OVERVIEW OF THE eRHIC RING-RING DESIGN*

C. Montag†, G. Bassi, J. Beebe-Wang, J.S. Berg, M. Blaskiewicz, J.M. Brennan, A. Fedotov, W. Fischer, W. Guo, Y. Hao, A. Hershcovitch, Y. Luo, F. Meot, R. B. Palmer, B. Parker, S. Peggs, V. Ptitsyn, V. Ranjbar, S. Seletskiy, T. Shaftan, V. Smaluk, S. Tepikian, D. Trbojevic, E. Wang, F. Willeke, H. Witte, Q. Wu, Brookhaven National Laboratory, Upton, NY 11973, USA

Abstract

The ring-ring electron-ion collider eRHIC aims at an electron-ion luminosity in the range from 10^{32} to $10^{33}\,\mathrm{cm^{-2}sec^{-1}}$ over a center-of-mass energy range from 30 to 140 GeV. To minimize the technical risk the design is based on existing technologies and beam parameters that have already been achieved routinely in hadron-hadron collisions at RHIC, and in electron-positron collisions elsewhere. This design has evolved considerably over the last two years, and a high level of maturity has been achieved. We will present the latest design status and give an overview of studies towards evaluating the feasibility.

INTRODUCTION

The electron-ion collider eRHIC currently being designed consists of an electron storage ring with an energy range from 5 to 18 GeV that is to be installed in the existing RHIC tunnel. In up to two interaction regions this electron beam is brought into collision with the ion beam in the Yellow RHIC ring, as schematically shown in Figure 1. Together with an energy range from 50 to 275 GeV for the polarized proton beam, this results in a center-of-mass energy range from 30 to 140 GeV, or up to 100 GeV/nucleon for electron-ion collisions. With a maximum RF power of 10 MW in the electron storage ring and proton beam emittances as or nearly as achieved in RHIC the peak luminosity reaches $2.9 \cdot 10^{33}\,\mathrm{cm^{-2}sec^{-1}}$ in this initial configuration, requiring 6.6 MW of RF power, and $1.2 \cdot 10^{34}\,\mathrm{cm^{-2}sec^{-1}}$ after installation of strong hadron cooling [1].

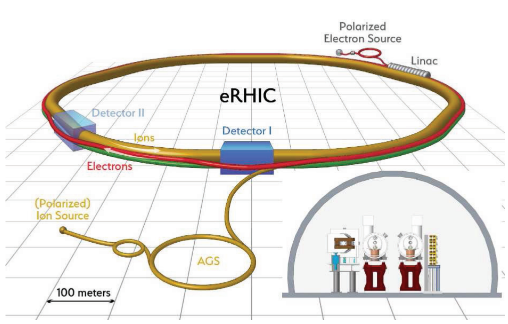

Figure 1: Schematic overview of the eRHIC facility.

BEAM PARAMETERS AND LUMINOSITY

The eRHIC facility is designed for an e-p peak luminosity of $1.2 \cdot 10^{34}\,\mathrm{cm^{-2}sec^{-1}}$ ("High Luminosity") which requires strong cooling of the hadron beam. Without cooling, a peak luminosity of $2.9 \cdot 10^{33}\,\mathrm{cm^{-2}sec^{-1}}$ ("Medium Luminosity") is achieved. In each of these scenarios, two operating modes are envisioned, namely a "High Divergence" (HD) mode with high luminosity, and a "High Acceptance" (HA) mode with reduced luminosity. In the HA mode the divergence of the proton beam at the IP is reduced, which allows detection of protons with transverse momenta as low as 200 MeV/c. Table 1 lists some key parameters of the machine; a more comprehensive table can be found in Ref. [1].

Table 1: Parameter table for 10 GeV electrons and 275 GeV protons. With 330 bunches the required RF power at 10 GeV reaches only 6.6 MW. Increasing the number of bunches to 500 boosts the "HD" luminosity to $4.5 \cdot 10^{33}\,\mathrm{cm^{-2}sec^{-1}}$ at a power consumption of 10 MW.

