PROGRESS OF THE eRHIC ELECTRON RING DESIGN*

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Abstract

Over the past year, a baseline design of the electron ring for the eRHIC hadron-lepton collider has been developed. This site-specific design is based on the understanding of the existing RHIC machine performance and its possible upgrades. The design includes a full energy polarized electron beam injector to ensure operational reliability and to provide high integrated luminosity. The electron ring energy range is 5 to 10 GeV. The electron beam emittance, the electron beam path length, and the interaction region optics have to be adjustable over wide ranges depending on the ion species and energy for collisions. We describe the design features and expected machine performance. The results of recent beam polarization and beam-beam studies are also discussed.

INTRODUCTION

The design goals of the ring-ring version of the eRHIC collider are to achieve high luminosity (10^{32}-10^{33} $cm^{-2}s^{-1}$ for e-p and 10^{30}-10^{31} for e-Au collisions) and to have high longitudinal polarization (>70%) at the Interaction Point (IP). The design is based on state-of-the-art storage ring concepts and technologies, with careful consideration given to the operational experiences of the B-factory rings and the HERA Collider. The electron ring design presented in the eRHIC ZDR [1] is the result of evolving design studies carried out in recent years [2] [3]. A primary objective of the ZDR ring design is to match electron beam parameters to RHIC ion beam parameters. The beam polarization requirements for the eRHIC e-ring represent a significant challenge not faced in B-factory rings. The bunch intensity requirement for the eRHIC e-ring is at least as high as in the B-factory rings. From the view of beam collisions, the eRHIC Collider is similar to HERA, the only existing lepton-hadron collider, but provides much higher luminosity etc. A unique feature of the eRHIC design is that it consists of rings with unequal circumferences. The intensity of the eRHIC e-ring beam will be at least one order of magnitude higher than that at HERA due to its lower energy range and applicable RF capacity. Therefore, very high beam-beam tune shift limits will be reached for both lepton and hadron beams in eRHIC.

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MACHINE DESIGN

General Layout and Design Overview

The electron ring layout has a quasi-racetrack shape. It consists of two 180^0 arcs, an interaction straight, and a utility straight (see Figure 1). The arcs consist of regular FODO cells with dispersion suppressors at the ends. The Interaction Region (IR) includes a pair of antisymmetric solenoidal spin rotators, which rotate the spin from vertical in the arc to longitudinal at the IP and back to vertical in the arc. A special arrangement to facilitate longitudinal polarization measurement is also provided. The utility section will host injection and the RF cavities. It consists of two achromatic bending sections that resemble the asymmetry layout of the IR to facilitate geometrical ring closure.

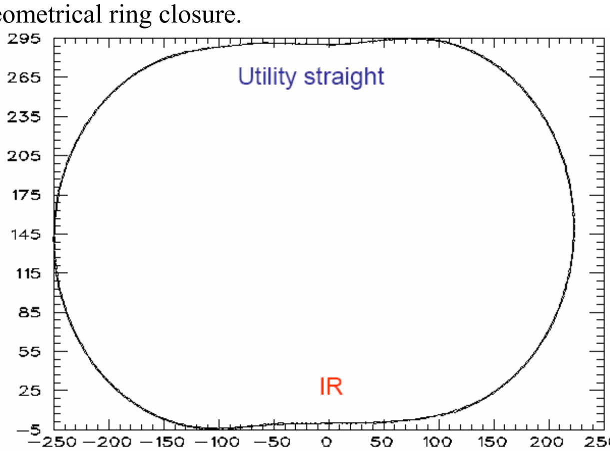

Figure 1: The e-ring layout

The key features of the design are:

- Flat beam, head on collision. High emittance aspect ratio (~20% at 10 GeV) at IP.
- Longitudinal polarization (>70%) at IP.
- Flexible lattice structure to allow large emittance variations.
- Beam path length adjustments up to 25 cm.
- Full energy injector (polarized for electrons) allows bunch-bunch, top-off or continuous injection.
- Vacuum, RF and other technical systems able to withstand high synchrotron radiation power and linear power density (up to 20 kW/m).
- Positron beam (self-polarized).

The flat beam head-on collision feature is constrained mainly by the available magnet apertures in the IR and difficulties to make a crossing angle for ion beams [1] [4]. The arc dipole radius and FODO cell numbers are carefully chosen to limit synchrotron radiation intensity at high energy and to provide flexibilities to adjust beam emittance. Other design features are discussed in subsequent sections. The main machine parameters are listed in Table.1.

