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DESIGN STATUS UPDATE OF THE ELECTRON-ION COLLIDER*

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Abstract

The design of the electron-ion collider EIC to be constructed at Brookhaven National Laboratory has been continuously evolving towards a realistic and robust design that meets all the requirements set forth by the nuclear physics community in the White Paper. Over the past year, activities have been focused on maturing the design and on developing alternatives to mitigate risk. These include improvements of the interaction region design as well as modifications of the hadron ring vacuum system to accommodate the high average and peak beam currents. Beam dynamics studies have been performed to determine and optimize the dynamic aperture in the two collider rings and the beam-beam performance. We will present the EIC design with a focus on recent developments.

INTRODUCTION

The electron-ion collider EIC (see Fig. 1) will be based on the existing RHIC complex. An electron storage ring (ESR) installed in the RHIC tunnel will provide a stored polarized electron beam with 5 to 18 GeV beam energy that will be brought into collision with polarized protons or light ions, or with unpolarized heavy ions stored in the hadron storage ring (HSR). Up to two interaction regions are feasible, with one (in IR6) being included in the EIC scope.

The ESR operates at fixed energy, with polarized electrons injected from the rapid cycling synchrotron (RCS). Bunches are continuously replaced during the store at a rate of two bunches once per second in order to achieve an average polarization of 80 percent.

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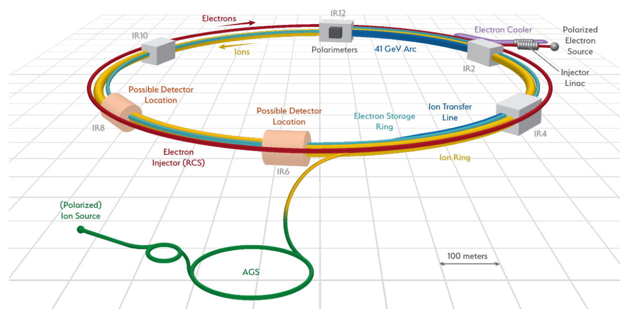

Figure 1: Schematic diagram of the EIC layout.

The hadron storage ring, composed of arcs from both the Yellow and Blue RHIC rings, will be modified to be suitable for the shorter bunch spacing and bunch length as well as the increased beam current w.r.t. RHIC. Strong hadron cooling will be added to achieve and maintain the required design emittances.

An interaction region has been designed to collide the electron and hadron beams under a total crossing angle of 25 mrad. A maximum electron-proton luminosity of $10^{34}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ is reached at a center-of-mass energy of 105 GeV.

RCS

A rapid-cycling synchrotron (RCS) [1] will be added in the existing RHIC tunnel. Two batches of four 7 nC bunches of polarized electrons will be generated in a polarized gun [2] and accelerated to 400 MeV in an S-band LINAC. An RF kicker [3] then injects these bunches into the RCS. On an intermediate acceleration porch around 1.5 GeV these two batches will then each be merged into two 28 nC bunches. The RCS will further accelerate these two bunches to 5 to 18 GeV for injection into the electron storage ring.

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The conditions for depolarizing intrinsic and imperfection resonances can be expressed as

$$a\gamma = nP \pm Q_y \qquad \text{intrinsic,} \qquad (1)$$
$$a\gamma = nP \pm [Q_y] \qquad \text{imperfection,} \qquad (2)$$

where $a = 1.16 \times 10^{-3}$ is the anomalous magnetic moment of the electron, P the periodicity of the accelerator, $[Q_y]$ denotes the integer part of the vertical tune, and n is an integer. The lattice of the RCS has a high periodicity of $P = 96$ and an integer tune of $[Q_y] = 50$ in order to be free of both intrinsic and imperfection spin resonances over the entire energy range from 400 MeV to 18 GeV, thus avoiding these depolarizing resonances on the ramp.

ELECTRON STORAGE RING

The electron storage ring (ESR) stores up to 2.5 A of spin polarized electrons in up to 1160 bunches, with the beam current limited by the superconducting RF system [4, 5] capable of providing 10 MW of power to the beam. The bending sections in the arcs are realized as super-bends that increase the damping decrement at energies below 10 GeV to facilitate a beam-beam parameter as high as $\xi_y = 0.1$ and to aid in providing the desired horizontal emittance of 20 to 30 nm over the entire energy range.

Dynamic aperture evaluation and optimization is being performed. A sextupole configuration yielding sufficient dynamic aperture has been found for the 10 GeV lattice with its FODO cell phase advance of 60 degrees, the focus is currently on the 18 GeV lattice with 90 degrees phase advance [6,7]. Spin tracking studies are underway as well [8,9]. Applicability of a novel compact spin rotator [10] has been studied that would provide more flexibility in the geometric layout of the ESR. Collective effects such as beam induced heating, short-range and long-range wakefields have been studied extensively [11–15], as well as the impact of uneven bunch patterns on the multibunch spectrum [16].

