-by-side, about 90 cm apart. RHIC is capable of accelerating and colliding protons up to 255 GeV, which corresponds to about 100 GeV/nucleon for heavy ions such as gold. Typically, about 110 bunches are stored in each ring and brought into collision at the nuclear physics detectors STAR and sPHENIX in IR6 and IR8, respectively. Over its life span of about 20 years, RHIC has been operated with a large variety of ion species, from protons over copper and gold to uranium. Proton polarization has reached about 60 percent at 255 GeV beam energy, which makes RHIC the world’s only polarized proton collider. Due to continuous upgrades and improvements, RHIC has exceeded its original design luminosity by a factor 44.

The EIC design is based on RHIC with its entire injector complex from the ion sources over the linac and booster to the AGS. The Hadron Storage Ring (HSR) will be composed of arcs from both the “Blue” and the “Yellow” RHIC rings, which require modifications and upgrades. Many RHIC beam parameters are already close to what is required for the EIC, with the notable exceptions of the number of bunches, 1160 instead of 110, a three times higher beam current, and a ten times smaller vertical emittance.

An Electron Storage Ring (ESR) with an energy range from 5 to 18 GeV with its corresponding injector complex will be added, thus providing the required electron-proton energy range from 29 to 140 GeV. The electron and hadron beams will collide in a dedicated interaction region in IR6 (see Figure 2). While only one interaction region and its detector are in the EIC scope, a second interaction region in IR8 is envisioned. This future addition is already anticipated in beam dynamics studies in order to ensure that the EIC can support two high luminosity interaction regions simultaneously.

The electron storage ring and its rapid cycling injector synchrotron will be installed in the existing RHIC tunnel, thus taking advantage of existing infrastructure to the largest extent possible.

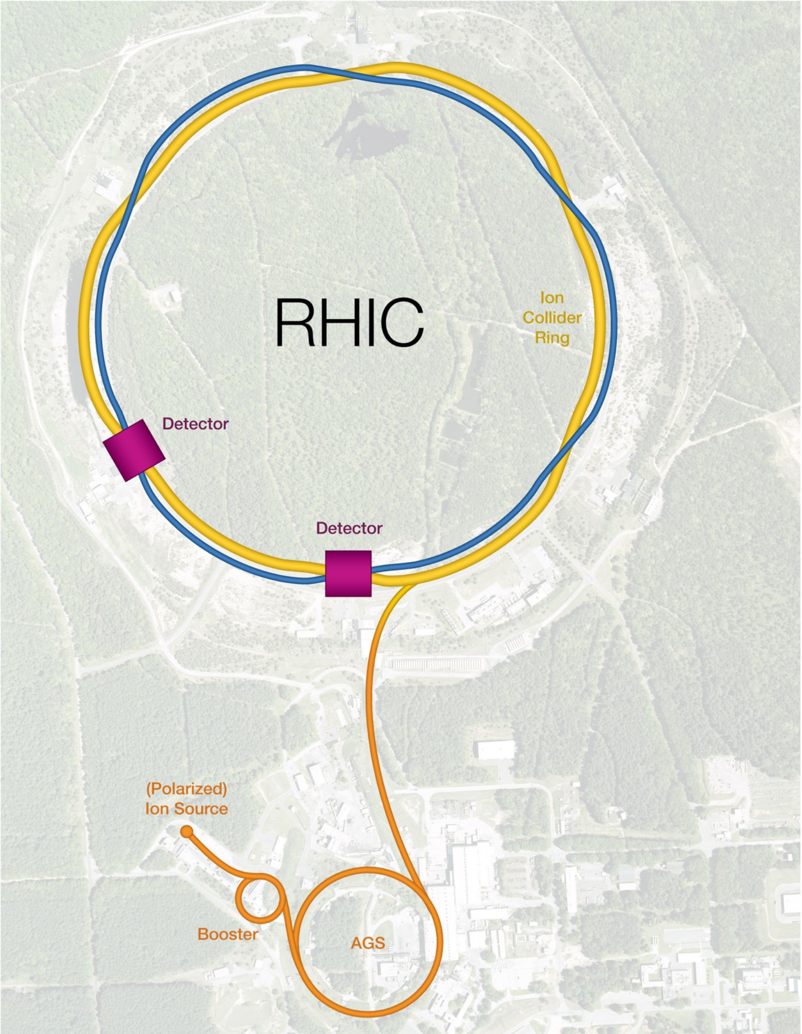

Figure 1: Schematic layout of the Relativistic Heavy Ion Collider (RHIC). Straight sections are designated in analogy to the dial of a clock, with the northernmost straight at the top of this picture designated as "IR12". IR6 and IR8 are equipped with the two nuclear physics detectors "STAR" and "sPHENIX", respectively.