Table 1: Design Parameters

Collision with	**P, 250 GeV**	**P, 50 GeV**
Beam Energy (GeV)	10	5
Circumference (m)	1277.95	1278.21
Arc dipole radius (m)	81.0	81.0
Bunch number	120	120
Bunch population	$1x10^{11}$	$1x10^{11}$
Beam current (A)	0.45	0.45
Energy loss/turn (MeV)	11.74	0.72
Arc SR Power/m (kW)	10	0.6
Emittance-x , (nm)	56	85
Emittance ratio (y/x)	0.18	0.45
β* (cm) x/y	19.2/26.6	35/20
SR damping time(x) (mS)	7.3	58.6
Self-pol. time (minutes)	22	705
RF frequency (MHz)(W/SC)	478.6/506.6	478.6/506.6
Rel. energy spread	$9.6x10^{-4}$	$4.8x\ 10^{-4}$
Bunch length (cm) σz	1.2	1.6
Beta tune (x/y)	26.105/22.146	
Natural chromaticity (x/y)	-35.6/-33.8	-28.5/-29.0
B-b parameters (x/y)	0.03/0.08	0.036/0.04
Peak Luminosity ($cm^{-2}s^{-1}$)	$0.44x10^{33}$	$0.15x10^{33}$

Lower Energy Operation

At 5 GeV, the synchrotron damping time is 8 times greater than that at 10 GeV. The radiation damping is a determining factor of the beam-beam limit due to intensity-dependent beam-beam blow-up [5]. The beam self-polarization time is also closely related to the synchrotron radiation intensity (for a fixed circumference isomagnetic ring, $\tau_{pol} \propto \rho^2 / E^5$, where ρ is the bending radius).

Two methods of increasing synchrotron radiation at low energies are under consideration: damping wigglers and modular arc dipoles. While damping wigglers in collider rings are being explored at the CESR Collider [6], using modular arc dipoles could be a simpler solution in our case. Each 3-m long arc dipole could be built as a combination of three short dipoles. At 5 GeV, only the central one would be powered. By increasing the bending field strength by a factor of three or more, the damping time at 5 GeV will be reduced to approximately 18 ms, so that the beam-beam limit reduction will be down to 20% from 50%. The self-polarization time will be about 1 hour, which will make polarized positron beams available for experiments at 5 GeV. The beam path length change in this case is about 5 cm, and the optical impact on the lattice is minimal.

Path Length Adjustment

To collide with ion beams of various energies, the electron beam path length must be adjusted. The path length adjustment required to go from colliding with proton beams of 50 GeV to 250 GeV is 20 cm. This can be accomplished by activating magnet chicanes in the arc. For example, it is possible to use four FODO cells to comprise a chicane capable of 8 cm of path length change. This scheme requires complicated movements of machine components in the radial directions. A more straightforward method is to translate one of the 180^0 arc. Both schemes are undergoing engineering evaluation.

Dynamic Aperture

Due to the large range of emittance variation (~10 for a given energy), the betatron phase advances per FODO cell have to be adjusted between ~72 and ~40 degrees. A chromaticity correction scheme with multi-family sextupoles is employed to achieve better cancellation of second-order geometric aberrations. Figure 2 shows beam dynamic aperture with large momentum deviations at 10 GeV. The tracking is performed using the fully symplectic tracking code LEGO [7]. The results from LEGO and SAD [8] are generally consistent. A thorough investigation of beam dynamic apertures with different operation lattices is needed along with exploration of local chromaticity correction schemes near the IR region.

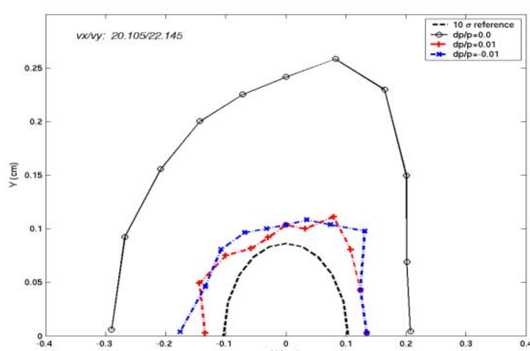

Figure 2 : Beam Dynamic Aperture at IP.

BEAM POLARIZATION

To maintain a high equilibrium polarization level in the ring, good vertical closed orbit corrections are essential. Figure 3 shows equilibrium polarizations calculated at first order when realistic imperfections are applied and the orbit is subsequently corrected. However, these good polarizations come with small r.m.s. vertical closed orbits of 0.13 mm. Simulations and experiments have shown that the polarization can suffer significantly from resonant depolarisation with loose orbit corrections. Therefore, strict alignment tolerances, ample provision of correction magnets, and highly precise beam position monitors are included in the ring design to ensure high polarization.

