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ELECTRON-ION COLLIDER DESIGN STATUS*

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Abstract

The Electron-Ion Collider (EIC) is being designed for construction at Brookhaven National Laboratory. Activities have been focused on beam-beam simulations, polarization studies, and beam dynamics, as well as on maturing the layout and lattice design of the constituent accelerators and the interaction region. The latest design advances will be presented.

OVERVIEW

The Electron-Ion Collider (EIC) will be constructed at Brookhaven National Laboratory, utilizing the existing infrastructure and accelerator complex of the Relativistic Heavy Ion Collider (RHIC). The hadron storage ring (HSR) comprises arcs of the two superconducting RHIC storage rings. An electron storage ring (ESR) will be installed in the existing RHIC tunnel, where it will provide beam collisions with the HSR hadron beam in up to two interaction regions. Fully polarized electron bunches will be provided to the ESR by a rapid-cycling synchrotron (RCS) in the same tunnel. An interaction region with a crossing angle of 25 mrad has been designed that reaches a luminosity of 10^{34} cm^{-2} sec^{-1}. A second interaction region is feasible, but not within the EIC project scope. layout of the EIC complex. 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.

ELECTRON PRE-INJECTOR

The EIC pre-injector provides 2×7 nC bunches within 2.5 µs. The LINAC will operate at 100 Hz to provide four pairs of bunches, with 10 msec spacing between pairs. A total of 8 bunches (4 pairs) will be provided at a repetition rate of 1 Hz. In the RCS, these will be merged to result in two 28 nC bunches. The polarized electron beam will be generated from a high voltage (HV) DC gun with a strained superlattice photocathode. The bunching section consisting of a 117.8 MHz pre-buncher, two of 591.1 MHz and a 2.856 GHz buncher will be used to compress the bunch length to 10 psec. Then eight of 2.856 GHz S-band normal conducting traveling wave plate LINACs boost the beam energy up to 400 MeV [1]. A dipole-solenoid spin rotator will be used for rotating the spin direction from longitudinal to vertical for injection into the RCS. The EIC HVDC polarized gun has achieved polarized electron beam with 7.5 nC bunch charge and 37.5 μA average current without QE decay [2].

RAPID-CYCLING SYNCHROTRON

A rapid-cycling synchrotron installed in the collider tunnel accelerates two bunches of polarized electrons every second to an energy of 5 to 18 GeV for injection into the ESR [3,4]. 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, including realistic machine imperfections such as misalignments [5]. Optimization of the chromatic correction scheme resulted in sufficiently large

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dynamic aperture over the entire energy range from 400 MeV to 18 GeV [6].

ELECTRON STORAGE RING

The electron storage ring (ESR) consists of normal-conducting magnets [7] arranged in a FODO cell struture. To achieve the horizontal design emittance of 24 nm over the entire energy range from 5 to 18 GeV, the betatron phase advance per FODO cell is set to 90 degrees at 18 GeV, and 60 degrees for energies of 5 and 10 GeV [8]. In addition, so-called super-bends with adjustable reverse bends in the arcs are employed at 5 GeV beam energy, both to achieve the 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 MHz RF system replenishes the radiation losses and provides the necessary longitudinal focusing [9, 10]. The entire ESR plane is tilted with respect to the hadron storage ring by 200 μrad around the axis through IPs 6 and 8 to facilitate the necessary crossing of the two rings in IRs 4 and 12 without the need of vertical orbit excursions in either ring.

Extensive spin matching [11] has resulted in an equilibrium polarization of 30 percent at 18 GeV in presence of misalignments, which is the most challenging. Together with continuous bunch replacement, this ensures an average polarization of 70 percent.

HADRON STORAGE RING

The hadron storage ring (HSR) comprises arcs from both the “Blue” and the “Yellow” RHIC rings. The straight sections connecting these arcs will be completely rebuilt to suit their purpose [12]. The existing RHIC injector complex will continue to be used for HSR injection, but the transfer line will be extended from the present injection location to the IR4 straight section, where the necessary number of fast injection kickers can be accommodated [13, 14]. A strong hadron cooling device to counteract intra-beam scattering will be installed in IR2, which requires extensive modifications to the straight section lattice there [15].

To accommodate the large hadron energy range from 41 to 275 GeV (for protons) and keep hadron and electron beams synchronized, the circumference of the HSR needs to be adjusted accordingly. Between 100 and 275 GeV, this is accomplished by a radial shift. At 41 GeV, an “inner” arc between IRs 10 and 12 is used as a “shortcut” instead of the outer arc, thus reducing the circumference of the HSR by approximately 90 cm. This implementation requires two dedicated “switch yards” in IRs 10 [16] and 12; in addition, IR12 also accommodates the collimation system [17]. The superconducting magnets will be retrofitted with copper-clad stainless-steel screens to reduce resistive wall heating due to the short bunches and high beam current [18]. In addition, these screens will be coated with amorphous carbon to reduce the secondary elecron yield, thus suppressing electron cloud built-up. The existing RHIC spin rotators will be re-used, but their different location in the interaction region makes their usage more challenging [19]. Dynamic aperture studies are being carried out to determine the allowable multipole errors in the superconducting IR magnets [20]. Since the luminosity optimization of the EIC is based on “flat” hadron beams with unequal horizontal and vertical emittances, betatron coupling has to be minimized. The feasibility of such precise decoupling is being investigated [21].

