eRHIC Accelerator Position Paper

For NSAC Long Range Plan 2007

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1. Introduction

In this section we describe the present status of the accelerator design of eRHIC. The design follows the physics program guidelines outlined in [1]. The eRHIC accelerator will take advantage of using the existing RHIC ion machine at BNL. RHIC presently operates with collisions of heavy ions as well as polarized proton beams for nuclear physics experiments.

The EIC/eRHIC scientific program calls for obtaining an integrated electron-nucleon luminosity of order 50 fb^{-1} over about a decade on both highly polarized nucleon and nuclear (A = 2-208) beams. The following species, accelerated in RHIC, will be of primary interest for electron-ion collisions in eRHIC:

- 50-250 GeV polarized protons
- up to 100 GeV/n gold ions
- up to 167 GeV/n polarized ^{3}He ions

Two accelerator design options for eRHIC were developed in parallel and presented in detail in the 2004 Zeroth-Order Design Report [2]. Presently the most promising design option is based on the addition of a superconducting energy recovery linac (ERL) to provide for the polarized electron beam. This ERL-based design option can achieve a peak luminosity for electron-proton collisions at the 2.6×10^{33} $cm^{-2}s^{-1}$ level and has the potential for even higher luminosities. R&D for a high-current polarized electron source is needed to achieve the design goals in the ERL-based design. Another design option is based on the addition of an electron storage ring to provide for polarized electron or positron beam. This option is technologically more mature and promises a peak luminosity for electron-proton collisions of 0.47×10^{33} $cm^{-2}s^{-1}$. In the following sections both design options will be presented in more detail. In the end, the decision on what to build to supply polarized leptons will be driven by a number of considerations, among them experimental requirements, cost and timeline.

2. ERL-based eRHIC design

2.1 Overview

The general layout of the ERL-based design option of the eRHIC collider is shown in Figure 2.1. In this design, a polarized electron beam is generated in a photo-injector and accelerated to the energy of the experiment in the ERL. After colliding with the hadron beam in as many as four IP(s), the electron beam is decelerated to an energy of a few MeV and dumped. The energy thus recovered is used for accelerating subsequent bunches to the energy of the experiment. The electron beam bypasses both the STAR and PHENIX experimental halls. Two superconducting linacs are used. Initial acceleration to an energy of 0.5 GeV is done by the smaller pre-acceleration linac. After that the electron beam is accelerated in the 3.9 GeV main linac. The electron beam passes the main linac five times during acceleration and five times during deceleration. In this scheme, both linacs as well as the injection and the beam dump are located just outside the RHIC rings, between the STAR and PHENIX experimental halls. Four high-energy recirculating passes of the ERL are placed in the RHIC tunnel near the presently existing Blue and Yellow ion rings.

To provide a positron beam, a conversion system for the positron production may be added and a compact storage ring, at one quarter of the RHIC circumference, may be built for positron accumulation, storage and self-polarization.
Another configuration is being studied (not shown) in which the whole electron ERL is located inside the RHIC tunnel. The advantage of this configuration is the reduced cost of civil construction.

