THE eRHIC RING-RING DESIGN [*]

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Abstract

The ring-ring version of the eRHIC electron-ion collider design aims at providing electron-proton collisions with a center-of-mass energy ranging from 32 to 141 GeV at a luminosity reaching 10^{33} cm^{-2}sec^{-1}. This design of the double-ring collider also supports electron-ion collisions with similar electron-nucleon luminosities, and is upgradeable to 10^{34} cm^{-2}sec^{-1} using bunched beam electron cooling of the hadron beam and more bunches. The baseline luminosities are achievable using existing technologies and beam parameters that have been routinely achieved at RHIC in hadron-hadron collisions or elsewhere in e+e- collisions. This minimizes the risk associated with the challenging luminosity goal and is keeping the technical risk of the e-RHIC electron-ion collider low. The latest design status will be presented.

INTRODUCTION

The ring-ring design of the electron-ion collider eRHIC aims at an electron-proton center-of-mass energy range of 32 - 141 GeV, with luminosities in the $10^{32} - 10^{33}$ cm^{-2}sec^{-1} range. This is realized by adding an electron storage ring with an energy range of 5 to 18 GeV to the existing RHIC facility, which will be operated at proton energies from 50 to 275 GeV. The upper electron energy limit has been chosen to limit the total synchrotron radiation power to 10 MW while still providing high luminosities at the highest center-of-mass energies. The number of bunches is increased 3-fold over the present RHIC configuration, to 330. This necessitates new injection kickers and in-situ copper coating of the existing stainless steel beam pipes to lower the resistive wall cryo load as well as the secondary electron yield [1, 2].
The luminosity scales as

$$\mathcal{L} \propto \sqrt{I_p I_e (1+K_x)(1+K_y)} \left(\frac{\xi_{x,p}\xi_{y,p}\xi_{x,e}\xi_{y,e}}{\beta^*_{x,p}\beta^*_{y,p}\beta^*_{x,e}\beta^*_{y,e}} \right)^{1/4}, \quad (1)$$

where I, ξ, and β denote the beam current, beam-beam parameter, and the β-function at the interaction point (IP), while $K_x = \sigma_x/\sigma_y$ and $K_y = \sigma_y/\sigma_x$ are the ratios of horizontal and vertical beam sizes at the IP, which are equal for both beams. The beam-beam parameters ξ_p for the protons are limited to what has been achieved in proton-proton collisions in RHIC, $\xi_p < 0.015$ [3], while we assume a maximum $\xi_e < 0.1$ for the electrons, as has been achieved in KEKB [4]. As Equation 1 shows, luminosity is increased with flat beams, $K_x = \sigma_x/\sigma_y >> 1$. Flat beams in eRHIC are achieved by intentionally increasing the horizontal proton beam emittance in conjunction with a large β-function ratio β_x/β_y between 6 and 140.

The eRHIC physics program requires detector acceptance for forward scattered protons with transverse momenta between 200 MeV/c and 1.3 GeV/c. These protons are detected by Roman Pots that are inserted into the beam pipe downstream of the main detector. This requires the scattered protons to have a transverse amplitude of about 10 σ, where σ denotes the RMS proton beam size at the location of the Roman Pot, which in turn limits the maximum allowable RMS beam divergence σ' at the IP. For a beam energy of 275 GeV, a transverse momentum of 200 MeV/c corresponds to a scattering angle $\phi = 730\,\mu$rad; the maximum allowable RMS beam divergence is therefore $\sigma' = 73\,\mu$rad. For given emittance this limits the IP β-function β^*, and therefore the luminosity. However, not the entire transverse momentum range has to be measured in the same machine configuration. Since events with small transverse momenta $p_\perp$ are plentiful, operating in a configuration with good acceptance at small $p_\perp$, where the luminosity is limited, over a small fraction of time provides sufficient statistics for the experimental program. The majority of the time the machine can then be operated with high luminosity to detect a sufficiently large number of protons with high $p_\perp$. Table 1 lists the design parameters at the beam energies giving the highest luminosities.

INTERACTION REGION

High luminosity requires small β^*. Since these small β-functions increase quadratically with the distance from the IP, it is necessary to place the innermost focusing magnets as close to the IP as possible to avoid excessive contributions to the machine chromaticity from those quadrupoles, and limit their aperture and, in turn, their peak fields. The low-β magnets for both the electron and the proton beam are therefore arranged in an interleaved pattern, as depicted in Figure 1. Since the detector requires a machine-element free region of ±4.5 m around the IP, the innermost (proton) quadrupole is located just outside the detector.

