III.4.7 The US electron ion collider

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The Electron-Ion Collider (EIC) will enable study of how partons (quarks and gluons) form nuclear matter and will uniquely address profound questions of nuclear physics involving details of nuclear structure at the quark-gluon scale (see info graphic [1]). To address these questions, the EIC will provide polarized electron-proton and electron-ion collisions over a center-of-mass (CM) energy range of 30 GeV to 140 GeV, with luminosities up to $1 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

The U.S. Department of Energy (DOE) approval of mission need (CD-0) was granted for the EIC in December 2019 [2], and CD-1 followed in June 2021. The EIC is being constructed at Brookhaven National Laboratory (BNL) as a unique DOE project partnership between BNL and Thomas Jefferson National Accelerator Facility (TJNAF). This partnership has matured and deepened since the project's inception.

III.4.7.1 EIC overview

A schematic diagram of the EIC layout is shown in Figure III.4.1. The EIC will take advantage of the entire Relativistic Heavy Ion Collider (RHIC) facility at BNL, including RHIC magnets, injectors and tunnel enclosure. The two existing large experimental halls and interaction regions (IRs) are at IR6 (STAR) and IR8 (sPHENIX). The Hadron Storage Ring (HSR), constructed from RHIC modifications, the new Electron Storage Ring (ESR) and the Rapid Cycling Synchrotron (RCS) electron injector will all be co-located in the existing RHIC tunnel. The polarized electron injector gun and linac will be located at IR12, and an energy-recovery linac (ERL) for hadron beam cooling will be constructed at IR2. Hadrons will circulate counter-clockwise in the HSR, while electrons will circulate clockwise in the ESR and RCS. A new high-luminosity IR for the new EIC detector will be constructed at IR6.

Table III.4.1 lists the EIC parameters at the maximum luminosity CM energy $E_{\mathrm{cm}} = 105\,\mathrm{GeV}$, achieved by colliding $275\,\mathrm{GeV}$ polarized protons and $10\,\mathrm{GeV}$ polarized electrons. The overall facility design strategy and main parameters have remained stable since CD-1 [3]; they satisfy the design requirements without exceeding fundamental beam dynamics limits. In particular, the design parameters remain within the limits for maximum beam-beam tune-shift parameters (hadrons: $\xi_p \leq 0.015$; electrons: $\xi_e \leq 0.1$) and space charge parameter (≤ 0.06), as well as beam intensity limitations and IR chromaticity contributions.

III.4.7.2 EIC luminosity and detector

Figure III.4.2 illustrates the EIC luminosity versus CM energy over the required range of $30\,\mathrm{GeV}$ to $140\,\mathrm{GeV}$. Proton beam energies are shown in blue, and electron beam energies are shown in red, with the maximum luminosity achieved with beam energies and parameters shown in Table III.4.1. The facility luminosity is limited by different effects at different collision energies. At the lowest center-of-mass energy, maximum acceptable hadron space-charge tune-shift limits the permissible hadron beam current. As this constraint is loosened with higher hadron beam energies, the design enters a region where the luminosity is limited by acceptable beam-beam tune shifts in both beams.

At $10\,\mathrm{GeV}$ and higher, the electron beam current is limited by the installed RF power that replaces the synchrotron radiation power emitted by the electron beam. The installed RF power of $10\,\mathrm{MW}$ is

