ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUYGBD3

eRHIC DESIGN STATUS*

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Abstract

The electron-ion collider eRHIC aims at a luminosity around 10^{34} cm^{-2}sec^{-1}, using strong cooling of the hadron beam. Since the required cooling techniques are not yet readily available, a version with a peak luminosity of 4.4×10^{33}cm^{-2}sec^{-1} is being developed as a fallback that can later be outfitted with strong hadron cooling. We will report on the current design status and the envisioned path towards 10^{34} cm^{-2}sec^{-1} luminosity.

INTRODUCTION

Brookhaven National Laboratory proposes eRHIC, a cost effective implementation of an electron-ion collider that meets all the requirements listed in the White Paper [1]. The design takes full advantage of the existing accelerator infrastructure of the RHIC complex, using the Yellow RHIC ring together with the entire hadron beam injector chain. A new electron storage ring in the RHIC tunnel will provide polarized electron beams for collisions between electrons and polarized protons or heavy ions. The center-of-mass energy in electron-proton collisions ranges from 29 to 141 GeV, accomplished by colliding 5 – 18 GeV electrons with 41 – 275 GeV protons. The peak luminosity reaches 10^{34} cm^{-2}sec^{-1}, as shown in Figure 1.

Polarized electrons are provided by a full-energy polarized injector synchrotron located in the RHIC tunnel, specifically designed to be free of intrinsic resonances over its entire acceleration range from 400 MeV at injection to 18 GeV. The beams collide in one or two interaction regions; a dedicated fill pattern ensures that each bunch collides only once per turn, thus sharing the luminosity equally between the two detectors without exceeding the beam-beam limit [2]. To maximize the luminosity, flat beams with unequal emittances $\epsilon_x \gg \epsilon_y$ in the two planes are focused to flat cross sections $\sigma_x \gg \sigma_y$ at the IP using unequal β-functions $\beta_x \gg \beta_y$. The hadron beam parameters are similar to what has been achieved in RHIC, with the exception that the number of bunches will be increased from 110 at RHIC up to 1320 in eRHIC. The total electron beam intensity is limited by the superconducting RF system [3] which will provide up to 10 MW of power to restore synchrotron radiation losses. Table 1 lists some of the key design parameters of eRHIC [4].

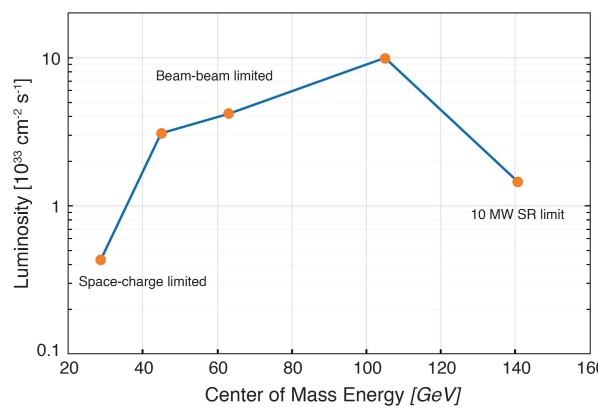

Figure 1: eRHIC electron-proton luminosity vs. center-of-mass energy with strong hadron cooling.

Table 1: eRHIC Key Design Parameters for Highest Luminosity

parameter	proton	electron
center-of-mass energy [GeV]	105	
energy [GeV]	275	10
number of bunches	1320	
particles per bunch [10^{10}]	6.0	15.1
beam current [A]	1.0	2.5
horizontal emittance [nm]	9.2	20.0
vertical emittance [nm]	1.3	1.0
β_x^* [cm]	90	42
β_y^* [cm]	4.0	5.0
tunes (Q_x, Q_y)	.08/.06	.315/.305
hor. beam-beam parameter	0.013	0.064
vert. beam-beam parameter	0.007	0.1
IBS growth time [h]	2.1	n/a
synchrotron radiation power [MW]	n/a	9.2
bunch length [cm]	5	1.9
hourglass and crab reduction factor	0.87	
luminosity [10^{34} cm^{-2}sec^{-1}]	1.05	

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy.
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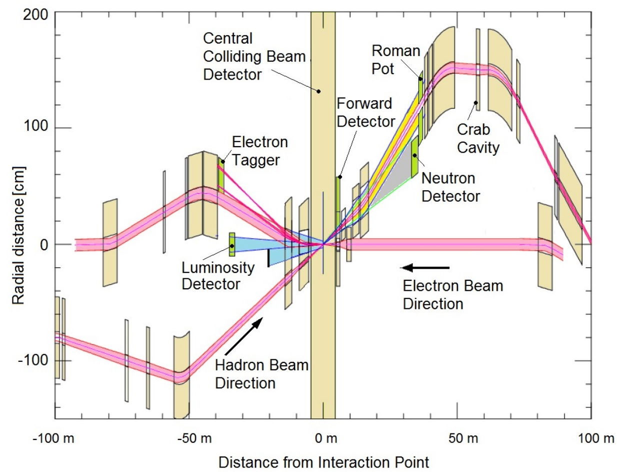

Figure 2: Layout of the eRHIC interaction region.