Since the eRHIC physics program requires detection of forward neutrons within a ±4 mrad cones, a strong dipole magnet (B1) deflects the proton beam away from that neutron cone which is then detected about 25 m downstream of the IP. A second dipole (B2) then bends the proton beam back, thus forming a dogleg with B1. Between the second dipole (B2) and the fourth proton quadrupole (Q4) there is a

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Table 1: Parameters at energies giving the highest luminosities. Numbers in parentheses correspond to a configuration with 50 percent horizontal acceptance down to $p_\perp = 200\,\mathrm{MeV}/c$ where only about 20 percent of the operating time would need to be spent (see text)

	protons	electrons
energy [GeV]	250	10
$\sqrt{s}$ [GeV]	100	
no. of bunches	330	
part./bunch [10^{10}]	11.1	30.5
norm. hor. emitt. [μm]	4.7	476
norm. vert. emitt. [μm]	1.8	76
β_x^* [cm]	95 (566)	70 (416)
β_y^* [cm]	4.2	7.4
σ_x' [μrad]	137 (56)	186 (80)
σ_y' [μrad]	400	230
ξ_x	0.015	0.099
ξ_y	0.002	0.033
IBS time long./transv. [h]	9.8/11.5	
synchr. rad. [MW]		6.3
RMS bunchlength [cm]	8.0	0.8
hourglass [%]	84	
luminosity [10^{33} cm^{-2}sec^{-1}]	2.6 (1.1)	

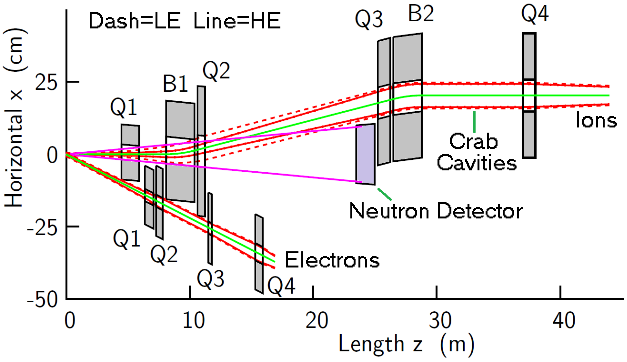

Figure 1: Layout of IR magnets and other components.

dedicated space for crab cavities, which are necessary due to the crossing angle of 22 mrad total. Over the entire proton beam energy range from 50 to 275 GeV the β-functions in the crab cavities scale such that the resulting beam size at all energies is equal or smaller than at 275 GeV despite the larger beam emittance, so as not to require a large crab cavity aperture.

ELECTRON RING DESIGN

The electron storage ring is composed of FODO cells in the arcs, and six dedicated straight sections. The main challenge is to tune the ring to the desired emittances at different energies, as required for beam size matching with the proton beam and to maximize luminosity. The horizontal design emittances range from 53 nm at 5 GeV to 24 nm at 18 GeV, i.e. higher energies require lower emittances. To achieve this the betatron phase advance per FODO cell has to be adjusted accordingly. In addition, one of the straight sections may be equipped with a Robinson wiggler for additional emittance adjustment via manipulation of the damping partition numbers. Alternatively, a small radial offset of the electron beam is being considered, as was done in HERA [5].

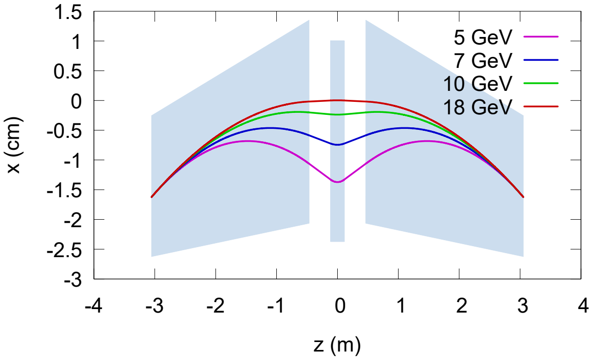

Figure 2: Split arc dipoles and orbits for several energies.

In order to allow large beam-beam tuneshifts over the entire energy range, strong synchrotron radiation damping is required. While at energies above 11 GeV the damping decrement is equal or larger than at KEKB, and therefore is expected to allow for similar beam-beam tuneshifts, at lower frequencies additional measures have to be taken to generate sufficient radiation damping. This is achieved by splitting each arc dipole into three sections, a short section in the center and two equally long ones at the ends, as schematically shown in Figure 2. For energies of 11 GeV and above, all magnets are set to the same field, while for energies below 11 GeV the polarity of the short center dipole is reversed, with its bending radius decreasing with energy. This arrangement results in a sufficiently large damping decrement at all energies while limiting the maximum orbit deviation to 14 mm.

