THE 2015 eRHIC RING-RING DESIGN*

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Abstract

To reduce the technical risk of the future electron-ion collider eRHIC currently under study at BNL, the ring-ring scheme has been revisited over the summer of 2015. The goal of this study was a design that covers the full center-of-mass energy range from 32 to 141 GeV with an initial luminosity between $2 \cdot 10^{32}$ cm^{-2} sec^{-1} and $1.2 \cdot 10^{33}$ cm^{-2} sec^{-1}, upgradeable to 10^{34} cm^{-2} sec^{-1} later on. In this presentation the baseline design will be presented. Future upgrades and higher luminosity options are under study [1].

INTRODUCTION

The eRHIC ring-ring design aims at a low-risk version of a future electron-ion collider based on the existing RHIC facility at Brookhaven, providing an initial e-p luminosity between $2 \cdot 10^{32}$ cm^{-2} sec^{-1} and $1.2 \cdot 10^{33}$ cm^{-2} sec^{-1} depending on the energies of the two beams. The design approach presented here is largely based on existing technologies, thus minimizing the technical risk. This results in reduced budget contingency as well as shortened commissioning time.

The basic assumptions of this design are:

- The electron ring is installed in the existing RHIC tunnel, thus avoiding costly civil construction.
- There is only a single interaction region with one detector. All parameters such as beam-beam tune shifts, bunch intensities, and luminosities are based on a single collision point. However, this does not preclude a second interaction region with appropriately modified parameters.
- Electron and proton beams have identical RMS beam sizes at the interaction point. The two beams intersect at a total crossing angle of 15 mrad. The resulting luminosity loss will be largely restored by crab cavities in the hadron beamline. The necessity of electron crab cavities is still under study [2].
- Hadron beam parameters are a moderate extrapolation of what has been achieved at RHIC, with the exception of a three-fold increase in the number of bunches, from 120 to 360, and the corresponding increase in average current.
- The maximum electron beam-beam parameter does not exceed 0.1, a level that has been routinely achieved at the B-factories with a synchrotron radiation damping decrement that is an order of magnitude smaller than in eRHIC at 20 GeV. Damping wigglers will provide the same damping decrement over the entire energy range.
- The RF power installed in the electron ring will be 10 MW, which corresponds to a linear synchrotron radiation power load of 4 kW/m in the arcs.

ELECTRON RING LATTICE

The electron ring lattice [3] will be based on FODO cells in the arcs. Adjustment of the horizontal emittance will be accomplished by chosing the appropriate phase advance, by a Robinson wiggler in one of the straight sections, and/or by a radial shift. In order to reduce cost, re-using PEP-II quadrupoles, sextupoles, and dipole correctors is foreseen. New arc dipoles will have to be designed and built due to the different cell length compared to PEP-II. The dipole bending radius of 300 m is maximized to limit the synchrotron radiation losses in the existing RHIC tunnel with its 381 m bending radius.

INTERACTION REGION

The interaction region [4] provides an element-free space of ±4.5 m for the central detector around the interaction point (IP). The electron and hadron beams intersect at a total crossing angle of 15 mrad. Crab cavities in the hadron beamline will largely restore the luminosity lost due to the crossing angle. A dogleg separates the hadron beam from the ±4 mrad neutron cone in the forward direction; Roman Pots are installed in-between the two bends of the dogleg to detect scattered protons with transverse momenta as small as 200 MeV/c. Focusing of the two beams is provided by a superconducting quadrupole triplet for the electrons, and a superconducting doublet for the hadrons. The apertures of the hadron quadrupoles are chosen such that the same values of the β-function can be maintained at the IP for proton beam energies as low as 50 GeV despite the five-fold larger emittance.

RF SYSTEMS

The synchronous voltage for 20 GeV electrons is 46 MV, and the required RF power is 10 MW. Assuming KEKB-style superconducting cavities which can each supply 2 MV of voltage and 380 kW of power at a frequency of 509 MHz, and a synchronous phase of 63 degrees, this voltage can be supplied by 26 cavities. Assuming 30 cavities, the total voltage increases to 60 MV and the available RF power to 11.4 MW.

With a circuit $R/Q = 50\,\Omega$ the detuning is given as

$$\delta f = -\frac{I_{\rm RF} f_{\rm RF}}{2V_c} \left(\frac{R}{Q}\right) \cos \Phi_s, \tag{1}$$

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where $I_{\mathrm{RF}} = 2eN_b f_{\mathrm{bunch}}$ is the RF component of the beam current with N_b the number of particles per bunch, e the electron charge, and $f_{\mathrm{RF}} = 18 f_{\mathrm{bunch}}$ the cavity RF frequency. V_c denotes the cavity voltage. Using $N_b = 3 \cdot 10^{11}$, $V_c = 2\,\mathrm{MV}$, and $\Phi_s = 0$ the resulting cavity detuning computes as $\delta f = -17.1\,\mathrm{kHz}$, which is a significant fraction of the 78 kHz revolution frequency. This may require feedback filtering similar to KEKB.

