DESIGN OF THE ELECTRON–ION COLLIDER*

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The Electron–Ion Collider (EIC) is under construction at Brookhaven National Laboratory partnering with Jefferson Laboratory. The collider is designed for collisions of 70% polarized electrons and ions with luminosities up to $L = 1 \times 10^{34}$ cm^{-2}sec^{-1} at the center-of-mass energies up to 140 GeV. The report summarizes the requirements, describes the design of the collider, and presents the present status of the project.

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1. Introduction and requirements

The EIC physics [1] addresses open questions on the properties and structure of nuclei and nucleons. The physics case has been strongly endorsed by the National Academy of Sciences with the expectation that the spin-off of required collider and detector technology will boost science and technology in other fields. To accomplish its mission, the EIC needs a luminosity of up to $L = 1 \times 10^{34}$ cm^{-2}sec^{-1}. It is operated over center-of-mass energies between 20–140 GeV, and will collide electrons with ions from protons to uranium. Both electron and ion beam need to be spin-polarized with a polarization of 70%. The EIC physics requires detection of hadrons scattered under a small angle off the collision point. This needs sufficient aperture in the final focus in the forward hadron beam line, space for installing near-beam particle detectors at this beam line, and a small beam emittance such that scattered particles can be intercepted by near-beam detectors without affecting the circulating beam. The EIC must be designed such that two colliding beam detectors can be included in the facility, while the EIC project initially supports only one detector region. These are conflicting requirements. The challenge of the collider design is to find a compromise that supports all parts of the physics program adequately. The design of the EIC meets this challenge [2].

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2. EIC design concept and parameters

The EIC design follows the principle demonstrated in previous colliders with unequal species (for example, HERA [3]). The collision parameters for each beam are chosen such as each would collide with a beam of the same species. The EIC luminosity is maximized by maximizing total beam currents for electrons and ions and by minimizing the beam cross section. The electron beam current is limited by the amount of installed RF power needed to replace the emitted synchrotron radiation power. The total beam current of the hadrons is limited by resistive heating of the vacuum chamber in the superconducting magnets. The density of the beam at the IP is limited by the corresponding forces acting on the particles of the opposite beam. These forces are determined by the ratio of particles per bunch n_{b} and the beam emittance ε. We can choose n_{b} but must adjust ε correspondingly, such that the beam–beam interaction remains within limits which have been demonstrated previously in electron and hadron colliders. The number of bunches is minimized to 1160, thereby reaching the limit of the bunch population due to single bunch instabilities. Maximum luminosity is thus achieved by a modestly small value of the beam emittance. This modestly small emittance is still larger than what is provided by the particle source and is still subject to growth by intrabeam scattering. Consequently, a cooling process is required to reach and maintain maximum luminosity during a long collision run. However, the choice of maximum bunch population minimizes the need for cooling which is important as cooling is the main accelerator physics challenge of the EIC. An unusual choice for the hadron beam are unequal transverse emittances $\varepsilon_{h,y}/\varepsilon_{h,x} \simeq 0.01$. This flat beam concept boosts the luminosity by a factor of three. Flat beams are achieved by employing bunched beam electron cooling at the hadron injection energy while heating the beam in the horizontal plane thereby reducing the emittance only in the vertical plane. Flat beams have another advantage. Hadrons scattered into a small forward angle are of particular interest for the EIC physics. Flat beams allow such particles to propagate outside the beam distribution where they can be intercepted by near-beam-detectors also called ‘Roman pots’. Table 1 shows the resulting beam parameters for maximum luminosity at a center-of-mass energy of 105 GeV.

Table 1. Maximum luminosity parameters.

Parameter	Hadron	Electron
Center-of-mass energy [GeV]	104.9	
Beam energy [GeV]	275	10
Number of particles per bunch [10^{10}]	6.9	17.2
Beam current [A]	1.0	2.5
Horizontal/vertical emittance [nm]	11.3/1.0	20.0/1.3
Horizontal β-function at IP β_x^* [cm]	80	45
Vertical β-function at IP β_y^* [cm]	7.2	5.6
Horizontal/vertical divergence at IP $\sigma_{x'}^*$ [mrad]	0.119/0.119	0.211/0.152
Horizontal/vertical beam–beamtune shift parameter	0.012/0.012	0.072/0.1
IBS growth time longitudinal/horizontal [hr]	2.9/2.0	—
Synchrotron radiation power [MW]	—	9.0
Bunch length [cm]	6	0.7
Luminosity [10^{34} cm^{-2}s^{-1}]	1.0	

3. EIC Design

3.1. Hadron storage ring

The EIC is based on the existing Relativistic Heavy Ion Collider with its two superconducting magnet rings that allow proton beam energies up to 275 GeV. The RHIC injectors will provide 80% polarized protons and ions for the EIC. The RHIC complex is continuously modernized and refurbished such that the accelerators and their infrastructure will be available for decades to come. The hadron ring will be composed of four sectors of the present RHIC "Yellow Ring" (two inner, two outer sectors) and two sectors of the "Blue Ring" (one inner, one outer sector). One additional inner "yellow" sector will be used as a low-energy (41 GeV) bypass to provide the same revolution time for all operating energies. The EIC hadron ring (HSR) will be operated with up to 1160 bunches which requires an update of the injection kicker system. Each bunch injected into the HSR will be split into four bunches using two new RF systems (48 MHz and 96 MHz respectively). The bunches will be compressed using the existing 196.8 MHz system assisted by a new 5-cell superconducting system at 591 MHz to achieve a bunch length of 6 cm as required for high luminosity.