POLARIZATION

The Sokolov-Ternov self-polarization time in a storage ring with dipole bending radius r, average radius R, and beam energy E can be calculated as

$$\tau_{\mathrm{S-T}}[\mathrm{sec}] = 98.66 \cdot \frac{R[\mathrm{m}]r^2[\mathrm{m}]}{E^5[\mathrm{GeV}]}. \qquad (2)$$

In the electron storage ring, neglecting the effect of the split dipoles, it ranges from 27 min at 18 GeV to several weeks at 5 GeV. When the split dipoles are included in the calculation, the self-polarizing time is still in the range of several hours for beam energies below 12 GeV, as shown in Figure 3. Using the Sokolov-Ternov effect to polarize the electrons in the electron storage ring is therefore not practical, and a full-energy polarized injector is required. However, such an injector has the advantage that arbitrary spin patterns can be provided in the electron ring, as is required by certain parts

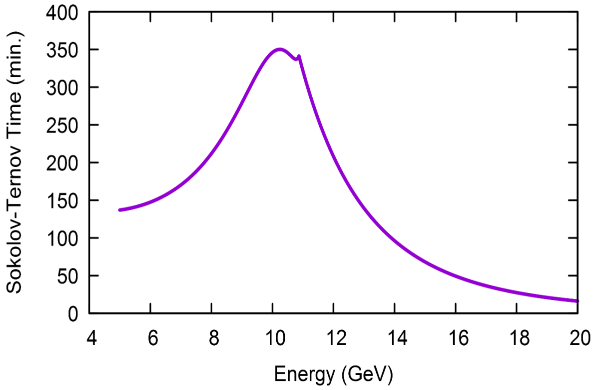

Figure 3: Sokolov-Ternov self-polarization time vs. energy.

of the physics program. These arbitrary spin patterns will be generated by injecting bunches with the appropriate spin orientation (“up” or “down”), which is then transformed into longitudinal polarization at the IP using a set of spin rotators. Since the Sokolov-Ternov effect would eventually polarize all bunches in the same direction (“up”), it is necessary to replace entire bunches on a time scale that is sufficiently short compared to the self-polarization time. With the shortest Sokolov-Ternov self-polarization time being 27 min, replacing bunches at a rate of 1 Hz would be sufficient, since with 330 bunches in the machine every individual bunch would be replaced every 5.5 min.

The spin rotators use sets of solenoids and dipoles to rotate the spin from the vertical direction into the longitudinal orientation, and back. Due to the presence of the detector solenoid this spin rotation has to be perfect over the entire energy range in order to avoid depolarizing effects. A spin rotator scheme based on two solenoids on each side of the IP, and the appropriate bending angles in-between, has been developed that can provide longitudinal polarization over the entire energy range from 5 to 18 GeV.

ELECTRON INJECTOR

The full-energy polarized electron injector is based on a recirculating linac scheme. Two superconducting linacs with a maximum energy of 3 GeV each are installed in adjacent straight sections of the RHIC tunnel, as shown in Figure 4. With two recirculation loops around the RHIC circumference the beam passes each of these linacs three times, thus gaining the required top energy of 18 GeV. Two different SRF frequencies are currently under consideration, namely 1.3 GHz and 650 MHz. Choosing 1.3 GHz would enable us to utilize existing technology as developed for the European X-FEL, LCLS-II, or the ILC, thus eliminating any risk associated with the injector linac. 650 MHz SRF cavities are currently being developed as part of the ERL-based linac-ring version of eRHIC [6]. Using those cavities would eventually enable us to convert the ring-ring scheme to a high-lumnosity ERL based linac-ring collider in a cost-effective manner.

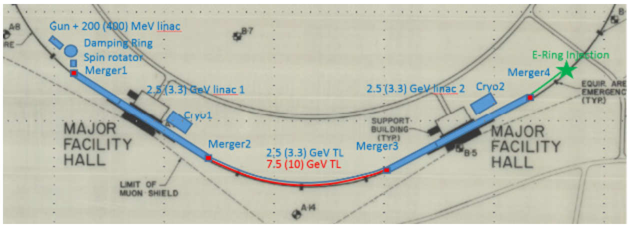

Figure 4: Electron injector.

LUMINOSITY UPGRADE PATH

To study the entire eRHIC physics case within a reasonable time frame the initial version of the machine needs to be luminosity upgradable to the $10^{33} - 10^{34}$ cm^{-2}sec^{-1} range. In the case of the ring-ring version, a first upgrade step is based on doubling the number of bunches in both rings, from the initial 330 to 660, by upgrading the injection kickers to faster rise and fall times. For electron energies up to 10 GeV this luminosity upgrade can be accomplished within the 10 MW synchrotron radiation limit, reaching a peak luminosity of $5.2 \cdot 10^{33}$ cm^{-2}sec^{-1}. This first upgrade step is relatively straightforward and low risk.

For ultimate performance electron cooling of the proton beam to very small vertical emittances of $\epsilon_{y,\mathrm{norm.}} = 0.1\,\mu$m is required. In addition, the number of bunches has to be doubled once more, to 1320. In this configuration, a peak luminosity of $12.4 \cdot 10^{33}$ cm^{-2}sec^{-1} is reached.

SUMMARY

The eRHIC ring-ring design provides a low risk approach towards an electron-ion collider with an initial luminosity in the $10^{32} - 10^{33}$ cm^{-2}sec^{-1} range over a center-of-mass energy range from 32 to 141 GeV. The luminosity of this machine is upgradable to more than 10^{34} cm^{-2}sec^{-1} by increasing the number of bunches and strong electron cooling for the hadron beam.

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