A 200 MeV electron linac in IR12 will inject polarized electrons from the polarized electron gun into the Rapid Cycling Synchrotron (RCS), which will accelerate them to the desired collision energy for transfer into the ESR. A Strong Hadron Cooling (SHC) facility will be added in IR2 to cool hadron beams to the desired emittances at injection energy, and to maintain those emittances during collisions.

2. Luminosity

The EIC reaches its peak electron-proton luminosity of 10^{34} $\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ at a center-of-mass energy of 105 GeV, which corresponds to electron and proton energies of 10 and 275 GeV, respectively. Since higher center-of-mass energies are achieved by increasing the electron beam energy,

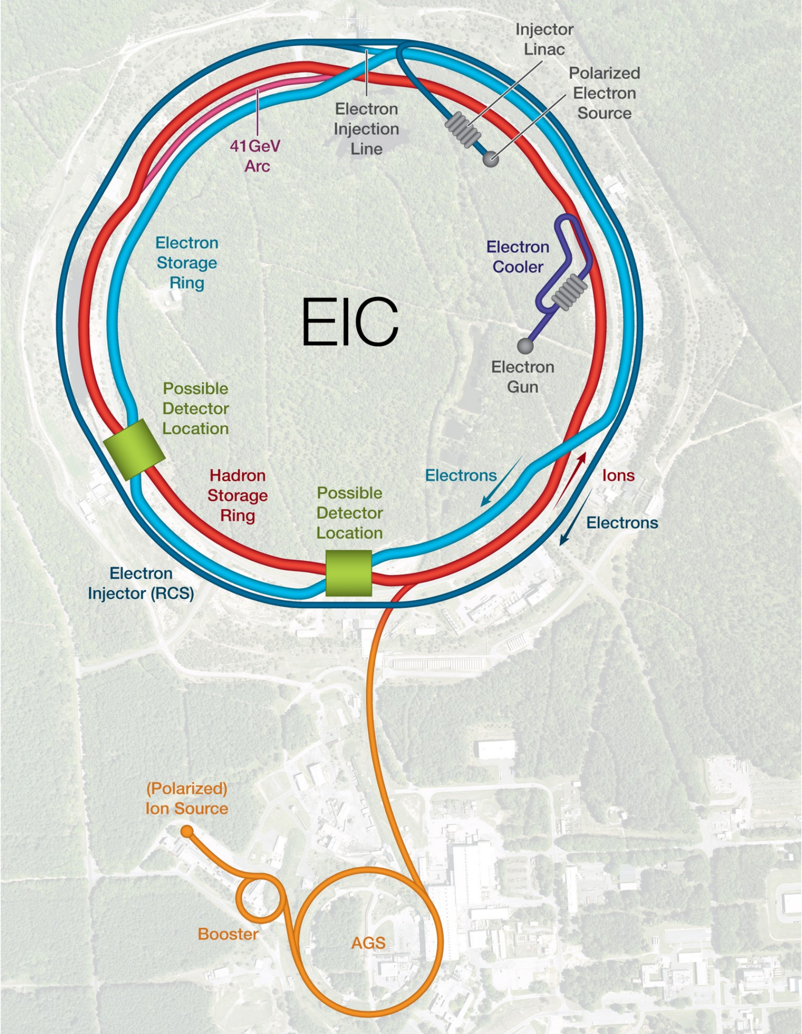

Figure 2: Schematic layout of the EIC in the existing RHIC tunnel.

which increases the synchrotron radiation losses proportionally to the 4th power of the beam energy, $P \propto E^4$, the electron beam intensity has to be lowered accordingly in order to keep the total synchrotron radiation power losses below the 10 MW limit. As a consequence, the luminosity decreases with increasing energy beyond the peak luminosity point, as shown in Figure 3. At center-of-mass energies below 105 GeV, bunch intensities have to be decreased in order to stay within the limits imposed by the beam-beam parameter, which would otherwise increase as γ^{-1}, where γ is the Lorentz parameter of the respective beam. At very low center-of-mass energies below some 45 GeV, the space charge force within the proton beam becomes dominant and requires a further reduction of the proton bunch intensity.