	Medium Lumi. 330 bunches		High Lumi. 1320 bunches	
	HD	HA	HD	HA
ϵ_e (x/y) [nm]	24/3.5		12.7/0.24	
$\epsilon_{p,n}$ (x/y)	4.7/1.8		2.6/0.1	
β_e^* (x/y) [cm]	62/7.4	383/7.4	104/1.9	208/3.7
β_p^* (x/y) [cm]	94/4.2	579/4.2	142/1.0	283/2.1
N_e/bunch	$30.5 \cdot 10^{10}$		$15.2 \cdot 10^{10}$	
N_p/bunch	$11.1 \cdot 10^{10}$		$5.6 \cdot 10^{10}$	
$\sigma_{s,p}$ [cm]	7		4	
luminosity $[10^{34}\,\mathrm{cm^{-2}sec^{-1}}]$	0.29	0.11	2.1	1.2

ELECTRON RING LATTICE

The electron storage ring lattice is based on FODO cells in the arcs, which provide the greatest dipole fill factor. This structure continues through the four non-colliding straight sections in order to minimize the chromatic contributions from those straights. To allow for an electron beam-beam parameter of $\xi = 0.1$ throughout the entire energy range from 5 to 18 GeV, as achieved by the B-factories, additional measures have to be taken to increase the synchrotron radiation damping decrement at energies below 11 GeV to the same value as at KEKB, $\delta_\perp = 2.5 \cdot 10^{-4}$. This is achieved by splitting all arc dipoles into three segments, as schematically shown in Figure 2. While at beam energies above 11 GeV all three segments are powered such that they provide equal bending, the center segment is powered with the opposite polarity at lower energies. This results in additional synchrotron radiation and therefore the desired fast damping.

* Work supported by the US DOE under contract number DE-SC0012704
† montag@bnl.gov

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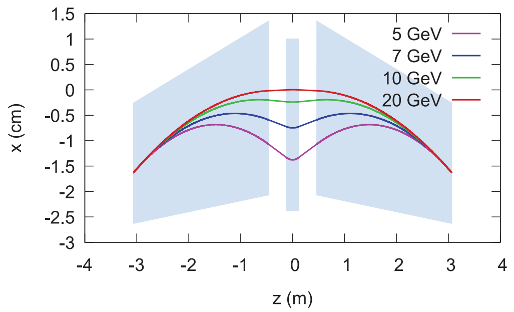

Figure 2: Superbends.

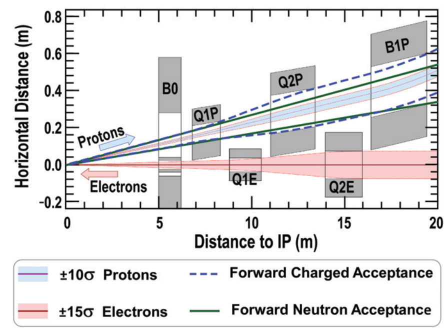

Figure 3: Interaction region.

MODIFICATIONS TO THE RHIC ION STORAGE RING

The increased number of bunches compared to the present configuration with 120 bunches requires several modification to the ion storage ring. Faster injection kickers with a rise time of less than 30 nsec need to be installed. Due to the increased length of these new kickers the present location, which is only about 6 m long, is insufficient. Instead, an extended transfer line from the present injection area in IR6 to IR4, where the necessary length of about 20 m can be provided, is required.

The threefold increase of the number of bunches together with the reduced bunch length results in an unacceptably high heat load in the superconducting magnets due to the resistivity of the stainless steel beam pipes. These therefore need to be copper-coated in situ to reduce their resistivity. A mole carrying a magnetron is currently being developed for that purpose. In addition to applying a thin copper layer, a second coating with amorphous carbon will be necessary to reduce the secondary electron yield sufficiently to suppress the electron cloud.