STRONG HADRON COOLING

Intrabeam scattering (IBS) and beam-beam effects will degrade the beam emittancein the HSR over the length of the store, limiting machine luminosity. To maintain high luminosity during long collision runs, it is desirable to cool the hadron beam. The EIC high luminosity parameters were selected to have an IBS growth time of about 2 hours. A proposed cooling method called Coherent electron Cooling (CeC) is selected as the baseline for EIC due to its high cooling rate [22]. The current cooling design using a 1D Cooling code shows sufficient cooling rates to counteract IBS at 275 GeV and 100 GeV [23]. 3D cooling studuies are under way. However, our studies show that strong hadron cooling is not able to achieve an inital vertical emittance of 0.3 μm. Furthermore, it is also very difficult to counteract IBS at 41 GeV beam energy. Therefore, a 24 GeV precooler is under consideration now, which will also be able to cool 41 GeV protons. The gun up to cooling section 3D simulation shows we can achieve 1 nC bunches with normalized emittance about 3 μrad, and micronbunching gain at optical wavelength (< 10*s* of micrometers) is nearly unity, indicating the beam noise is near shot noise [24]. A 100 mA energy recovery linac lattice for both strong hadron cooling and the precooler has been developed.

INTERACTION REGION

Electron and hadron beams collide under a total crossing angle of 25 mrad [25]. Focusing is provided by superconducting low-β quadrupoles, some of which share a common yoke. To compensate betatron coupling induced by the detector solenoids, some of these superconducting magnets will be equipped with an additional skew-quadrupole coil [26]. This scheme will also compensate for the effects of the tilted ESR plane.

A second interaction region, though not within the scope of the EIC project, has been conceptually designed for IR8 [27]. Due to the slightly different geometry of the overall machine layout in IR8 compared to IR6, this interaction region is based on a larger crossing angle of 35 mrad to fit into the available tunnel space.

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 beam-beam effects, polarization, and collective effects, as well as dynamic aperture [28]. Dynamic aperture studies have been performed in both the

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hadron (HSR) and the electron storage ring (ESR). A significant reduction of about 3σ is observed in the hadron storage ring due to the crab crossing scheme, compared to the dynamic aperture with head-on collisions. As a consequence the IR magnet field errors have to be controlled to within one unit to ensure sufficient dynamic aperture. Dynamic aperture studies in the ESR have focused on the most challenging scenario, namely the 18 GeV, 90 degree 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 [29–31].

With beam currents as high as 2.5 A in the ESR and 1 A in the HSR, collective effects are a serious concern in both rings, and vacuum system components have to be designed and optimized to a high degree. The single-bunch instability threshold in the ESR is above the requirement 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 as well as fast beam-ion instabilities. A longitudinal damper is foreseen in the ESR to limit coherent longitudinal oscillations which are detrimental to the hadron beam emittance via the associated arrival time jitter at the interaction point.

Parameters at the interaction point have been optimized inorder to minimize hadron beam emittance growth rates while simultaneously retaining high luminosity [32]. The large total crossing angle of 25 mrad requires crab cavities to recover the geometric luminosity loss as well as to ensure stable beam operations. The resulting unique beam-beam dynamics has to be studied in extensive simulations to ensure the attainability of the large beam-beam parameters associated with the high luminosity, and an acceptable hadron beam emittance growth rate [33–35]. 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, which results in artificially large hadron beam emittance growth rates that would not be acceptable in the real machine. Extensive studies are underway to understand the effect of these deficiencies, and to develop a scaling law that allows extrapolation of the obtained strong-strong growth rates to the actual number of beam particles, which is several orders of magnitude larger than in simulations. Coherent beam-beam effects have been investigated in strong-strong simulations [36].

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 [37]. 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 [38].

The effect of the 200 μrad tilt of the ESR relative to the HSR has been studied both analytically and in simulations. Since the detector solenoid is a significant source of betatron coupling that needs to be compensated locally to avoid detrimental effects in conjunction with crab crossing, the same correction scheme can be used to compensate for the effects of the tilt [26].

The effects of the beam-beam interaction and beam-gas scattering on transverse electron beam tails have been simulated [39]. With the minimum apertures in the ESR being $13\sigma_x$ horizontally and $23\sigma_y$ vertically, beam lifetimes of approximately 10 hours are expected for a vacuum pressure of 5 nTorr.

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