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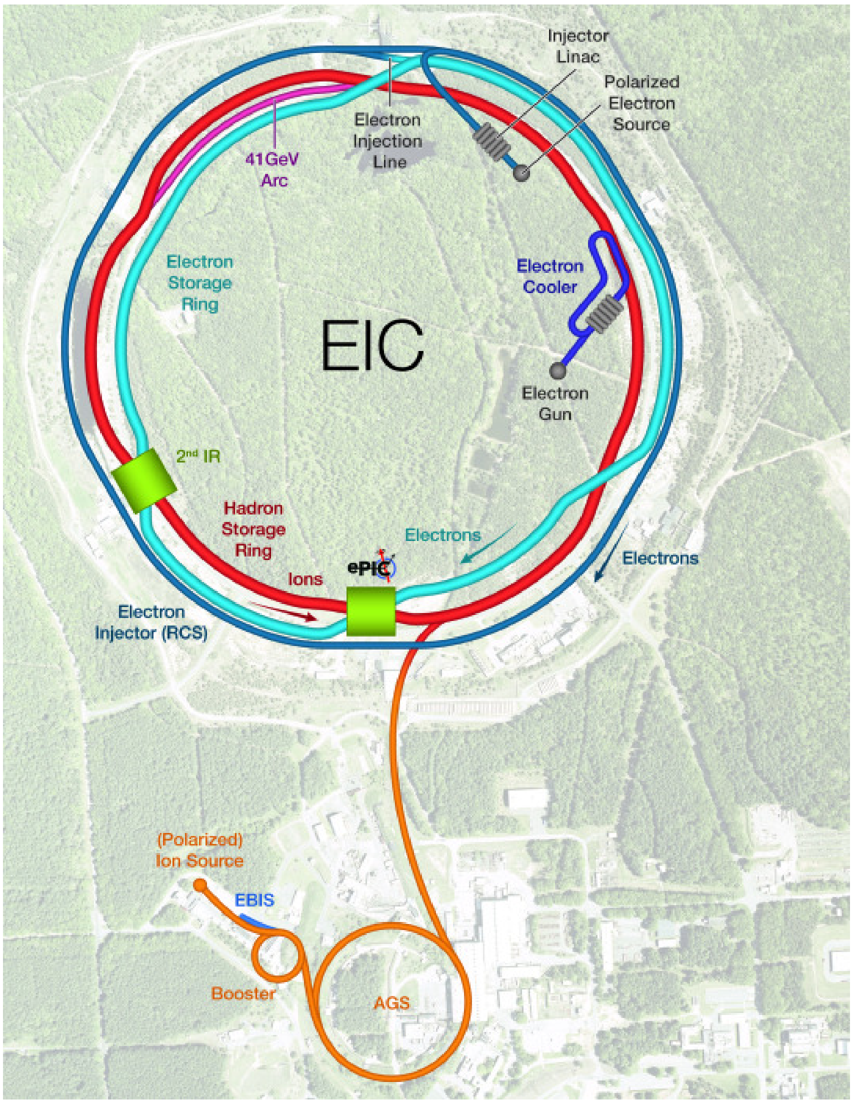

Fig. III.4.1: Schematic diagram of the EIC layout.

Table III.4.1: EIC parameters at maximum luminosity.

Parameter	**Protons**	**Electrons**
Center-of-Mass Energy [GeV]	105	10
Energy [GeV]	275	10
Number of bunches	1160	
Particles per bunch [10^{10}]	6.9	17.2
Average beam current [A]	1.0	2.5
RMS emittance [nm]	11.3 / 1.0	20.0 / 1.3
β^* [cm]	80 / 7.2	45 / 5.6
Beam divergence at IP [mrad]	0.119 / 0.119	0.211 / 0.152
Beam-beam parameter $\xi_{x,y}$	0.012 / 0.012	0.072 / 0.100
IBS growth time (long/horz) [h]	2.9 / 2.0	–
Synchrotron radiation power [MW]	–	9.0

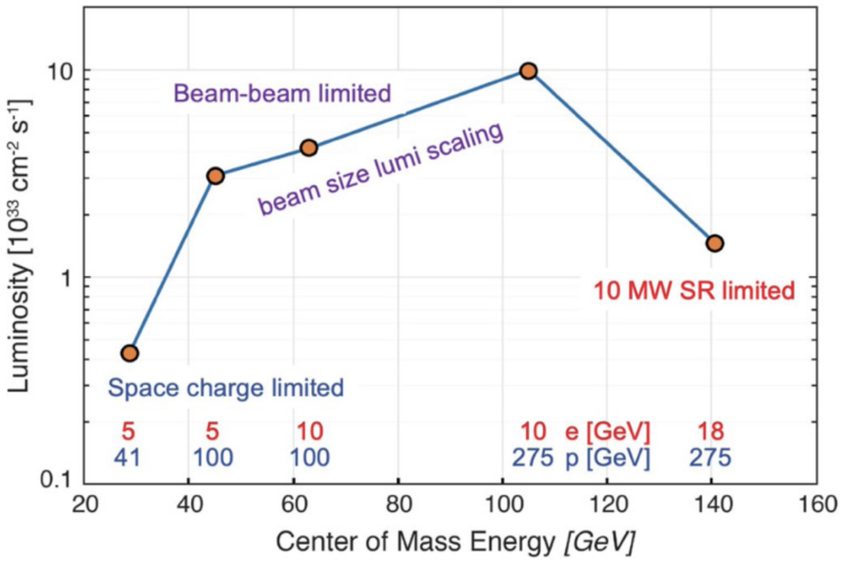

Fig. III.4.2: EIC luminosity as a function of center-of-mass energy.

not an intrinsic technical limit but is rather a design choice to balance facility performance with construction and operation costs. The electron beam's current and achievable luminosity become limited by the available RF power and synchrotron radiation losses for electron beam energies beyond $10\,\mathrm{GeV}$, corresponding to CM energies beyond $100\,\mathrm{GeV}$.