To match a specific ion beam for maximum luminosity, the electron beam has an optimum emittance aspect ratio [1]. The optimal emittance aspect ratios range from ~20% to ~40%. At HERA vertical dispersion bumps and skew quadrupoles can be used to increase vertical emittance. However, large vertical emittance and vertical closed orbit manoeuvres are generally in contradiction with the concept of maintaining high polarization by having small vertical beam size and small vertical closed orbits. An extrapolation of the results from the HERA machine upgrade study will be helpful. A sophisticated non-linear Monte-Carlo spin-orbit tracking code: SLICKTRACK [9] is being developed for better predictions.

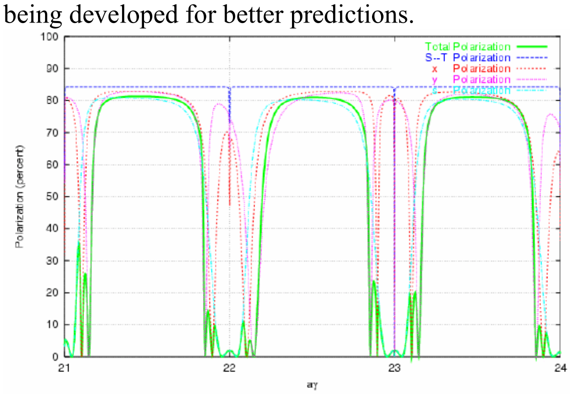

Figure 3: Equilibrium polarizations with misalignment and appropriate orbit corrections.

BEAM-BEAM EFFECTS

The circumference of the electron ring is chosen to be one third of that of RHIC in order to have more flexibilities and cost savings in the design. Each electron bunch will circulate three times and collide with three ion bunches during each revolution of the ion beam. Such a configuration of unequal circumferences was not favoured in the design of B-factories due to the concerns about coherent beam-beam effects [10].

The beam-beam effect in eRHIC has been studied with the strong-weak approximation of the beam-beam interaction [11]. But since both beams have large beam-beam parameters, coherent beam-beam effects could be important to the luminosity reduction in eRHIC [12]. To examine the beam-beam limit of eRHIC, a self-consistent beam-beam simulation was recently conducted by using the particle-in-cell method with one electron bunch and three proton bunches [13]. The tracking has been done with two million macro-particles for up to 3×10^5 turns of the electron beam. With the parameters in the ZDR design, no coherent beam-beam instability has been observed and the beam-beam interaction only results in a very limited luminosity reduction (<10%). If there are missing bunches in the proton beam, an electron bunch could collide with just one or two proton bunches during each revolution of the proton beam. In this case, we observed the onset of a spontaneous beam-size oscillation (high order coherent beam-beam instability) that results in a significant luminosity reduction.

In the ZDR design, the selection of the beam-beam parameter of the proton beam is based on RHIC operation experience with the consideration of three IPs (one for e-p). In a dedicated single IP mode, there is a possibility to further increase the luminosity by having a higher electron bunch current. Figure 4 plots the horizontal emittance growth of the proton beam for various electron bunch currents. The emittance blow-up in cases (d)-(f) is due to the onset of the coherent beam-beam instability [13]. The threshold of the coherent beam-beam instability is therefore $\xi_x \approx 0.01$ for the proton beam in eRHIC.

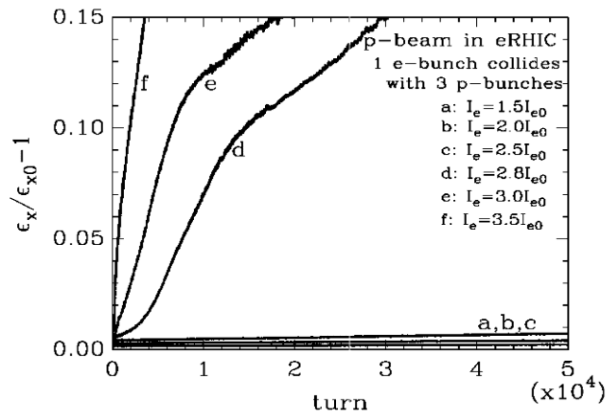

Figure 4: Emittance growth of the proton beam for various electron bunch currents. ε_{x0} is the design emittance. I_{e0} is the design electron bunch current. I_e is the bunch current used in the simulation.

SUMMARY

The electron ring design in the eRHIC ZDR is based on realistic considerations. Driven by the requirements of the nuclear physics program, the design has to address special and challenge beam-beam, polarization, lattice and technical system specifications. Advancing the design to meet peak and integrated luminosity goals (10^{33} $cm^{-2}s^{-1}$ and ~90 pb^{-1} per day, respectively, for 10/250 GeV e-p collisions) will be the main challenge.

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