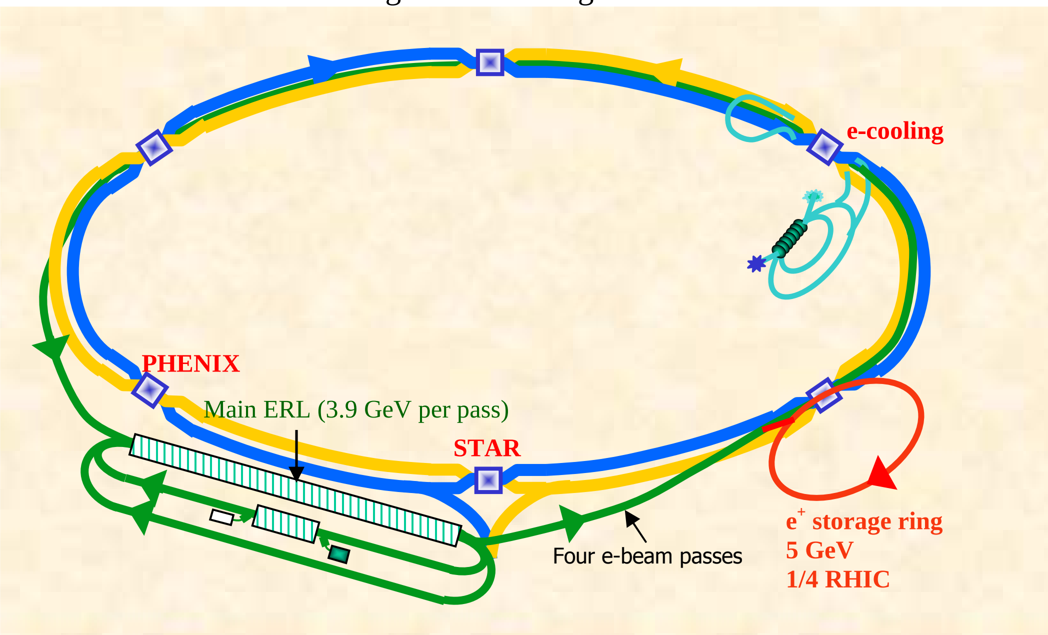

Figure 2.1: Design layout of the eRHIC collider based on the Energy Recovery Linac.

In the present design, the ERL provides electrons in the energy range from 3 to 20 GeV, leading to a Center-of-Mass Energy (CME) range from 25 to 140 GeV.

We list here the main highlights of the design based on the electron ERL:

- a luminosity of 10^{33} cm^{-2} s^{-1} and higher in electron-hadron collisions;
- high electron beam polarization (~80%);
- full polarization transparency at all energies for the electron beam;
- multiple electron-hadron interaction points (IPs) and detectors;
- very long “element-free” straight section(s) for detector(s);
- ability to take full advantage of electron cooling of the hadron beams;
- easy variation of the electron bunch frequency to match it with the ion bunch frequency at different ion energies.

2.2 Main beam parameters and luminosities

To maximize the luminosity and minimize beam-beam effects, we use round beams of equal size at the collision point(s). Since the electron beam is used for collisions only in one pass, the electron beam-beam parameter is not a luminosity-limiting factor. In fact, the luminosity is limited by the parameters related only to the proton (or ion) beam and can be written as

$$L = \gamma_i f_c N_i \frac{\xi_i A_i}{\beta_i^* Z_i r_p} \tag{2.1}$$

where N_i is the ion bunch intensity, A_i and Z_i are the ion mass and charge number respectively, r_p is the classical proton radius, β_i^* is the ion beta function at the collision point, and ξ_i is the ion beam-beam parameter. The design parameter tables 2.1.a and 2.1.b are based on setting the limiting value of the ion beam-beam parameter to ξ_i =0.015, following the experience of RHIC operation with polarized proton beams. Clearly the achievable luminosity scales with the assumed beam-beam parameter and a good understanding of this limit is necessary in any machine.

Although the design ion beam-beam parameter ξ_i=0.015 is supported by the performance of the RHIC and Tevatron colliders with proton-proton collisions, we recognize that HERA, the only operating electron-proton collider, operates with a proton beam-beam parameter of only 0.003. This limit is set by background in the detectors generated by beam loss with a larger beam-beam parameter. This subject requires further study of both the detector and collimation design as well as the effect of electron cooling on the very slow beam loss (of about 20 hours lifetime).