INTERACTION REGION

The interaction region serves multiple purposes:

- Strong focusing of the electron and hadron beams to equally small spot sizes at the interaction point. This is accomplished using superconducting low-β quadrupoles located right outside the central detector which extends to ±4.5 m from the interation point (IP). On the forward side, electron and hadron quadrupoles are arranged in an interleaved scheme, while on the rear side the magnets for the two beams share a common yoke (Fig. 2) [5, 6].
- Separation of the electron and hadron beams. Rather than using separator dipoles that would generate large amounts of synchrotron radiation near the detector, this is realized with a 22 mrad crossing angle. The geometric and beam dynamics effects of this crossing angle are compensated by crab cavities for both beams. Novel instrumentation is being developed to monitor the crabbing process in the hadron ring [7].
- Separation of the hadron beam from the forward-scattered 4 mrad neutron cone.
- Separation of the electron beam from the Bethe-Heitler photons used for luminosity monitoring.

ELECTRON STORAGE RING

The electron storage ring is comprised of 16 FODO cells in each of the six arcs. To achieve the required design emittance of 20 – 22 nm over the entire energy range from 5 to 18 GeV, it is operated with different phase advances per FODO cell - 90 degrees at 18 GeV, and 60 degrees at 10 GeV and below. The arc dipoles are realized as super-bends, each consisting of two 2.66 m long dipoles with a short, 0.44 m long dipole in-between. At energies of 10 GeV and above, all dipoles are powered uniformly, resulting in the maximum possible bending radius which minimizes the emitted synchrotron radiation. Below 10 GeV the field of the short central dipole is reversed in order to create additional synchrotron radiation damping due to the small bending radius and therefore allow for large beam-beam parameters. At the same time, this reverse bend also helps to achieve the desired emittance. The vertical emittance is controlled by a long vertical dispersion bump. The magnets are described in Ref. [8].

MODIFICATIONS TO THE HADRON STORAGE RING

Some moderate modifications of the hadron ring are necessary, mostly to accomodate the increased beam current and large number of bunches. It is planned to inject and ramp 330 bunches, and then split these into 1320 bunches once store energy is reached. This three-fold increase in the number of bunches at injection reduces the bunch spacing by a factor three compared to present RHIC, which requires injection kickers with a faster rise time. Since the available space in the present injection kicker location is not sufficient for these new, longer kicker sections, the existing transfer line from the AGS to RHIC will be extended to IR 4 by means of the otherwise obsolete Blue arc. There is sufficient warm space in IR 4 to install the new injection kickers [9, 10].

The increased beam current and peak bunch current will cause unacceptable heating of the cryogenic stainless steel beam pipes. To improve the surface conductivity of the vacuum pipes a thin layer of copper will be applied in-situ. A layer of amorphous carbon will then be applied on top of the copper coating to reduce the secondary electron yield and therefore suppress the formation of electron clouds. In addition, all BPMs will need to be replaced to allow for the large number of short, intense bunches.

The large energy range of the hadron beams requires adjustment of the ring circumference in order to keep the electron and hadron bunches synchronized. This is accomplished by two methods. Between 100 and 275 GeV proton energy, a ±14 mm radial shift is sufficient to account for the variation in velocity of the hadron beam. For proton beam operation at 41 GeV, the beam will travel through the (inner) Blue arc between IRs 12 and 2 instead of the (outer) Yellow arc, thus reducing the circumference by 93 cm, which corresponds to a proton beam energy of 41 GeV.

The RF system will be replaced to allow operation with up to 1320 bunches [11].

BEAM DYNAMICS

Both the large number of bunches and high bunch current are challenging features of eRHIC, especially in the electron storage ring. Simulations including the four impedance values listed in Table 2, short range resistive wall and coherent synchrotron radiation indicate that the beam-beam force is sufficient to damp transverse coupled bunch modes, while longitudinal coupled bunch oscillations can be damped with a longitudinal damper with gain $g_z = 5 \times 10^{-3}$. To overcome the longitudinal microwave instability with the

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Table 2: Impedances Assumed in Simulations

impedance type	R_{sh}	Q	f_{res}
broad band longitudinal	51 kΩ	2	20 GHz
broad band transverse	1.4 MΩ/m	2	20 GHz
narrow band longitudinal	360 kΩ	80	856 MHz
narrow band transverse	10.8 MΩ/m	80	1.0 GHz

impedances listed in Table 2, an RMS momentum spread of $\sigma_p/p = 8.2 \times 10^{-4}$ is required. The impedance budget of the electron storage ring is presented in [12].