A single high-luminosity IR and detector will be installed in IR6 as part of the project. The EIC Detector Proposal Advisory Panel reviewed detector collaboration proposals and, in March 2022, unanimously identified the ECCE design proposal for construction as the first EIC detector [3]. The new collaboration is named ePIC, and rapid progress is being made on detector design to satisfy project CD-2 requirements.

The luminosities in Figure III.4.2 are shown for a single collision per turn, or with a single operational detector. The overall design accommodates a second interaction region and detector to be constructed later at IR8. To avoid unacceptably large beam-beam effects from multiple crossings per turn, these two detectors would share luminosity in an operational mode where the total luminosity at the two collision points equals the luminosity for operations with a single interaction point.

III.4.7.3 EIC accelerators

To accommodate the large hadron energy range from 41 to $275\,\mathrm{GeV}$ (for protons), while keeping hadron and electron beams synchronized, the circumference of the HSR must be adjusted accordingly. Between 100 and $275\,\mathrm{GeV}$, this is accomplished by a radial shift. At $41\,\mathrm{GeV}$, an "inner" arc between IRs 10 and 12 is used instead of the outer arc (Fig. III.4.1), reducing the HSR circumference by approximately $90\,\mathrm{cm}$.

The HSR superconducting magnets recovered from RHIC will be retrofitted with copper-clad stainless-steel screens to reduce resistive-wall heating due to the short bunches and high beam current. In addition, these screens will be coated with amorphous carbon to reduce the secondary-electron yield, thus suppressing electron cloud build-up.

Intrabeam scattering (IBS) and beam-beam effects will degrade the beam emittance in the HSR over the length of each store, limiting integrated machine luminosity. It is necessary to cool the hadron beam to counteract these effects and maintain high luminosity during long collision runs. The EIC high-luminosity parameters were optimized to have an IBS growth time of about two hours. A proposed cooling method called Coherent electron Cooling (CeC) was selected as the baseline for EIC due to its high cooling rate. The current design, simulated using a 1D cooling code, promises sufficient cooling rates to counteract IBS at $275\,\mathrm{GeV}$ and $100\,\mathrm{GeV}$, with 3D cooling studies underway. Hadron beams will also be pre-cooled at $24\,\mathrm{GeV}$ by the ERL.

Electron and hadron beams collide under a total crossing angle of $25\,\mathrm{mrad}$, requiring beam crabbing in both the HSR and ESR. Focusing is provided by superconducting low-beta quadrupoles, some of which share a common yoke. To compensate for betatron coupling induced by the detector solenoid, some of these superconducting magnets will be equipped with an additional skew-quadrupole coil. This scheme will also compensate for the effects of the tilted ESR plane.

The EIC pre-injector will provide $2\times 7\,\mathrm{nC}$ bunches within $2.5\,\mu\mathrm{s}$. The $2.856\,\mathrm{GHz}$ linac will operate at $100\,\mathrm{Hz}$ to provide four pairs of bunches, with $10\,\mathrm{ms}$ spacing between pairs. A total of 8 bunches (4 pairs) will be provided at a repetition rate of $1\,\mathrm{Hz}$ to the RCS. The polarized electron beam will be generated from a high-voltage (HV) DC gun with a strained superlattice photocathode. The EIC HVDC polarized gun prototype has achieved a polarized electron beam with $7.5\,\mathrm{nC}$ bunch charge and $37.5\,\mu\mathrm{A}$ average current without QE decay [6].

The RCS will merge the two batches of four polarized electron bunches from the linac into two $28\,\mathrm{nC}$ bunches and then accelerate them in $1\,\mathrm{Hz}$ cycles to the ESR collision energy of 5 to $18\,\mathrm{GeV}$. This scheme continuously replaces stored bunches in the ESR to facilitate arbitrary spin patterns and ensure high average polarization in both spin states. A dedicated design with high periodicity ensures that no depolarizing resonances are encountered during the entire energy ramp. This concept has been validated in extensive spin tracking studies that realistic machine imperfections such as misalignments.