The beam parameters and luminosities shown in Tables 2.1.a and 2.1.b correspond to the *dedicated operation mode* where the ion beam collides with the electrons only (and only one collision point is assumed). Another possible operational mode, called the *parallel mode*, is where the ion beam collides with both the electrons in one interaction point and with the counter-rotating ion beam in the two main RHIC ion detectors. In a pessimistic scenario the luminosity of e-ion collisions in the parallel operation mode will drop by about a factor of three, because of the increased number of the interaction points. However, in a more optimistic scenario, harmful effects of the e-ion and ion-ion collisions can partially compensate each other, which should lead to a smaller luminosity reduction for the parallel mode. Since to date there have been no colliders operating with simultaneous e-ion and ion-ion collisions, R&D studies are required to establish more clearly the beam-beam limit and the luminosities for parallel mode operation.

Table 2.1.a. Luminosities and main beam parameters for electron-proton collisions.

	High energy setup		Low energy setup	
	p	e	p	e
Energy, GeV	250	20	50	3
Number of bunches	166		166	
Bunch spacing, ns	71	71	71	71
Bunch intensity, 10^{11}	2	1.2	2.0	1.2
Beam current, mA	420	260	420	260
95% normalized emittance, π mm$\cdot$mrad	6	115	6	115
Rms emittance, nm	3.8	0.5	19	3.3
β*, x/y, cm	26	200	26	150
Beam-beam parameters, x/y	0.015	2.3	0.015	2.3
Rms bunch length, cm	20	0.7	20	1.8
Polarization, %	70	80	70	80
Peak Luminosity, 1.e33 $cm^{-2}s^{-1}$	2.6		0.53	
Aver.Luminosity, 1.e33 $cm^{-2}s^{-1}$	0.87		0.18	
Luminosity integral /week, pb^{-1}	530		105	

Table 2.1.b. Luminosities and main beam parameters for electron-Au collisions.

	High energy setup		Low energy setup	
	Au	e	Au	e
Energy, GeV (or GeV/n)	100	20	50	3
Number of bunches	166		166	
Bunch spacing, ns	71	71	71	71
Bunch intensity, 10^{11}	1.1	1.2	1.1	1.2
Beam current, mA	180	260	180	260
95% normalized emittance, π mm $\cdot$ mrad	2.4	115	2.4	115
Rms emittance, nm	3.7	0.5	7.5	3.3
β* x/y, cm	26	200	26	60
Beam-beam parameters, x/y	0.015	1.0	0.015	1.0
Rms bunch length, cm	20	0.7	20	1.8
Polarization, %	0	0	0	0
Peak Luminosity /n, 1.e33 $cm^{-2}s^{-1}$	2.9		1.5	
Aver.Luminosity /n, 1.e33 $cm^{-2}s^{-1}$	1.0		0.5	
Luminosity integral /week /n, pb^{-1}	580		290	

In addition to the above-mentioned issues, R&D beam-beam studies are underway for the following topics:

- Beam-beam induced head-tail type instability of the proton beam (kink instability)
- Electron beam transverse disruption by beam-beam interactions
- Proton beam emittance growth due to fluctuations of electron beam current, electron beam size, and transverse collision offset

Unlike electrons, the positrons will collide with the ions while circulating in the storage ring. Because of this the luminosity of positron-ion collisions will be one order of magnitude less than for the corresponding electron-ion collisions.

The peak luminosity listed in the tables 2.1.a and 2.1.b, will be observed at the beginning of the beam stores. Following RHIC experience, the average luminosity will be a factor three less than the peak luminosity because of the luminosity deterioration during the course of the store and the time spent between stores. The luminosity integral shown in the tables is based on the average luminosity.

As a standard rule, the luminosity of any collider decreases with the beam energies. With a linac as the electron accelerator in the eRHIC design, the influence of some luminosity reduction factors, such as the electron beam-beam limit and the interaction region aperture limitation, can be avoided. The dependence of the collider luminosity on the CME energy of eRHIC is shown in Figure 2.2, where the area enclosed by the lines contains luminosities for all possible beam energy scenarios. In accordance with the formula (2.1) the luminosity does not depend on the energy of the electrons accelerated by the ERL.