The existing RF system will have to be replaced by higher-frequency cavities, for instance 560 MHz instead of the present 197 MHz, to facilitate short bunches.

INTERACTION REGION

The interaction region is based on a 22 mrad total crossing angle to provide early separation of the two beams and therefore allow focusing of both beams close to the interaction point (IP) [2]. To compensate for the luminosity loss due to the crossing angle, a pair of 336 MHz crab cavities will be installed in the hadron beam line. Crab crossing of the electrons is also foreseen to avoid synchro-betatron resonances associated with the crossing angle configuration of the IP.

The individual cold masses of the superconducting magnets are arranged in an interleaved pattern to minimize the required crossing angle, as depicted in Figure 3. To shield the nearby electron beam from the stray field of the hadron quadrupoles, some of those magnets are equipped with anti-quadrupole windings [3]. Dipole magents in the downstream side of the hadron beamline provide large dispersion to allow for detection of scattered protons with transverse momenta as small as 200 MeV/c.

RF SYSTEMS

The synchronous voltage required at 18 GeV is 41 MV. Assuming a gap voltage of 2 MV per cell of a superconducting RF cavity, about 36 cells need to be installed to provide a sufficient bucket area. The actual design of those 560 MHz cavities will be based either on the KEKB superconducting single-cell cavities, or a 2-cell cavity currenty being developed at BNL.

The crab cavities need to compensate for a total crossing angle of $\Theta = 22$ mrad. The RF frequency is chosen as $f_{\mathrm{crab}} = 336$ MHz, and the required voltage computes as

$$\begin{aligned} V_{\mathrm{crab}} &= \frac{\Theta E/q}{2k\sqrt{\beta_{\mathrm{crab}}\beta^*}} \\ &= 10\,\mathrm{MV}. \end{aligned} \tag{1}$$

Here, $\beta_{\mathrm{crab}} = 1000$ m and $\beta^* = 0.626$ m denote the horizontal β-functions at the crab cavity and the IP, respectively, while $E = 275$ GeV is the proton beam energy, q the proton charge, and k the crab cavity RF wave number.

POLARIZATION

The eRHIC Physics program requires spin-polarized beams with arbitrary bunch-to-bunch spin patterns. Such patterns in the electron storage ring can only be achieved by a full-energy polarized injector. Once injected, the polarization will evolve towards the equilibrium value, which is expressed as

$$P_{\mathrm{eq}} = \frac{8}{5\sqrt{3}} \frac{\oint (\mathrm{d}s/|\rho(s)|^3)\vec{b}\cdot\vec{e}_3}{\oint (\mathrm{d}s/|\rho(s)|^3)}, \tag{2}$$

where $\rho(s)$ is the local bending radius, and $\vec{b}$ and $\vec{e}_3$ are unit vectors in the direction of the local dipole field and the stable spin direction, respectively. The product $\vec{b}\cdot\vec{e}_3$ therefore changes sign according to the local direction of the dipole field. The time constant for this polarization evolution is given as the Sokolov-Ternov self-polarization time

$$\tau_{\mathrm{ST}}^{-1} = \frac{5\sqrt{3}}{8} c\lambda_e r_e \frac{\gamma^5}{2\pi R} \oint \frac{1}{|\rho|^3}\,\mathrm{d}s, \tag{3}$$

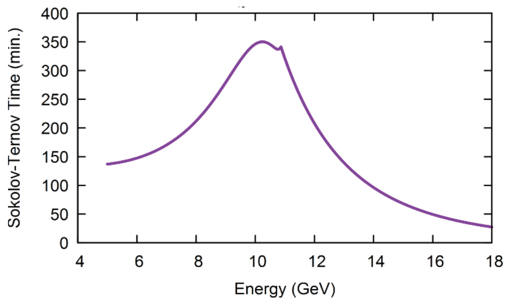

Figure 4: Sokolov-Ternov self-polarization time in the eRHIC electron storage ring as function of beam energy.