Both weak-strong and strong-strong beam-beam simulations were performed to study the feasibility of the proposed high beam-beam parameters, $\xi_e = 0.1$ for electrons and $\xi_p = 0.015$ for protons [13, 14]. The threshold for coherent beam-beam oscillations was found to be about a factor two beyond the proposed bunch intensities in both beams, and therefore is not considered a concern. Tune scans were performed in weak-strong simulations to determine the optimum tune space for the electrons, which was found to be around $(Q_x, Q_y) = (.08/.06)$ to $(.12/.10)$.

The dynamic aperture in both the hadron and the electron ring has been assessed in tracking studies. The dynamic aperture in the hadron ring was found to be very similar to present RHIC, and therefore suffient. Lattice work in the electron ring has so far focused on the 10 GeV lattice, which corresponds to the highest luminosity (see Table 1). The dynamic aperture of this 60 degree FODO lattice was found to be greater than 10σ in all dimensions. While this is sufficient, the effect of misalignments and multipole errors still needs to be assessed, as does the dynamic aperture of the 90 degree lattice at 18 GeV.

POLARIZATION

The eRHIC physics program requires polarization levels of 70% in both electron and proton beams, as well as arbitrary spin patterns. RHIC has routinely provided proton-proton collisions with approximately 60% polarization in arbitrary spin patterns. Upgrading the Yellow ring by installing four additional Siberian snakes for a total of six snakes is expected to increase the store polarization to the required levels, as well as allow operation with polarized ^{3}He beams.

The required spin patterns in the electron storage ring are achieved by injecting polarized electron bunches with the desired spin orientation at full storage energy. Since the Sokolov-Ternov effect will lead to depolarization of bunches with spins parallel to the main dipole field, frequent bunch replacement of entire single bunches at about 20% of the Sokolov-Ternov time constant τ_{S-T} is required to keep the time-averaged polarization sufficiently high. The effect of this replacement on the emittance of the stored proton beam has been studied experimentally in RHIC [15] and was found to be tolerable. To minimize depolarization due to spin diffusion, spin matching has to be employed. Simulation

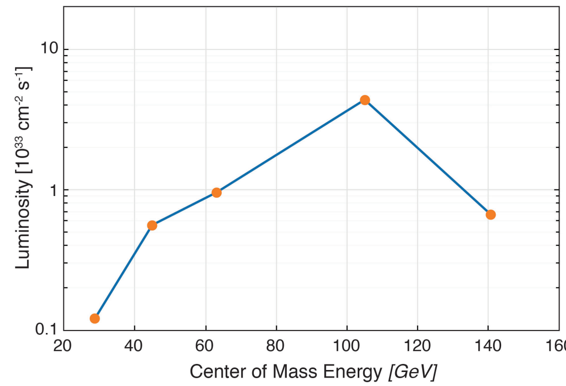

Figure 3: eRHIC luminosity without strong hadron cooling.

studies confirm that the spin performance of the storage ring is sufficient [16, 17].

STRONG HADRON COOLING

A luminosity of 10^{34} cm^{-2}sec^{-1} can only be achieved using strong hadron cooling due to the short IBS growth time of 2 h. Two cooling schemes are currently under consideration, namely bunched beam electron cooling [18], and coherent electron cooling (CeC) [19, 20]. The required high beam intensities for a bunched beam electron cooler exceed the capabilities of present-day electron guns by far. To overcome this limitation, a scheme where the electron beam is stored in a small storage ring equipped with strong damping wigglers is being evaluated. A coherent electron cooling test facility has been installed in RHIC, and is expected to show first cooling results in 2018.

Strong hadron cooling is very challenging and therefore considered a design risk. To mitigate this risk we have developed a parameter set that has a minimum IBS growth time of 8 h, comparable to present RHIC. With these parameters, eRHIC reaches a peak luminosity of 4.4×10^{33} cm^{-2}sec^{-1} without any cooling, as shown in Figure 3.

ELECTRON INJECTOR

A purpose-built rapid-cycling synchroton (RCS) with high periodicity will serve as cost-effective full-energy polarized electron injector [21] using normal-conducting RF cavities [22]. The high periodicity together with the appropriate choice of tunes ensures that intrinsic spin resonances occur outside the ramp energy range of the RCS. Simulation studies have shown that even in the presence of magnet misalignments as large as 0.5 mm RMS the polarization transmission efficiency is still 97%. Experimental studies at the Cornell synchrotron are being prepared in an effort to confirm this [23]. The magnet design for this machne is described in Ref. [24].

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