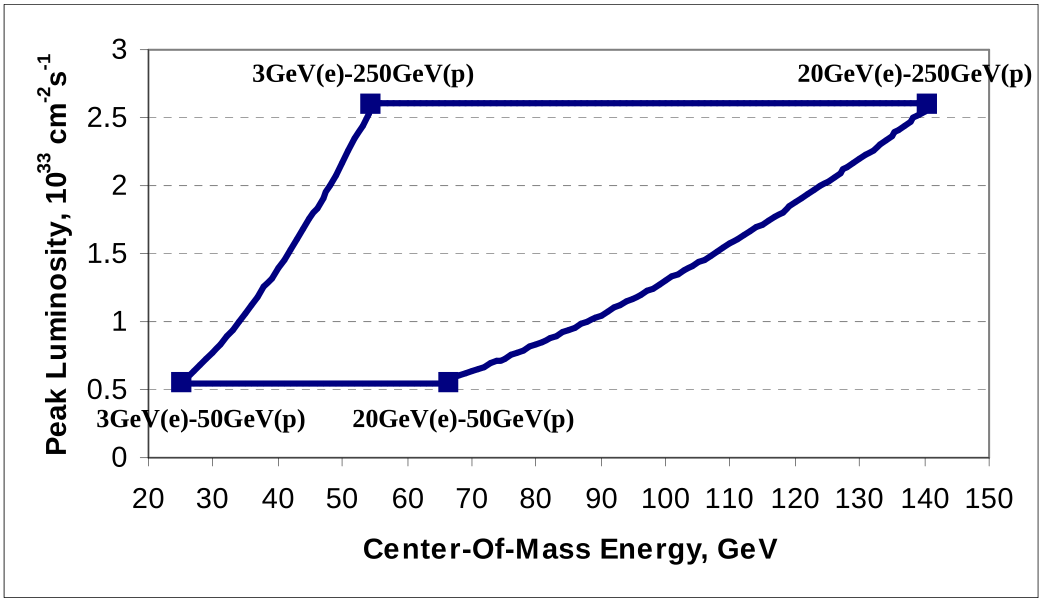

Figure 2.2. Luminosity scaling with the center-of-mass energy of eRHIC for e-p collisions.

2.3 Polarization

RHIC is the world's only facility for high-energy polarized proton beams. State-of-the-art technologies are used in RHIC and its pre-accelerators in order to preserve the high polarization of the beam during the acceleration process. In RHIC, with two full Siberian Snakes per ring, 100 GeV proton beams with 65% polarization were provided during the last run. Further polarization improvements are planned within the next few years, including operation at 250 GeV proton energy. The first successful acceleration of polarized protons to 250 GeV has been demonstrated already in the last RHIC run. Longitudinal polarization of the proton beam in the e-p interaction point(s) will be created using spin rotators based on helical magnets. Such spin rotators have been successfully used in polarized p-p experiments in RHIC.

The ERL-based eRHIC has no forbidden energy ranges, and a desirable polarization of electrons can be maintained at any electron energy without using spin-matching sections or snakes. 80% polarization produced at the polarized electron source is easily transportable to the collision point. Creating longitudinal polarization of the electron beam at the interaction point(s) does not require spin rotators. It can be facilitated by a proper choice of the energy gain in the pre-accelerator and main ERLs.

2.4 Interaction region design

The interaction region design of the ERL based eRHIC has the following main features:

- Head-on collision scheme (no crossing angle);
- Round-beam collision geometry to maximize luminosity;
- Fast beam separation using detector integrated dipoles in order to prevent parasitic beam-beam collisions;
- Small e-beam emittance resulting in relaxed aperture requirements for the electron beam;

- Normal conducting final focusing quadrupoles, located as far as 5m from the collision point;
- A 3 m vertical excursion of the second RHIC ring around the eRHIC collision region.

The IR design geometry provides for a safe passage for the electron beam emitted synchrotron radiation through the detector, and distant interception. A well-designed masking system has to ensure that only a small, tolerable fraction of photons backscatter from those distant surfaces.