The ESR has many similarities to high-intensity electron storage rings, such as the B-factories of KEK and SLAC, and will benefit from the technologies established by those facilities. It will consist of normal-conducting magnets arranged in a FODO cell structure. To achieve the horizontal design emittance of $24\,\mathrm{nm}$ over the entire energy range from 5 to $18\,\mathrm{GeV}$, the betatron phase advance per FODO cell is set to $90°$ at $18\,\mathrm{GeV}$ and $60°$ for 5 and $10\,\mathrm{GeV}$. Super-bends with adjustable reverse bends in the arcs are employed at $5\,\mathrm{GeV}$, both to achieve design emittance and to provide additional radiation damping to allow for a beam-beam parameter as high as $\xi_y = 0.1$. A superconducting $591\,\mathrm{MHz}$ RF system replenishes the radiation losses and provides the necessary longitudinal focusing. The ESR plane is tilted with respect to the HSR by $200\,\mu\mathrm{rad}$ around the axis through IP6 and IP8 to facilitate the necessary crossing of the two rings in IRs 4 and 12 without vertical orbit excursions in either ring.

The HSR comprises arcs from both the “Blue" and the “Yellow" RHIC rings. The straight sections connecting these arcs will be rebuilt to suit their purpose. The existing RHIC injector complex will continue to be used for HSR injection; the transfer line will be extended to the IR4 straight section, where the fast injection kickers can be accommodated. A strong hadron cooling system to counteract intra-beam scattering will be installed in IR2, which requires extensive modifications to the straight section lattice there.

III.4.7.4 Beam dynamics

The challenging beam parameters in the EIC collider rings require careful study of a large variety of related beam dynamics effects, such as dynamic aperture, collective effects, beam-beam effects and polarization.

Dynamic aperture (DA) studies have been performed for both collider rings. A significant reduction in DA is observed in the HSR from crab crossing, compared to that with head-on collisions without crabbing. The IR magnet field errors must therefore be controlled to within one unit to ensure sufficient HSR DA. ESR DA studies have focused on the most challenging scenario: the $18\,\mathrm{GeV}$, $90°$; lattice with two interaction regions. The minimum goal of 10σ in all three planes has been successfully demonstrated based on a novel chromatic compensation approach.

With beam currents as high as shown in Table III.4.1, collective effects are a serious concern in both rings, and vacuum system components must be designed and optimized to a high degree. The ESR single-bunch instability threshold is above requirements for stable operation; the large beam-beam tune spread of up to $\xi = 0.1$ provides sufficient Landau damping to counteract transverse coupled-bunch instabilities. An ESR longitudinal damper is planned to limit coherent longitudinal oscillations that are detrimental to the hadron beam emittance via crab cavity arrival time and beam- beam interactions.

Collision parameters have been optimized to minimize hadron beam emittance growth rates while simultaneously retaining high luminosity. The unique beam-beam dynamics with crabbing is being studied to ensure the attainability of the large beam- beam parameters. Weak-strong simulations indicate that stable operations can indeed be achieved, given a careful selection of machine parameters, such as working points. Strong-strong simulations suffer from numerical effects due to the limited number of macroparticles. Studies are underway to understand these models and develop a scaling law that allows extrapolation of the obtained strong-strong growth rates to the actual number of beam particles. Strong-strong coherent beam-beam effects have been studied, with threshold onset at twice design intensities.

Multipole components of the crab cavity fields are a potential concern due to the time-dependent nature of these fields and their modulation with the synchrotron frequency. Simulation studies are being performed to establish the required field quality tolerances. The effect of crab cavity RF noise on hadron beam emittances has been investigated.

Extensive spin matching for the ESR has resulted in an equilibrium polarization of 30 percent at $18\,\mathrm{GeV}$ in presence of misalignments, which is the most challenging operating scenario. With continuous bunch replacement, this ensures an average polarization during operations of 70 percent, even at $18\,\mathrm{GeV}$.

III.4.7.5 Conclusion

The EIC partnership project between BNL and TJNAF capitalizes on each lab's strengths with well-defined scope ownership and a commitment to seamless inter-lab collaboration. The EIC project is moving forward with a mature design to deliver a world-class, unique complex that will enable unprecedented exploration of fundamental nuclear physics questions.

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