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DESIGN STATUS OF THE ELECTRON-ION COLLIDER*

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Abstract

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.

OVERVIEW

The Electron-Ion Collider (EIC) will be built at Brookhaven National Laboratory in a partnership between BNL and TJNAF. The project utilizes the existing infrastructure of the Relativistic Heavy Ion Collider (RHIC) accelerator complex. The Hadron Storage Ring (HSR) consists of a mix of arcs of the two superconducting RHIC storage rings that need to undergo some necessary modifications to make them suitable for the HSR beams. An electron storage ring (ESR) will be added in the existing RHIC tunnel, where it will provide collisions with the hadron beams stored in the HSR. Electron and hadron beams will collide in up to two interaction regions (IRs), located in the IR6 and IR8 straight sections of RHIC that currently house the STAR and sPHENIX detectors, respectively. While only the interaction region and corresponding detector in IR6 are within the scope of the EIC, a second interaction region is highly desirable. Therefore, it is mandatory to demonstrate that the EIC is indeed capable of supporting two interaction regions, both in terms of geometric layout and beam dynamics.

The highest luminosity of $1.0 \cdot 10^{34}$ cm^{-2} sec^{-1} is reached with 10 GeV electrons colliding with 275 GeV protons, which corresponds to a center-of-mass energy of 105 GeV.Higher center-of-mass energies are achieved by increasing the electron energy. To limit the total synchrotron radiation losses to 10 MW, the electron beam intensity has to be reduced accordingly, resulting in a corresponding reduction in luminosity.

HADRON STORAGE RING

The hadron storage ring (HSR) consists of a mixture of the superconducting arcs of the existing RHIC facility, with some necessary modifications, both to the lattice and layout of the straight sections, and to technical systems [1, 2]. The new interaction region in the IR6 straight section requires lattice modifications that extend past the present transition jump quadrupoles in that area, thus requiring a different approach to transition crossing [3]. Dynamic aperture studies [4] are being carried out to ensure stable operation with sufficient beam lifetimes in the presence of the new interaction region as well as radial orbit shifts required to synchronize the electron and hadron beams over the entire hadron beam energy range [5]. To accommodate the large number of high intensity, short bunches, pre-coated, actively cooled beam screens will be inserted into the beam pipes. The copper coating of these sleeves will reduce the resistive wall heating to levels manageable by the cryogenic system, while an additional amorphous carbon coating will reduce the secondary electron yield to avoid electron cloud build-up. A dedicated probe [6] has been developed to survey the available aperture around the hadron ring to ensure safe insertion of the beam screens. The existing RHIC beam position monitors (BPMs) will need to be replaced by new button BPMs as a response to the higher beam current and shorter bunch length which would damage the existing system [7–9]. The collimation system will be relocated and upgraded with a momentum collimator to account for the more demanding background tolerances of the EIC detector. To facilitate the ramp and storage of polarized ^{3}He ions as well as to im-

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prove the polarization transmission for protons on the ramp, four additional Siberian snakes will be installed in the HSR, bringing the total number to six [10–12]. Spin tracking simulations have been performed to demonstrate the feasibility of accelerating polarized ^{3}He in this configuration [13]. The spin rotators around the interaction point will be relocated to accommodate the EIC interaction region [14]. While it is not in the EIC scope, a second interaction region [15] has been designed for installation in the IR8 straight section to ensure that the EIC can indeed support two interaction regions in the future, both in terms of geometric layout and beam dynamics.

ELECTRON STORAGE RING

The electron storage ring (ESR) is based on a regular FODO lattice structure with "super-bends" to enhance radiation damping at energies below 10 GeV [16]. In an effort to reduce cost, the existing quadrupoles, sextupoles and dual-plane dipole correctors of the Advanced Photon Source (APS) will be re-used throughout the arcs and most of the straight sections. Dipole magnets as well as a small number of special quadrupoles for installation in tight spaces are being designed. Dynamic aperture studies based on the measured multipoles of these magnets and realistic assumptions of the dipole field quality have been performed, and the minimum required dynamic aperture of 10σ in all three dimensions has been demonstrated [17–20]. Careful spin matching ensures polarization lifetimes that are sufficient to guarantee an average polarization of 70 percent, with single bunches replaced at a rate of one bunch per second [21, 22]. A particular challenge in this respect is the generation of a vertical emittance of about 3 nm (10 percent emittance coupling) without negatively affecting polarization [23]. Preliminary design of the components of the ESR is underway, like the SRF cavities [24], vacuum components [25], or collimators [26].