The crab cavities need to compensate a total crossing angle of $\Theta = 15\,\mathrm{mrad}$. With a horizontal β-function of $\beta^* = 2.16\,\mathrm{m}$ at the IP and $\beta_{\mathrm{crab}} = 2400\,\mathrm{m}$ at the crab cavity, a proton beam energy of $E = 250\,\mathrm{GeV}$, and a crab cavity RF wave number k, the required voltage is

$$V_{\mathrm{crab}} = \frac{\Theta E/q}{2k\sqrt{\beta^* \beta_{\mathrm{crab}}}}, \tag{2}$$

where q denotes the proton charge. For a 112 MHz crab cavity this translates into a required voltage of $V_{\mathrm{crab}} = 11.2\,\mathrm{MV}$.

Assuming a crab cavity radius of $r = 10\,\mathrm{cm}$ yields a maximum longitudinal voltage of $V_z = krV_{\mathrm{crab}} = 2.6\,\mathrm{MV}$, which will occur at the left and right apertures and be of opposite sign at the two sides. The superconducting 400 MHz crab cavities proposed for the LHC supply 3 MV of transverse voltage. Keeping the same maximum electric and magnetic fields while scaling all dimensions of those cavities by a factor 4 yields a transverse voltage of 12 MV, thus indicating the feasibility of the eRHIC cavities. Alternatively, a dual harmonic crab cavity system with 168 and 336 MHz RF frequency could be used, resulting, in smaller, more manageable cavities at the expense of a second RF harmonic.

COLLECTIVE EFFECTS

Instability studies in the electron storage ring have been carried out for energies of 5, 10, and 20 GeV, using the simulation code TRANFT, a multipurpose coherent instability simulation code developed to study instabilities for NSLS-II [5]. Only single bunch instabilities were considered at this time. The transverse and longitudinal impedances were modeled as resonators with quality factor 1 and resonant frequency 10 GHz. The longitudinal impedance was adjusted such that $\Im\left(\frac{Z}{n}\right) = 1\,\Omega$ at low frequency, and the transverse impedance at low frequency to $Z_x = Z_y = 10\,\mathrm{M\Omega/m}$. The simulations were performed at zero synchronous phase and a cavity voltage of 40MV at $h = 18 \times 360$, corresponding to a 508 MHz RF frequency. Due to the short bunches the effect of the synchronous phase is expected to be negligible. Bunches turned out to be stable for bunch intensities up to 10^{12} electrons per bunch at 10 and 20 GeV, and up to $3 \cdot 10^{11}$ electrons per bunch at 5 GeV.

POLARIZATION

The Sokolov-Ternov self-polarization time in an electron storage ring with dipole bending radius r, circumference $2\pi R$, and energy E is calculated as

$$\tau = \frac{8}{5\sqrt{3}} \cdot \frac{E_0^6 \cdot R \cdot r^2}{\hbar^2 \cdot c^2 \cdot r_e \cdot E^5}, \tag{3}$$

where $E_0 = m_e c^2$ is the electron rest energy, c the velocity of light, and r_e the classical electron radius. Using the eRHIC parameters $r = 300\,\mathrm{m}$ and $R = 610\,\mathrm{m}$ we compute a self-polarization time of about 20 min at $E = 20\,\mathrm{GeV}$, and 20 days at $E = 5\,\mathrm{GeV}$ [6]. Self-polarization is therefore not applicable at eRHIC, thus requiring a full-energy polarized electron injector. In addition, for physics systematics control, alternating polarizations are needed for both hadrons and electrons.

A full-energy polarized electron injector allows such alternations of bunch polarizations in the electron storage ring. Bunches with the "un-natural" polarization direction will slowly depolarize and eventually build up polarization in the "natural" orientation due to the Sokolov-Ternov effect. As long as bunches are replaced at time intervals sufficiently short compared to the self-polarization time it is feasible to store and collide bunches with opposite spin directions at the same time. Assuming that the full-energy injector replaces bunches at a rate of 1 Hz, each of the 360 bunches will be stored for only 6 minutes, which is short even at the highest energy. If necessary, bunches with the "natural" spin direction can be stored longer, allowing faster replacement of bunches with "un-natural" spin direction, thus increasing the average store polarization.

While the spins will be oriented vertically in the arcs of the storage ring, spin rotators in the interaction region will rotate these into the longitudinal direction for collision with the hadrons. This rotation, which requires spin-matched beam optics, is accomplished by a set of solenoids and dipole magnets [6].

