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eRHIC ELECTRON RING DESIGN STATUS*

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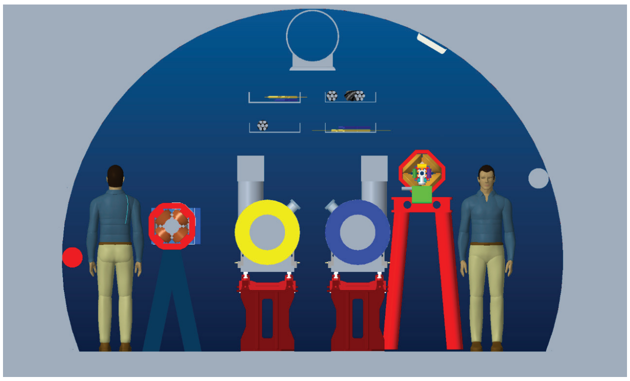

Figure 1: eRHIC tunnel cross section with the electron storage ring in the same plane as the two existing RHIC ion rings, and the injector synchrotron above.

Abstract

For the proposed electron-ion collider eRHIC, an electron storage ring will be installed in the existing RHIC tunnel. To reach the high luminosity of up to $10^{34}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$, beam currents up to 2.5 A have to be stored. Besides high luminosity the physics program requires spin polarization levels of 70 percent, with both spin "up" and spin "down" orientations present in the fill. This is only feasible by using a full-energy spin polarized injector that replaces bunches faster than the depolarization rate. To limit the repetition rate of that injector to about one hertz, the polarization lifetime in the storage ring has to be maximized by proper spin matching and countermeasures for the machine misalignments. We will give an overview of the electron storage ring design.

INTRODUCTION

The proposed electron-ion collider eRHIC [1] at Brookhaven National Laboratory consists of an electron ring installed in the existing RHIC tunnel, and colliding beams with the existing "Yellow" RHIC ring in IRs 6 and 8. This new storage ring wil be installed in the same plane as the RHIC ion rings, as shown in Figure 1. The two RHIC rings intersect in the center of each of the six straight sections, resulting in each ring being composed of three inner and three outer arcs. To achieve the same circumference in the electron storage ring, it therefore has to consist of three inner and three outer arcs as well.

The necessary large center-of-mass energy range of 30 to 140 GeV requires an electron beam energy range from 5 to 18 GeV, and a proton beam energy range from 41 to 275 GeV. To optimize the luminosity over the entire energy range the horizontal emittance of the electron beam needs to be 20 nm independent of energy, see Table 1 [2]. To achieve the desired large beam-beam parameter of $\xi = 0.1$ over the entire energy range, sufficient synchrotron radiation damping is required. While radiation damping at energies of 10 GeV and above is already naturally fast enough, increasing it at low energies requires dedicated measures.

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Table 1: Key Design Parameters of the Electron Storage Ring

energy [GeV]	5	10	18
beam current [A]	2.5	2.5	0.26
bunch intensity [10^{11}]	3.0	3.0	0.6
hor. emittance [nm]	20	20	20
beam-beam parameter	0.1	0.1	0.1

LATTICE DESIGN

The six arcs of the electron storage ring are composed of FODO cells with a cell length of roughly 16 m. To fulfill the conflicting requirements of minimum synchrotron radiation power at high energy and fast radiation damping at low energy, each bending magnet is split into three segments - a short, 45 cm long dipole in-between two 2.66 m long dipoles, as schematically shown in Figure 2. At energies of 10 GeV and above, all three segments are powered uniformly to provide a smooth bend with maximum curvature, therefore minimizing the generated synchrotron radiation. Below 5 GeV, the center dipole is powered with the opposite polarity, with magnetic fields reaching up to 0.7 T. This result in a sharp bend in the center of the super-bend that generates enough synchrotron radiation for a transverse radiation damping time equivalent to 10000 turns.

To achieve the desired horizontal emittances, the ring is operated with different betatron phase advances, namely 90 degrees per FODO cell at 18 GeV, and 60 degrees at 5 and 10 GeV. The super-bends required for fast radiation damping at 5 GeV contribute significantly to increasing the emittance to the design value of 20 nm. Small adjustments, if required, can then be achieved by a small radius change.

SPIN ROTATORS

To provide longitudinally spin-polarized beams at the interaction point (IP), spin rotators that transform the vertical polarization direction in the arcs to the longitudinal direction at the IP are required. For the electron beam energy range in eRHIC, a solenoid-based scheme is the most efficient one in terms of space requirement. In this scheme, the vertical spin

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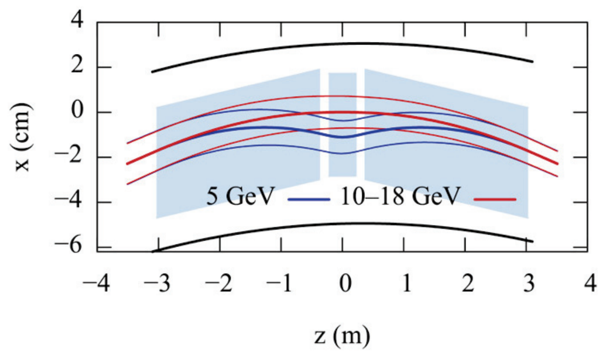

Figure 2: Schematic layout of a super-bend dipole.