2.5 Main R&D items for the electron beam

The eRHIC design is based on two rapidly developing accelerator technologies: energy recovery superconducting RF linacs and high-current polarized electron sources.

2.5.1 Energy recovery linacs

The basic element of the eRHIC ERL is a state-of-art 703.75 MHz 5-cell RF cavity. The superconducting cavity design was developed at BNL in the course of the electron cooling project. The design allows the minimization and efficient damping of the higher order modes, opening a way for higher electron currents. Simulations of multi-bunch and multi-pass breakup instabilities showed that the design eRHIC currents can be achieved in an ERL based on this cavity. The present ERL design assumes 19.5 MeV energy gain per cavity. 200 cavities are used in a 600m long linac to provide 3.9 GeV of acceleration in one beam pass.

Further R&D for the energy recovery linac includes thorough beam tests with an ERL prototype based on the 5-cell cavity. Also, beam loss tolerances and the cavity protection system will be evaluated.

2.5.2 Polarized electron source

To achieve the design eRHIC luminosities, a sufficiently high electron current is required. Therefore a polarized electron source (PES) which can provide such currents has to be developed. Recently, several PES development centers around the world intensified their quest for a higher electron current needed for the International Linear Collider as well as for electron-ion colliders. The best existing sources operate with current densities of about 50 mA/cm^2. The development of large cathode guns should provide a path to electron currents of tens to hundreds of milliamps.

Further R&D studies are planned to evaluate various aspects of the PES design for eRHIC. These include:

- Cathode lifetime and cooling;
- Proper gun geometry;
- Schemes with electron current combined from several guns;
- New cathode materials.

3. Ring-Ring Design

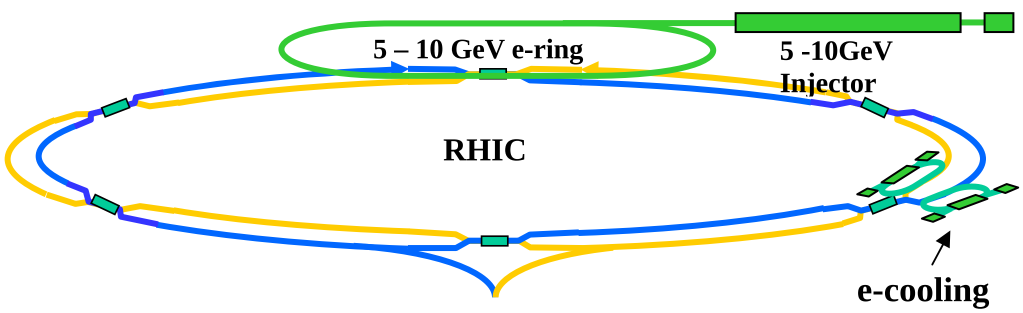

Figure 3.1: Design layout of the eRHIC ring-ring collider.

The design is described in ref. [2] although a number of optimizations and studies have been carried out since. Figure 3.1 shows the layout of the alternate ring-ring collider design for eRHIC.

A pair of recirculating linacs of 2 GeV each provide polarized electrons or unpolarized positions of 5 to 10 GeV at 0.1mA which are stacked into a storage ring up to currents of 0.5 – 1 A. The storage ring has 1/3 of the circumference of RHIC and a race-track shape with two 200 m long straight sections, one of which intersects the RHIC ring at the "12 o'clock" interaction point.

3.1 Lepton Polarization

The electron ring is designed to maintain electron polarization and self-polarize positrons at non-resonant energies between 5 and 10 GeV (energy steps of 0.5 GeV). Polarization is vertical in the arcs and made longitudinal at the interaction point by spin rotators. Advanced spin tracking codes were developed to identify and eliminate depolarizing effects of magnet imperfections, misalignment etc. From those simulations polarizations of 70% to 80% are expected.