3.2. Strong Hadron Cooling

To maintain the hadron beam emittance during luminosity operations, Coherent Electron Cooling is applied. This method is a cousin of stochastic cooling and provides cooling for high-energy protons and ions. Pick-ups, RF amplifiers, and kickers are replaced by an electron beam. The 150 MeV electron beam of 100 mA is generated by a superconducting energy recovery linac and travels with similar velocity together with the hadrons. Electrons pick up density fluctuations in the hadron beam that imprint an electron energy modulation. These modulations are transformed into a density modulation by a combination of chicanes and subsequent plasma oscillations. The final peaked electron density profile then interacts with hadrons and works against the hadron betatron amplitudes and energy spread. Cooling rates of up to (0.5–1) hour^{-1} can be achieved. Challenges to overcome are to generate an electron beam with a Poisson-like density distribution and to ensure the hadron beam and electron beam remain synchronized to femtosecond precision through the 200 m long cooling section.

3.3. Electron storage ring

The electron ring of the EIC (ESR) must have the same circumference (revolution time) as the hadron ring and is fitted in the existing RHIC tunnel. The six arcs of the electron ring are composed of a regular FODO-cell structure implemented by normal conducting magnets. The ring is designed for operations up to 18 GeV. The beam current of 2.5 A is very large. At 10 GeV, the beam radiates a total of 9 MW of synchrotron radiation in the arc. The planned RF power of 12 MW matches the corresponding requirement. This power is transferred to the beam by 17 superconducting single-cell 591 MHz RF low-impedance cavities. The power of beam-induced higher-order mode power is absorbed by the Si–C beam-pipe absorbers that are installed next to each cavity cryostat. The electron beam needs to be 70% spin-polarized (averaged over the storage time) with both polarization directions present in the same beam. Polarized electron bunches with a polarization of 85% are provided by the electron injector chain and launched frequently (up to once every second) into the electron ring during collision operation, while the used bunches are extracted simultaneously. The electron emittance is maintained in an energy range between 5 GeV and 18 GeV by adjusting the betatron phase advance per FODO cell between 60 and 90 degrees. In addition, the dipole magnets in each FODO-half cell are split into three dipoles. The center magnet will be reversed at low-energy operation thereby increasing the synchrotron radiation to maintain damping time and beam emittance.

3.4. Rapid cycling synchrotron

The rapid cycling synchrotron (RCS) provides 85% polarized electron bunches once per second for injection at up to 18 GeV into the ESR. It is installed in the RHIC tunnel. The ramp rate is 1 Hz. Good polarization transmission is obtained by suppressing systematic depolarizing resonances that occur every 340 MeV during acceleration by high lattice periodicity. The RCS has a quasi-periodic lattice. The six arcs have a high periodicity of 16. The six arcs are connected by straight sections where the beam transport is described by a unity matrix. This way, a quasi-periodicity of 96 is achieved which suppresses all intrinsic depolarizing resonances up to the maximum extraction energy of 18 GeV.

3.5. Interaction region

The EIC interaction region is based on a 25 mrad crossing angle geometry to accommodate the 1160 colliding bunches without detrimental parasitic crossings. The beams are separated quickly after collisions and independent final focus magnets for both beams can by placed relatively close to the IP. This geometry also supports placing a zero-degree neutron spectrometer between the hadron and the electron beam line. The detector requires a magnet-free space between −5 m and +5.5 m around the collision point (IP). The first magnet on the forward site is a large aperture spectrometer magnet (1 Tesla field). Both hadron and electron beams pass through the aperture. The electron beam must be shielded against the spectrometer dipole and, at the same time, receive the vertically focusing field. The remainder of the superconducting electron and hadron final focus quadrupoles are installed tightly spaced in the same cryostat on both sides of the IP. The crossing angle needs to be compensated by rotating the bunches in the horizontal plane by 12.5 mrad by using transverse 200 MHz and 400 MHz RF resonators (crab cavities). The beam sensitivity to the corresponding 'crab-kicks' is enhanced by large horizontal β-functions for both beams. The interaction region also accommodates the spin rotators that rotate the spin from the vertical position in the arc to a longitudinal position. The hadron ring uses the existing helical dipoles. For the electron spin rotation is achieved by two solenoids separated by quadrupole magnets that accomplish compensation of x–y cross-coupling. Two such rotator pairs are needed on both sides of the IP to provide spin rotation at different energies.

4. Status

The final design of the EIC is well underway. The conceptual design phase was completed in June 2021. The schedule calls for the authorization of long lead procurements by January 2024. The schedule and cost of the project are expected to be baselined in January 2025 and authorization to start the remainder of the EIC component production will be received in April 2025. The RHIC program will come to a conclusion in the summer of 2025. Removal of obsolete parts of the present RHIC will start immediately. The installation of the EIC will begin in 2027 and the commissioning of the new accelerator complex will start in 2029. In 2032, collision operation will be established at which point the colliding beam detector will be brought into position. EIC is expected to start the full physics program in 2034.

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