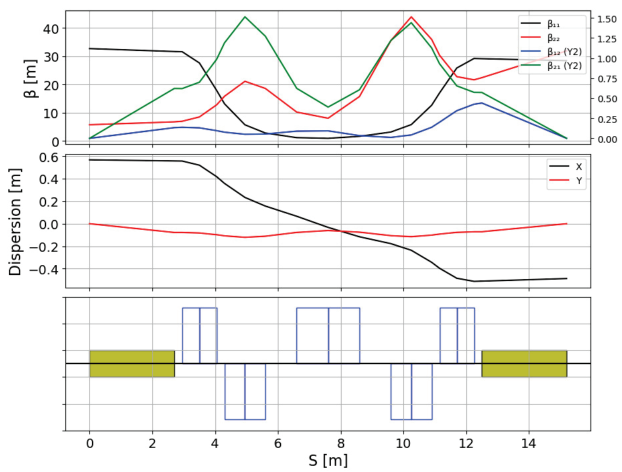

Figure 3: Rotator solenoid section with five quadrupoles in-between solenoid segments for coupling compensation.

direction coming from the arc is first rotated into the radial direction by means of a solenoid, and then transformed into longitudinal polarization using a dipole magnet.

Since the required integrated solenoid and dipole fields of the spin rotator depend on the beam energy, dedicated spin rotators are required for the two extreme beam energies of 5 and 18 GeV. For energies in-between these two extremes, the respective solenoids can be tuned such that longitudinal polarization is achieved at all energies.

Betatron coupling induced by the spin rotator solenoids is compensated by splitting each individual solenoid into two segments of equal length, with five quadrupoles in-between to provide the proper betatron phase advance in the two transverse planes such that the two half-solenoids compensate each other in terms of betatron coupling, as shown in Figure 3.

DYNAMIC APERTURE

For sufficient beam lifetime of several hours a minimum dynamic aperture of 10σ in all three planes is required. Multiple sextupole families are necessary to compensate the off-momentum β-beat induced by the strong low-β quadrupoles where β-functions reach several hundreds of meters. As a minimum, three sextupole families per transverse plane are required at a FODO cell phase advance of 60 degrees. At 90 degrees, as it is the case at 18 GeV beam energy, two sextupole families per transverse plane are necessary, with the additional constraint that the first sextupole is at a betatron phase advance of $n \times 90$ degrees from the IP.

Initial dynamic aperture opimization efforts yield an on-momentum dynamic aperture of $20\sigma_x$, and a momentum acceptance of $12\sigma_p$. No magnet errors or beam-beam effects that will likely reduce the dynamic aperture have been taken into account yet, but neither has the possibility of adding geometric sextupoles in the dispersion-free straight sections which are expected to improve the situation. These studies are still on-going.

POLARIZATION PERFORMANCE

The physics program of the electron-ion collider requires simultaneous storage of electron bunches with spins "up" and "down" in the arcs of the storage ring, with average polarization levels of at least 70 percent. In eRHIC, this is accomplished by means of a full-energy, polarized injector that delivers bunches with the desired spin direction. During the store, the polarization of these bunches will then evolve based on the Sokolov-Ternov effect, which would eventually result in all bunches having their polarization aligned anti-parallel to the main dipole field in the arcs. In order to maximize the average polarization in both orientations, entire bunches will be replaced every 5 to 6 minutes, which is much faster than the shortest Sokolov-Ternov time constant of 30 min.

In addition to depolarization of bunches with spin parallel to the main dipole field due to the Sokolov-Ternov effect, spin diffusion results in polarization loss in both orientations. In order to minimize these effects, careful spin matching of the interaction region straight section with its solenoid spin rotators is required. Operationally, careful orbit correction in conjunction with measures such as harmonic bumps will be employed to minimize depolarization.

Spin tracking studies have been performed to determine the level of polarization that can be achieved in the eRHIC storage ring. Preliminary studies indicate that an average polarization of −63 percent can be achieved at a beam energy of 18 GeV in the presence of realistic magnet misalignments even without the use of harmonic orbit bumps, assuming an injected polarization of −80 percent, while for bunches with spins antiparallel to the main dipole field the average polarization is +72 percent for an injected polarization of +80 percent. At lower beam energies, depolarizing effects are weaker, resulting in higher average polarization.