ELECTRON COOLING

The eRHIC interaction region design with its 15 mrad crossing angle and associated, reasonable crab cavities requires a proton bunch length of 20 cm at all energies. While this can be achieved at 250 GeV with the current longitudinal RHIC emittance, this would result in unacceptably large momentum spreads at lower energies. To overcome this, longitudinal electron cooling is required. Table 1 lists the proton beam parameters at three different energies, together with the resulting IBS growth times. At 50 and 100 GeV proton energy continuous longitudinal cooling is necessary to compensate for the IBS emittance growth, while above 160 GeV pre-cooling at injection or some other intermediate energy like 50 or 100 GeV becomes sufficient to reduce the longitudinal emittance to the required level due to the relatively slow longitudinal emittance growth. Without any electron cooling, luminosities with 50 GeV protons are reduced by a factor 3, while the reduction with 100 GeV protons is 40 percent.

INJECTION

Full intensity polarized electron bunches will be injected into the eRHIC electron storage ring at a rate around 1 Hz, thereby replacing the circulating bunch upon injection. The polarized injector can be realized in different ways:

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Table 1: eRHIC Proton Beam Parameters at Different Energies

energy [GeV]	50	160	250
bunch intensity [10^{11}]	3	3	3
RMS normalized emittance [nm]	2.5	2.5	2.5
longitudinal bunch area [eVsec]	0.32	0.66	1.6
RF frequency [MHz]	197	197	197
RF voltage [MV]	0.48	1.8	3.0
RMS momentum spread [10^{-4}]	5.2	5.2	5.2
RMS bunch length [cm]	20	20	20
long. IBS growth time [min]	25	131	250
transv. IBS growth time [min]	198	320	407

- A recirculating linac with FFAG arcs in the RHIC tunnel that can later on be converted into an ERL for a linac-ring collider scheme.
- A recirculating pulsed linac based on ILC cavities with separate, conventional arcs; acceleration up to 10 GeV can be accomplished using small radius arcs in a dog-bone configuration, thus reducing the number of beam-lines around the entire RHIC circumference.
- A highly symmetric rapid-cycling synchrotron.

BEAM PARAMETERS AND LUMINOSITY

The eRHIC ring-ring design assumes hadron beam parameters similar to those already routinely achieved in RHIC. For instance, proton bunch intensities of up to $3 \cdot 10^{11}$ are assumed in this design, while $2.4 \cdot 10^{11}$ are already achieved in routine operations. Likewise, the assumed transverse normalized RMS emittance of 2.5 μm has already been achieved.

Bunch intensities are limited by the beam-beam parameter on the oncoming beam, as well as synchrotron radiation power losses of the electrons. The latter is maximized at 10 MW, which corresponds to a linear power load of 4 MW/m in the arcs, a value well below the state-of-the-art technical limit of 10 MW/m.

Table 2 lists the main beam parameters of the eRHIC ring-ring design for highest luminosity performance, which is achieved with 13.7 GeV electron colliding with 250 GeV protons. At higher electron energies the electron bunch current is limited by the 10 MW synchrotron radiation power, while at lower electron beam energies the electron beam-beam parameter limits the proton bunch intensity. When the proton beam energy is lowered, the beam size at the IP increases due to the larger emittance, resulting in reduced luminosity. Since the RMS sizes of both beams at the IP have to be matched, the electron beam size has to increase as well. This is accomplished by simultaneously increasing the emittances and the β-functions of the electron beam at the IP [4]. Figure 1 shows the resulting luminosity curves for a number of proton beam energies as function of the center-of-mass energy $\sqrt{s}$, with the electron beam energy as the free variable.

Table 2: eRHIC Electron-Proton Parameters for Highest Luminosity

	electrons	protons
energy [GeV]	13.7	250
bunch intensity [10^{11}]	2.1	2.1
beam current [mA]	935	935
emittance h/v [nm]	53/9.5	9.5/9.5
β^* h/v [m]	0.38/0.27	2.16/0.27
beam-beam parameter	0.1	0.015
RMS bunch length [cm]	1	20
polarization [%]	80	70
luminosity [cm^{-2} sec^{-1}]	$1.2 \cdot 10^{33}$	

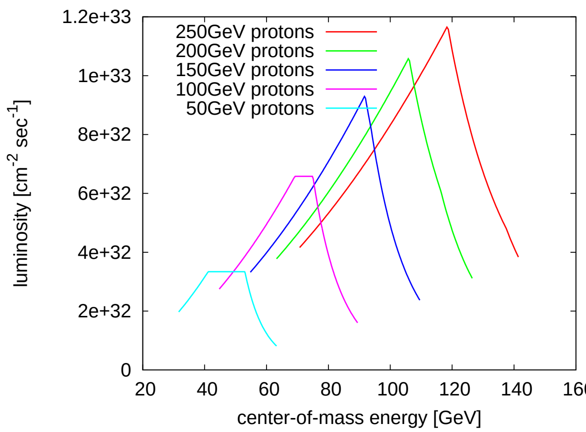

Figure 1: Luminosity curves for five different proton beam energies.

The existing 28 MHz RF system provides the 360 buckets required for eRHIC; however, new, faster injection kickers will have to be installed. The increased number of bunches together with the short RMS bunch length of 20 cm requires replacing the existing BPM cables, and in-situ coating of the stainless steel RHIC beampipes.

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