with $2\pi R$ being the circumference of the storage ring, λ_e the de Broglie wavelength of the electron, r_e the classical electron radius, and c the speed of light. As Figure 4 shows, this time constant ranges from 27 minutes to several hours. In order to keep the average beam polarization sufficiently high, bunches therefore need to be replaced at a rate that is fast compared to the self-polarization time. Replacing each of the 330 electron bunches every few minutes therefore requires injection of a single bunch at a rate of about one hertz.

ELECTRON INJECTOR

The full-energy electron injector has to be capable of accelerating a full intensity (50 nC) polarized electron bunch to 18 GeV while preserving polarization. The latter is generally impossible in a synchrotron due to the crossing of many depolarizing resonances during acceleration. However, this limitation can be overcome by a special optics configuration [4]. With the maximum energy being 18 GeV, we have $G \cdot \gamma = 40.9$, where G is the anomalous gyromagnetic ratio of the electron. A circular synchrotron comprised of 192 identical FODO cells with 90 degrees phase advance has a superperiodicity of $P = 192$. If we now set the integer tune to $G \cdot \gamma = 41 < \nu < 150$, the resonance condition

$$G \cdot \gamma \quad = \quad k \cdot P \pm l \cdot \nu, \tag{4}$$

with

$$\begin{aligned} k &= \; = 0, 1, 2, \ldots \\ l &= \; -1, 0, +1 \end{aligned}$$

is only fulfilled outside the actual energy range of the synchrotron. Hence, intrinsic resonances are completely avoided in such a machine.

Since the RHIC tunnel in which such an injector synchrotron would have to be installed resembles a hexagon with rounded corners rather than a perfect circle, the forementioned concept has to be modified to fit the machine into the given geometric constraints of that tunnel. It can be shown that this can be accomplished by designing the straight sections with an identity transfer matrix, as is schematically shown in Figure 5.

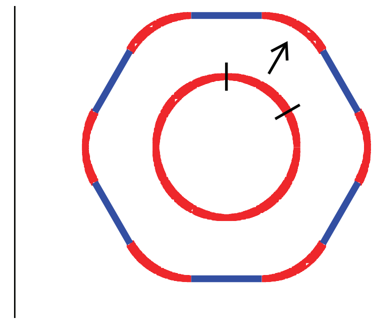

Figure 5: Schematic of the rapid-cycling synchrotron with 6 straight sections.

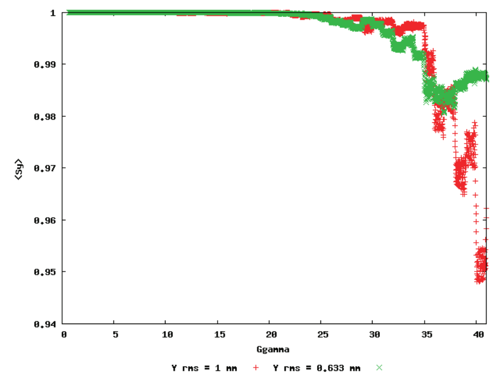

Figure 6: Polarization in the RCS on the ramp for different values of the RMS orbit error. Only the latter part of the ramp is shown here for better visibility. No depolarization occurs in the earlier part.

Spin tracking studies have been performed to verify the validity of this concept. As Figure 6 shows, at an integer vertical tune of $\nu = 65$ there is less than one percent depolarization on the ramp for vertical RMS orbit errors of up to 0.63 mm. The ramp is performed in 4000 turns in this study, which corresponds to 50 msec in a RHIC-sized synchrotron. More detailed simulation studies are still ongoing, and this ramp rate could be increased if studies indicate a necessity.

As an alternative scheme, a recirculating linac could be used as full-energy injector (see Figure 1), albeit at higher cost.

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