3.2 Lepton Ring Lattice

The ring lattice includes a new feature called "superbends". These are triplet bending magnets which allow adjustment of the bending radius of the inner magnet at energies below 10 GeV such that the interaction luminosity is only varying linearly with gamma of the leptons. This lattice also allows positrons to self-polarize within the entire 5-10 GeV energy range.

3.3 Hadron Energy Variations

Since the hadron's velocity is varying measurably with energy, the resulting change in orbital frequency has to be matched by the orbital frequency, i.e. the circumference, of the lepton ring, as adjusting RHIC's circumference is not practical. Studies have shown that this can be best achieved by moving an entire arc of the lepton ring by up to 33 cm (for 30 GeV/n hadrons) to lengthen the straight sections ("trombone"). Preliminary engineering solutions providing such adjustment within a reasonable amount of time and suitable position accuracy have been costed at a small fraction of ring costs.

3.4 Ring-Ring Performance

The analogous expression to equation (2.1) for the ring-ring luminosity is

$$\mathcal{L} = \pi f_c (1+k)^2 / k^2 \; \frac{\gamma_e \xi_e}{r_e} k_e \sqrt{\varepsilon_{ex} / \beta_{ex}} \, \frac{\gamma_i \xi_i}{r_i} \sqrt{\varepsilon_{ix} / \beta_{ix}} \qquad (3.1)$$

where γ_e ζ_e, ν_e and ε_e are the electron beam parameters corresponding to the ones defined for ions, k_e is the ratio $\varepsilon_{ey}/\varepsilon_{ex}$ and k the aspect ratio of the beam profile at the interaction point. The relevant parameters for the ring-ring design for a single high-luminosity interaction region with ±1m element-free space around the collision point are listed in Table 3.1 for leptons colliding with protons (values for Au scale with those of table 2.1.b). Note that a larger proton beam emittance is chosen here compared to Table 2.1.a.

Table 3.1. Luminosities and main beam parameters for electron-proton collisions.

		High energy setup		Low energy setup	
		p	e	p	e
Energy, GeV	GeV	250	10	50	5
Number of bunches		165	55	165	55
Bunch spacing	ns	71	71	71	71
Particles / bunch	10^{11}	1.00	2.34	1.49	0.77
Beam current	mA	208	483	315	353
95% normalized emittance	π mm·mrad	15		5	
Emittance ε_x	nm	9.5	53.0	15.6	130
Emittance ε_y	nm	9.5	9.5	15.6	32.5
βx^*	m	1.08	0.19	1.86	0.22
βy^*	m	0.27	0.27	0.46	0.22
Beam-beam parameter ξ_x		0.015	0.029	0.015	0.035
Beam-beam parameter ξ_y		0.0075	0.08	0.0075	0.07
Bunch length σ_z	m	0.20	0.012	0.20	0.016
Polarization	%	70	80	70	80
Peak Luminosity	10^{33}, $cm^{-2}s^{-1}$	0.47		0.082	
Average Luminosity	10^{33}, $cm^{-2}s^{-1}$	0.16		0.027	
Luminosity Integral /week	pb^{-1}	96		17	

3.5 Variants, R&D, and Upgrades
A variant of the interaction region with a ± 3m component-free detection space was studied. It would reduce the available luminosity by about 35%. A decision on this involves iteration with the experimenters about the scientific program.

The ring-ring design is entirely based on existing technology requiring no significant R&D, and is ready for detailed design and realization. Nevertheless, continued engineering on superbend magnets, high-heat load vacuum chambers in the arcs and length adjustments of the straight sections of the lepton ring are called for. Development of a booster ring for full-energy polarized injection could significantly reduce costs. Furthermore, development efforts in polarization control, interaction region design and integration into detector design, and developing beam-beam parameter limits have the potential for significant improvements of the luminosity.