The luminosity concept of the EIC is based on a large number of bunches, high bunch intensities, and small β functions at the interaction point (IP), as listed in Table 1. Beam-beam parameters are adopted from colliders such as KEKB (electron-positron) and RHIC (proton-proton), assuming that similar beam-beam parameters can be achieved in collisions of unequal species, namely electrons

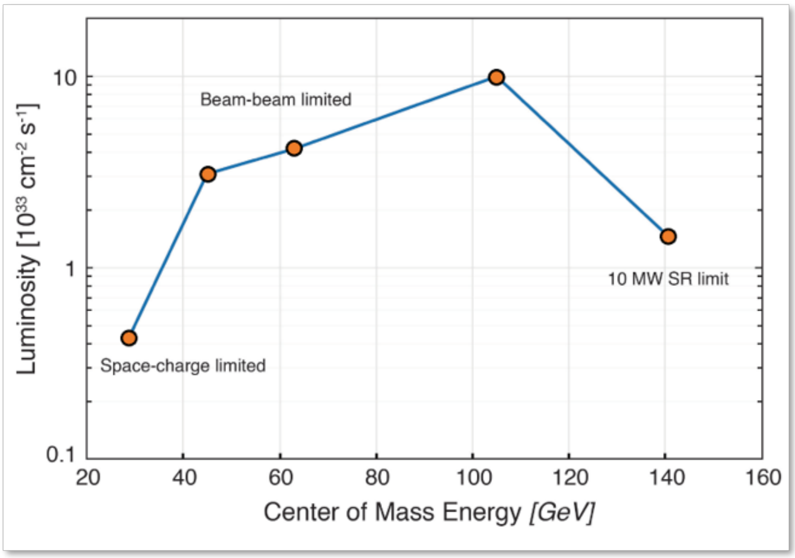

Figure 3: Electron-proton luminosity as function of center-of-mass energy.

Table 1: EIC electron-proton parameters for highest luminosity

	protons	electrons
no. of bunches	1160	
energy [GeV]	275	10
bunch intensity [10^{10}]	6.9	17.2
beam current [A]	1.0	2.5
$\epsilon_{\rm RMS}$ hor./vert. [nm]	9.6/1.5	20.0/1.2
$\beta^*_{x,y}$ [cm]	90/4	43/5
beam-beam parameter hor./vert.	0.014/0.007	0.073/0.100
σ_s [cm]	6	0.7
$\sigma_{{\rm d}p/p}$ [10^{-4}]	6.8	5.8
$\tau_{\rm IBS}$ long./transv. [h]	3.4/2/0	N/A
L [10^{33} cm^{-2}sec^{-1}]	10.05	

and hadrons in the EIC.

On of the novel feature of the EIC is the utilization of hadron beams with unequal transverse emittances (“flat beams”), while all past and present hadron colliders operate with equal, “round” emittances. The feasibility of this concept has been experimentally demonstrated with gold ions in RHIC, as shown in Figure 4. This was achieved using vertical stochastic cooling, while letting the horizontal emittance naturally increase due to intrabeam scattering (IBS). Once an emittance ratio of approximately $1:10$ was reached in both beams, beams were brought into collision.

One important limiting factor in the EIC is hadron beam emittance growth due to intrabeam scattering, which leads to luminosity degradation. To counteract this effect and therefore preserve