RAPID CYCLING SYNCHROTRON

Bunches circulating in the ESR are replaced on a regular basis in order to maintain high average polarization levels, using a rapid cycling synchrotron (RCS). The RCS needs to ramp over a wide energy range, from 400 MeV at injection to up to 18 GeV at extraction into the ESR. This raises concerns about the magnetic field quality at injection energy, when due to the low field values errors from remanent field effects can be particularly large. To raise the dipole field at injection to levels demonstrated at other facilities, each dipole is therefore split into three segments of equal length, and only the center dipole is powered to 190 G at injection while the two outer ones are at zero field after some de-gaussing process. Studies on the magnetic field tolerances are underway [27]. Bunches are supplied to the RCS from a 400 MeV S-band LINAC, operating at a repetition rate of 100 Hz. Four 7 nC LINAC bunches supplied by the gun [28, 29] are injected into the RCS and merged there into a single bunch at around 1 GeV [30].

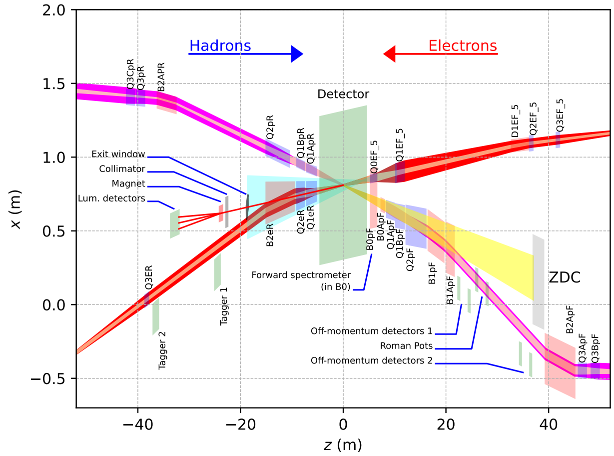

Figure 1: Layout of the EIC interaction region.

INTERACTION REGION

The interaction region (IR) [31] is based on a crossing angle of 25 mrad, compensated by crab cavities in both the electron and the hadron beam line [32–34], see Figure 1. Beams are focused to small cross sections with β-functions of typically 60 cm horizontally and 5 cm vertically, depending on the beam energies, by an arrangement of superconducting low-β quadrupoles around the interaction point. These magnets are placed about 5 m from the interaction point (IP) to provide sufficient space for the 9 m long detector. The outgoing, or "forward" hadron beam line is equipped with "Roman Pots" to detect scattered particles with transverse momenta as low as 200 MeV/c. To facilitate this, the forward hadron low-β quadrupoles need to have apertures that are much larger than required by the circulating beam alone. On the rear side of the detector, the electron low-β quadrupoles need large apertures to safely pass the synchrotron radiation photons generated by the upstream quadrupoles through the interaction region. These large apertures and the presence of the nearby beamlines for the electrons on the forward and the hadrons on the rear side, with their respective low-β magnets, make these magnets rather challenging [35]. The 2 T detector solenoid introduces significant coupling that needs to be compensated by skew quadrupoles that need to be integrated in the interaction region as well [31]. Placement of dipole correctors and beam position monitors is crucial to guide the beams as well as the synchrotron radiation fan safely through the interaction region [36, 37]

HADRON COOLING

To achieve the required design emittances of the hadron ring, a two-stage hadron cooling system is required. Hadron beams are first cooled by a bunched-beam electron cooler at injection energy to the normalized emittances required at store [38]. After ramping those beams to collision energy, these emittances are then maintained by a second cooler. This high energy cooler will be based either on microbunch

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coherent electron cooling [39, 40], or on bunched beam cooling by a high intensity racetrack ring [41–43]. A high intensity, low emittance electron gun for the hadron cooler is being designed and optimized [44–46].

BEAM DYNAMICS

Beam dynamics in the various accelerators that comprise the EIC have been extensively studied to ensure safe, successful operation of the facility [47]. Both weak-strong and strong-strong beam-beam simulations [48–50] have been carried out to study the effects of numerous imperfections on crab crossing, such as non-closure of the crab bump or transverse beam jitter [51–56]. The crab cavities themselves could have a negative impact on machine performance due to multipole field errors [57] or RF noise [58, 59], which needs to be studied carefully in order to determine the tolerances on these errors and to design the low level controls accordingly [60].

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