AGS BOOSTER UPGRADES

The AGS Booster has been equipped with an AC dipole to preserve polarization during acceleration of polarized helions to $|G\gamma| = 10.5$. While extraction from the AGS Booster at $|G\gamma| = 7.5$ is possible, it would involve crossing an intrinsic resonance in the AGS. Tracking studies have been performed to evaluate the resulting dynamic aperture with the optics strongly distorted by the Siberian snake [17].

HADRON STORAGE RING

The superconducting hadron storage ring (HSR) is comprised of arcs from both the Blue and the Yellow RHIC rings. The shorter bunch spacing of 10 nsec necessitates new, faster injection kickers [18] that will be relocated to IR4. The feasibility of re-using the existing stripline BPMs despite the higher average and peak beam currents has been investigated [19]. To reduce resistive wall heating and the secondary electron yield of the vacuum chamber, copper-clad stainless steel screens [20] pre-coated with amorphous carbon [21] will be inserted throughout the entire hadron storage ring. The impact of these sleeves on the impedance has been studied [22], as have been thermal and vacuum performance issues [23,24]. Four additional Siberian snakes will be installed in order to facilitate acceleration and storage of polarized ^{3}He beams, and to increase spin polarization transmission for protons on the ramp to 275 GeV to nearly 100 percent. The feasibility of polarized deuteron acceleration has been studied as well [25,26]. Dynamic aperture studies are being carried out [27,28].

STRONG HADRON COOLING

To reach a peak luminosity of 10^{34} cm^{-2}sec^{-1}, the EIC utilizes "flat" hadron beams of unequal transverse emittances. Together with the short RMS bunch length of $\sigma_s = 6$ cm and a bunch intensity of $N = 0.7 \times 10^{11}$ protons per bunch this results in an IBS growth time of 2 hours. Achieving and maintaining these emittances in the HSR therefore requires strong hadron cooling, realized in the form of micro-bunched electron cooling. This scheme is essentially a high-bandwidth stochastic cooling system, with an electron beam acting as the pickup and kicker, and a micro-bunch instability utilized to amplify the imprint the protons leave on the electron beam in the pickup section. Accelerator design of the strong hadron cooler is underway [29, 30], and extensive simulation studies are being performed [31]. A high-intensity, low-emittance electron gun for the cooler is under development [32].

As an alternative to strong hadron cooling, a scheme involving the second, unused RHIC ring as a full energy injector to the HSR has been explored as well [33]. In this concept the entire hadron beam is regularly replaced during stores, at intervals of 30 minutes to one hour. However, after a careful analysis of the alternatives this scheme was abandoned in favor of strong hadron cooling.

INTERACTION REGION

The EIC interaction region is based on a total crossing angle of 25 mrad [34]. Detrimental geometric and beam dynamics effects arising from this crossing angle are compensated using crab cavities. Since the proposed crab cavities lack axial symmetry, a multipole analysis has been performed to ensure the applicability of these devices to the EIC [35].

The interaction region design features a ±4.5 m magnet-free region for the detector, and a forward spectrometer magnet for detection of hadrons scattered under small angles. A weak dipole magnet separates the outgoing electron beam from synchrotron radiation and bremsstrahlung photons. Novel magnet designs [36] are employed, all based on conventional NbTi technology in order to reduce risk and cost. The geometric layout of the IR vacuum chamber has been optimized to minimize its impedance [37]; as a result the total power loss due to higher-order modes in the central

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vacuum chamber is expected to be less than 250 W. The vacuum pressure profile has been simulated with SynRad and Molflow+ [38]. Coupling compensation schemes of the detector solenoid have been studied as well [39]. Due to the 25 mrad total crossing angle, the solenoid, which is aligned with the electron beam trajectory, causes vertical closed orbit distortions on the hadron beam that necessitate vertical dipole correctors as well as vertical crab kicks.

A second interaction region [40] with measurement capabilities complementary to those of the first IR [34] is currently being designed.

BEAM-BEAM

To achieve the desired high luminosity both beams have to operate near the beam-beam limit, with beam-beam parameters of $\xi_e = 0.1$ for electrons and $\xi_h = 0.015$ for hadrons, respectively. Similar beam-beam parameters have been successfully demonstrated in routine operations at colliders such as KEKB, RHIC, and the LHC. However, many features of the EIC beam-beam interaction have not been demonstrated at any existing facilities, such as crab crossing for hadrons, hadron beams with unequal ("flat") transverse emittances, collisions of beams with vastly different bunch lengths, etc.

Extensive beam-beam simulation studies have been performed to ensure the feasibility of the proposed collision scheme. Parameter scans were performed [41] to minimize the observed proton beam emittance growth in strong-strong simulations. Tune scans were performed to find the optimum working point [42], and the ideal beam size ratio σ_y/σ_x at the interaction point [43] was determined as well.

The non-linearity of the crab kick due to the finite RF wavelength of the crab cavities has been identified as a major source of emittance growth. This effect is significantly mitigated by adding a second harmonic (394 MHz) crab cavity system to the fundamental 197 MHz crab cavities [44]. The effect of other imperfections such as spurious dispersion or a less-than-perfect betatron phase advance between the interaction point and the crab cavities has been studied as well [45].

Strong-strong simulations were performed to study the effects of continuous electron bunch replacement on hadron beam emittance growth [46].

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