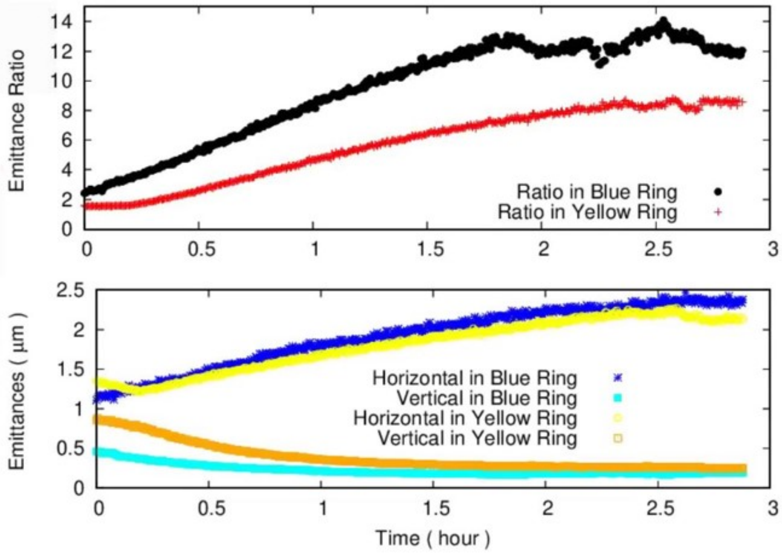

Figure 4: Flat beam demonstration with gold beams in RHIC. While the vertical emittances in both rings are reduced using the stochastic cooling system, the horizontal emittances increase due to intrabeam scattering. The emittance ratio eventually reaches a value of $\sigma_x/\sigma_y \approx 13$ in the Blue ring, and approximately 8 in the Yellow ring.

the small hadron beam emittances, strong phase space cooling needs to be imployed. Realistically achievable are cooling times of approximately two hours; hence, beam parameters were chosen such that IBS growth rates do not exceed $0.5\ h^{-1}$.

When a second interaction region and detector are eventually added, the luminosity has to be shared in order to operate both detectors simultaneously. Since both electron and hadron beams are already operating at their respective beam-beam limits with a single interaction point, colliding at two interaction points would double the beam-beam parameter and therefore exceed that limit. While reducing the bunch intensity in each beam by a factor two would result in a beam-beam parameter within the limits, this would also reduce the luminosity at each interaction region by a factor four. Thus, the total luminosity of the collider with two detectors would only be half of the luminosity that is achieved with a single interaction point.

Instead of reducing bunch intensities, two trains of electron bunches will be injected and stored that are offset by an additional RF bucket with respect to each other. With the interaction point in IR8 shifted by half that offset amount, one electron bunch train will therefore collide with hadron bunches in IR6, while the other bunch train will collide with its respective hadron counterparts in IR8. As a result, the total luminosity is preserved, and each detector receives half the luminosity of the single-detector scenario, up to $0.5 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1}$.

3. Beam energies

To provide collisions over a wide energy range, beam energies of both the electrons and the hadrons need to be changed. While electrons are highly relativistic and therefore practically do not change their velocity over the ESR energy range from 5 to 18 GeV, this is not the case for hadrons in the HSR. In order to keep both beams synchronized and colliding at the interaction point(s), the path length of the hadron beam has to be adjusted accordingly, such that both electrons and hadrons circulate at the same revolution frequency. Within an energy range that corresponds to a Lorentz-γ between 107 and 293, this is accomplished by a slight radial shift of the beam orbit inside the HSR vacuum chamber. To extend the available energy range in the HSR, an “inner” RHIC arc is used as a “shortcut” in the sextant between IR10 and IR12, see Figure 2. With inner and outer RHIC arcs being apart by 90 cm, utilizing an inner arc in one sextant of the ring reduces the path length by about 94 cm, which allows synchronization of $\gamma \approx 43.7$ hadrons with the circulating electron beam.

The highest hadron beam energy is limited by the magnetic field strength of the HSR dipoles. For fully stripped ions with a charge number Z and consisting of A nucleons, this upper limit is given as

$$E/\text{nucleon} = \frac{Z}{A} \times 275\ \text{GeV}. \tag{1}$$

For optimum luminosity over the entire energy range, the electron beam emittance in the ESR needs to be kept constant at about 24 nm. To accomplish this, the ESR is operated at a betatron phase advance of 90 degrees per FODO cell at 18 GeV, and at 60 degrees for beam energies of 10 GeV and below. In addition, “super-bends” are used below 10 GeV in order to help generate the required emittance. As a consequence, any electron beam energy between 5 and 18 GeV is feasible; however, since only two discreet FODO cell phase advances of 60 and 90 degrees are available, the resulting emittance at intermediate energies between 10 and 18 GeV is not at its optimum value of 24 nm, and therefore the luminosity is somewhat reduced.

4. Polarization

The physics program at the EIC requires simultaneous storage of bunches with spin “up” and “down” in both the HSR and the ESR to reduce systematic errors. While this is already standard practice in RHIC and can therefore be considered straightforward in the HSR as well, special measures have to be taken to accomplish this in the ESR.