To obtain a second interaction region, the most promising approach is to build a second, possibly specialized, lepton ring or ERL intersecting the second hadron beam of RHIC at a separate interaction point. Although this concept requires a second ring (or linac), it provides a second interaction region which is independent in energy and particle species for the lepton beam and in particle species for the hadron beam and which does not lower the luminosity at the first interaction point.

3.6 Staging
The lepton injection offers natural possibilities for staging. A first stage would consist of a low-energy linac (1-2 GeV) to accelerate unpolarized electrons to be injected into the ring. Alternately, the electrons would serve to produce positrons which would then be accelerated in the linac and injected into the ring. The ring would be ramped up to the required energy where the leptons would self-polarize. This stage would not allow topping up the ring current and may produce lower electron polarization. At a second stage, a booster, which potentially preserves polarization ("figure 8", see ref. [2]), would be added for full energy injection, allowing limited topping up operation. A third stage would add a polarized electron source and if necessary replace the booster with a polarization-preserving recirculating linac to inject positrons and polarized electrons at full energy. Adding a second interaction region as described in paragraph 3.5 can be considered a fourth stage. Cost estimates have been done for the various stages in the project.

4. Ion beam

The following upgrades have to be realized in the RHIC ion ring in order to achieve the design luminosities.

4.1 Electron cooling
The required transverse beam emittances for eRHIC are below typical values presently used in operation. Electron cooling will be required to achieve the design transverse emittances. Beams of all species can be cooled at the RHIC injection energy and accelerated to the storage energy afterwards. In addition, gold ion beams will be cooled at the storage energy of 100 GeV/n to counteract the effect

of intrabeam scattering. Electron and stochastic cooling will also be needed to prevent longitudinal emittance increases during the course of a store, also caused by intrabeam scattering.

Stochastic cooling is under development for RHIC. A high-energy proton bunch of low intensity was cooled longitudinally for the first time in RHIC in 2006. A longitudinal stochastic cooling system for ions is planned to be operational for one ring in 2007, and is anticipated to stop the longitudinal emittance growth. Design work on a transverse system has started.

An electron cooling system is presently under development for RHIC-II, intended to lead to an order of magnitude higher ion-ion luminosities in RHIC. The same system will be used for eRHIC.

4.2 Increased number of bunches

166 bunches in the ion beam has been selected to be the design number of bunches for eRHIC. It is higher than the number of bunches used during ion-ion RHIC operation (111 bunches were used in latest RHIC run). The intended bunch number increase will require modifications of the RHIC injection system as well as a better understanding of harmful effects caused by electron clouds. In addition, an upgrade of the beam abort system would be required. Further increase of the number of bunches to 333 is consistent with the present RHIC RF system, but requires considerable R&D for the injection system and electron cloud effects. Potentially it may increase the luminosities of both design options.

4.3 Polarized ^{3}He

^{3}He ions have not yet been used for experiments in RHIC. EBIS, the new ion source under construction at BNL, will provide the ability to produce polarized ^{3}He beams. The existing RHIC Siberian Snakes can be used to preserve the beam polarization during the acceleration. Since depolarization effects for ^{3}He beams are stronger than for protons (due to much larger anomalous magnetic moment), additional R&D studies are planned to understand better the machine tolerances required for polarization preservation in RHIC as well as in the pre-accelerators.

5. Conclusion

Two design options exist for an electron-ion collider for QCD physics, using the RHIC facility at BNL. These options hold promise for a strong experimental program, with differing limitations and developments needed, as detailed in the preceding sections. We are confident that, in collaboration with the experimental physicists, a collider can be built that will meet the needs of the QCD physics program.

References:

[1] The EIC white paper submitted to NSAC LRP 2007; A. Deshpande et al., Annual Reviews of Nucl. & Part. Sci. 55, (2005) 165-207;
The eRHIC/EIC white paper submitted to NSAC LRP 2002.

[2] eRHIC Zeroth-Order Design Report, Editors: M. Farkhondeh and V. Ptitsyn, BNL CA-D Note 142, 2004.