INJECTION AND EXTRACTION

In order to maximize spin polarization in both "up" and "down" orientation, individual electron bunches need to be replaced every 5 to 6 minutes, which translates to one such bunch replacement per second. However, the high bunch intensity of up to 3×10^{11} electrons per bunch at 10 GeV and

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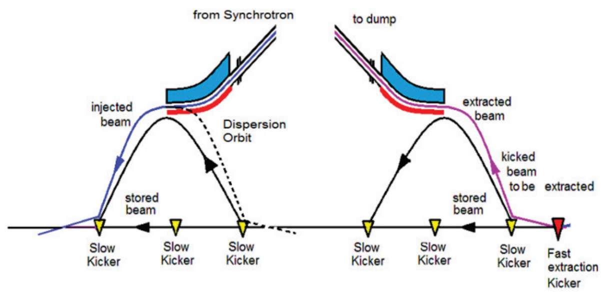

Figure 4: Schematic view of the off-energy injection and extraction scheme.

below requires accumulation of up to 5 injected bunches in the storage ring since these high intensity bunches would be unstable at the low 400 MeV injection energy of the Rapid Cycling Synchrotron. To avoid synchrotron radiation background issues in the detector during accumulation, bunches will be injected off-energy onto a dispersive orbit. With the dispersion in the interaction region being zero, these bunches will therefore travel through the IR on the nominal closed orbit, thus avoiding synchrotron radiation generation due to large offsets in the low-β quarupole magnets. Figure 4 shows a schematic view of the injection and extraction scheme.

MAGNETS

The magnet system of the electron storage ring is comprised of normal-conducting magnets made of 1006 magnet steel. Conceptual designs of all magnets have been developed, with field qualities better than 10^{-4} at the 15 mm reference radius for quadrupoles and sextupoles, and at 21 mm for dipoles. The spin rotator solenoids are superconducting, with maximum fields of 7 T. The interaction region is comprised of superconducting quadrupoles, some of which share a yoke with the corresponding hadron magnets.

RF SYSTEMS

The main RF system consists of 14 superconducting, 2-cell, 591 MHz cavities with 2 fundamental power couplers and 4 higher-order mode dampers per cavity, as depicted in Figure 5. These cavities reach a gradient of 8 MV/m and will be installed in the IR10 straight section. To provide sufficient space for the installation of these cavities in the tunnel, the electron ring is laid out such that there is no cross-over in IR10, so both adjacent arcs are "inner" arcs, without a cross-over in-between. Likewise, the two arcs surrounding IR2 are "outer" arcs to achieve the correct overall circumference.

With the interaction regions being based on a 25 mrad crossing angle between the electron and the hadron beam, crab crossing needs to be employed in both rings to compensate for both the geometric and beam dynamics effects of the crossing angle. This is accomplished by a single 400 MHz crab cavity on either side of the interaction point (IP), at a

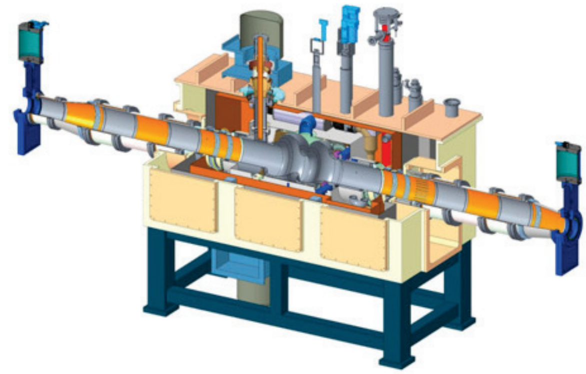

Figure 5: 591 MHz RF cavity with fundamental power couplers and higher order mode dampers.

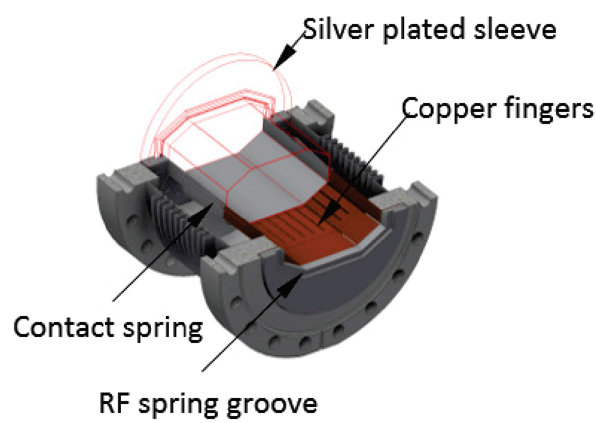

Figure 6: NSLS-II bellows with RF fingers on the outside.

horizontal betatron phase advance of 90 degrees from the IP. These crab cavities are identical to the ones installed in the hadron ring.

VACUUM SYSTEM

The 3.8 km long vacuum system is made of CuCrZr alloy, which has been chosen due to its radiation shielding properties, weldability, comparatively low cost, and availability. Distributed NEG pumping will be provided, with the NEG strips installed in an ante-chamber. The bellows will be based on the proven NSLS-II design shown in Figure 6.

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