While stored electron beams self-polarize due to the Sokolov-Ternov effect, this only results in one spin state, namely polarization anti-parallel to the main dipole field in the storage ring. Polarization parallel to the main dipole field can therefore only be achieved by injecting polarized bunches with the desired spin direction into the storage ring. Since the Sokolov-Ternov effect will slowly first depolarize these bunches and then re-polarize them into the opposite direction, anti-parallel to the main dipole field, bunches need to be continuously replaced at a rate much faster than the Sokolov-Ternov polarization rate.

Since the equilibrium polarization level of the ESR is likely lower than the required average polarization, bunches with polarization anti-parallel to the main dipole field need to be replaced as well as those with parallel polarization direction, albeit at a lower rate. Figure 5 shows the polarization evolution in a single bucket in the ESR, for parallel and anti-parallel spin direction, assuming an equilibrium polarization of only 30 percent. Bunches are injected with their desired spin direction at a polarization level of 85 percent. This polarization then decays exponentially

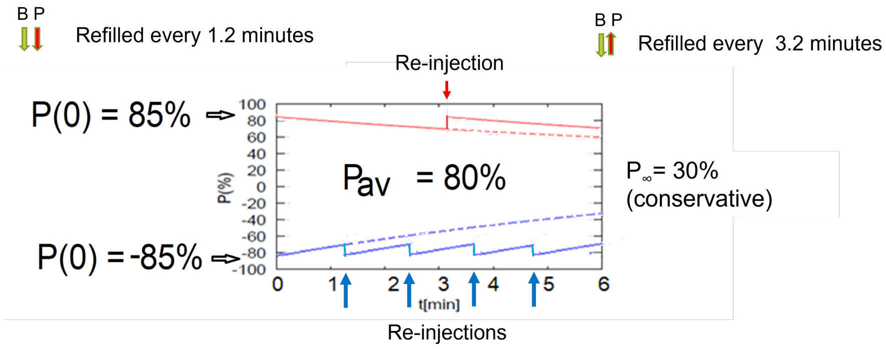

Figure 5: Polarization evolution in a single ESR bucket.

towards the equlibrium polarization level. However, after 1.2 minutes for parallel polarization and 3.2 minutes for antiparallel polarization, respectively, the bunch is replaced with a fresh one, polarized to 85 percent. As a result, the time-average polarization in each bucket, and therefore the ensemble average polarization of the entire fill in the storage ring, is maintained at 80 percent.

A Rapid Cycling Synchrotron [5], cycling at 1 Hz, serves as full-energy, polarized injector to the ESR. Its special lattice design ensures nearly 100 percent polarization transmission during the energy ramp from its 400 MeV injection energy to 18 GeV, which is accomplished by a highly periodic lattice.

Depolarizing spin resonances occur at

$$\begin{aligned} G\gamma &= nP \pm Q_y \qquad \text{(intrinsic)}, \\ \text{and} & \\ G\gamma &= nP \pm [Q_y] \qquad \text{(imperfection)}, \end{aligned} \tag{2}$$

where G denotes the anomalous gyromagnetic factor of the electron, γ the Lorentz factor, P the lattice periodicity, and Q_y and $[Q_y]$ the vertical tune and its integer part, while n is an integer. During the ramp from 400 MeV to 18 GeV the spin tune $G\gamma$ increases over an interval

$$0.907 < G\gamma < 41. \tag{3}$$

With a proper choice of the periodicity P and the integer tune $[Q_y]$, for instance $P = 96$ and $[Q_y] = 50$, the first two intrinsic spin resonances occur outside the ramp range (Eq. 3) at

$$G\gamma = 50 + \nu_y \tag{4}$$

and

$$G\gamma = 96 - (50 + \nu_y) = 46 - \nu_y, \tag{5}$$

while the first imperfection resonance occurs at

$$G\gamma = 96 - 50 = 46. \tag{6}$$

Here, ν_y denotes the fractional part of the vertical tune, $Q_y = [Q_y] + \nu_y$. Thus, the spin resonance conditions (Eq. 2) are not fulfilled during the energy ramp, and as a consequence polarization is preserved.

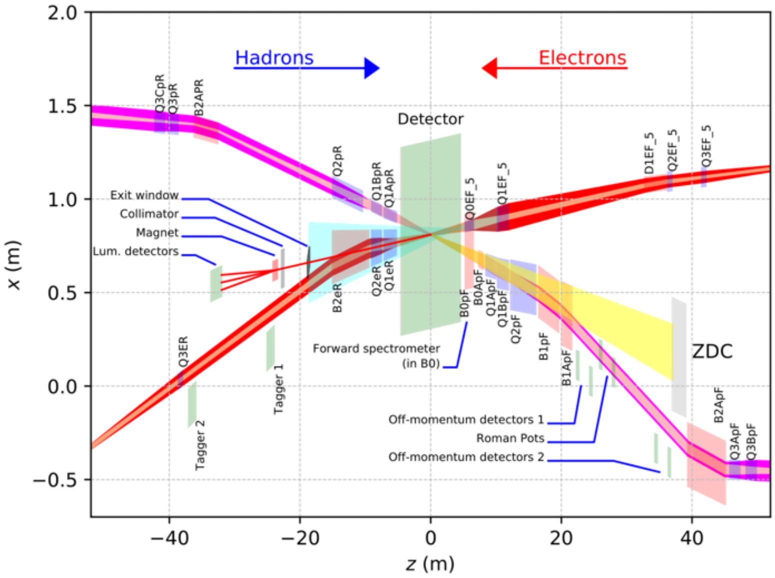

Figure 6: Layout of the central section of the interaction region.

The Hadron Storage Ring (HSR) will be equipped with six Siberian snakes, four more than in present RHIC, in order to increase proton polarization transmission on the ramp to nearly 100 percent and to facilitate operation with polarized ^{3}He. Latest simulation results show that ^{3}He polarization is preserved up to 140 GeV/nucleon. Studies are underway to understand depolarizing mechanisms at higher energies and to find possible remedies to overcome these, allowing polarized ^{3}He operation all the way up to the maximum achievable energy of 183 GeV/nucleon.

5. Interaction Region

The EIC interaction region (IR) is based on a 25 mrad crossing angle that allows placing electron and hadron focusing elements side-by-side right outside the central detector, about 5 m from the interaction point (IP), as shown in Figure 6. Since such a large crossing angle in conjunction with the long hadron bunches would significantly reduce the transverse overlap of the two beams in collision and therefore the luminosity, a set of crab cavities rotates the bunches around the vertical axis such that they are aligned with each other at the IP, thus essentially restoring head-on collisons. As a consequence, the actual collision point moves slightly in the transverse, horizontal direction during the collision of the two bunches, which has to be taken into account in the physics analysis.

Low-β focusing around the IP is provided by superconducting quadrupole doublets, with electron and hadron magnets installed in a common cryostat. The matching sections between these doublets and the arcs are very challenging due to many geometric and optical constraints. Electron spin rotation from the vertical spin orientation in the arcs to longitudinal at the IP, and back to vertical in the downstream arc, is accomplished by a combination of solenoid magnets and dipoles. First, a solenoid rotates the vertical spin coming out of the arc by 90 degrees around the beam direction into the radial direction, followed by a horizontal bend to rotate the spin by 90 degrees around the vertical axis into the longitudinal direction. Since the spin rotation angle ϕ_{spin} due to the dipoles depends on the Lorentz factor γ,

$$\phi_{\text{spin}} = G\gamma \cdot \phi_{\text{orbit}}, \tag{7}$$

where ϕ_{orbit} is the net horizontal orbit angle between the exit of the spin rotator solenoid and the IP, two sets of solenoids are needed on either side of the IP at appropriate orbit angles, one set for 5 GeV and a second set for 18 GeV. For operation at intermediate energies, both sets of solenoids are employed. The hadron spin rotators consists of sets of helical dipoles and are identical to the ones in RHIC. Since their spin rotation angle is flexible they do not inpose similar geometric constraints on the HSR lattice as the spin rotators in the ESR.

Electron dipoles upstream of the detector need to be located as far as possible from the IP to avoid related synchrotron radiation background in the detector. In the EIC, the closest dipole is located approximately 35 m upstream, and dedicated photon masks will shield the detector. Together with the geometric constraints imposed by the spin rotators this makes it very challenging to fit the interaction region into the existing tunnel.

6. Summary

The EIC will be the next large nuclear physics facility, starting operations in the early 2030s. It meets or even exceeds all the requirements listed in the White Paper [2], thus facilitating a rich physics program. These requirements make the EIC a very challenging machine, with high beam currents, polarized beams, a novel hadron cooling technique, a large energy range, crab crossing collisions, etc.

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