eRHIC, A FUTURE ELECTRON-ION COLLIDER AT BNL*

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Abstract

We review recent progress in the design of eRHIC, a proposed high luminosity, polarized electron-ion collider which would make use of the existing RHIC machine. The eRHIC collider aims to provide collisions of electrons and positrons on ions and protons in the center-of-mass energy range of 30-100 GeV, with a luminosity of 10^{32}-10^{34} $cm^{-2}s^{-1}$ for e-p and 10^{30}-10^{32} $cm^{-2}s^{-1}$ for e-Au collisions. An essential design requirement is to provide longitudinally polarized beams of electrons and protons (and, possibly lighter ions) at the collision point. An eRHIC ZDR [1] has been prepared which considers various aspects of the accelerator design. An electron accelerator, which delivers about 0.5A polarized electron beam current in the electron energy range of 5 to 10 GeV, would be constructed at BNL, near the existing RHIC complex and would intersect an ion ring in at least one of the available ion ring interaction regions. In order to reach the luminosity goals, some upgrades in the ion rings would also be required.

INTRODUCTION

In the past few years the physics interest in a high energy, high luminosity, polarized electron-ion collider for studying the fundamental structure of matter using deep inelastic scattering, has led to an intensification of work on possible designs for such a collider. A convenient opportunity for this machine is presented by the existing heavy ion collider RHIC at BNL which produces collisions of ion-ion beams as well as collisions of longitudinally or transversely polarized proton beams [2]. RHIC has interaction regions where no detectors for ion-ion collision have been installed and which are available for possible utilization for electron-ion collisions.

A number of eRHIC designs have been considered in recent years [3,4]. In this paper the summary of detailed design work by a collaboration of accelerator physicists from several laboratories is presented. The collaboration generated a Zeroth-Order Design Report (ZDR) for eRHIC early this year [1]. The report included two possible design concepts for the electron machine: a) ring-ring and b) linac-ring options.

Besides the addition of an electron accelerator, the requirement for high luminosities calls for upgrades in.the proton (ion) beam parameters. The main upgrades are related to decreasing the beam emittance (by cooling) and increasing the beam intensity (by increasing the number of bunches).

MAIN DESIGN OPTION (RING-RING)

At present the main design line for eRHIC is based on the ring-ring scenario, where an electron beam of 5-10 GeV energy circulates in a storage ring, which intersects an existing ion ring in one point (see Figure 1).

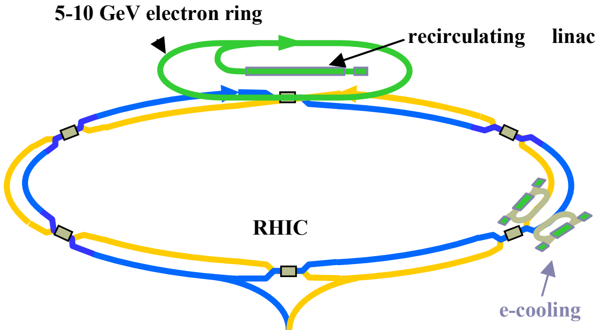

Figure 1: eRHIC design for the ring-ring option.

The electron beam in this design is produced by a polarized electron source and accelerated in a linac injector to energies of 5 to 10 GeV. In order to reduce the injector size, and therefore the injector cost, the injector design includes recirculation arcs so that the electron beam passes through the same accelerating linac sections multiple times. Two possible polarization preserving linac designs, superconducting and normal conducting, have been considered. The polarized beam is accelerated by the linac to the required collision energy and injected into the storage ring. Injector options involving a polarization preserving booster synchrotron or a FFAG based injector are also under investigation.

The electron storage ring should be capable of storing 5-10 GeV electron beams with appropriate beam emittance values. It does not provide any additional acceleration of the beam. Depolarization effects should be minimized to keep the electron beam polarization at the

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*Work performed under the auspices of the United States Department of Energy high level of >70% with storage times of order of several hours.

The injector system also includes a conversion system for positron production. After production, the positrons are accelerated to 10 GeV and injected into the storage ring in the same way as the electrons. Unlike electrons the positrons are produced unpolarized and must self-polarize in the ring. Therefore the design of the ring should allow for sufficiently small polarization times. The current ring design provides a polarization time of about 20 min at 10 GeV. But since the polarization time increases sharply as the beam energy decreases, the use of polarized positrons in the current design is limited to 10 GeV.

Ref. [5] describes the electron ring in more detail. It is important to note that the electron accelerator design is based on currently available accelerator technology and does not require extensive R&D.

For collisions with electrons the ion beam in the RHIC Blue ring will be used, since the Blue ring can operate alone, even when the other ion ring, Yellow, is non-operational. The design of the interaction region is presented in Ref. [6]. The design provides fast beam separation for the electron and the Blue ring ion bunches, strong focusing at the collision point and provision for handling the high levels of synchrotron radiation produced by the electron beam. The Yellow ion ring will make a 3 m vertical excursion around the collision region, avoiding collisions with both the electron and the Blue ion beams and providing adequate space for the detector installation. The interaction region will include spin rotators, in both electron and Blue ion rings to produce longitudinally polarized beams of electrons and protons at the collision point.

The design luminosity is mainly limited by the maximum allowable collision-induced tune shifts (beam-beam parameter) and by interaction region magnet apertures. It can be expressed as a function of the beam-beam parameters (ξ_e,ξ_i) and the rms angular spreads at the interaction point (σ'_{xi}, σ'_{ye}):

$$L = f_c \frac{\pi\gamma_i\gamma_e}{r_i r_e}\xi_{xi}\xi_{ye}\sigma'_{xi}\sigma'_{ye}\frac{(1+K)^2}{K} \qquad (1)$$

where f_c=28.15 MHz is the collision frequency, assuming 360 bunches in the ion ring and 120 bunches in the electron ring. $K=\sigma_y/\sigma_x$ is the ratio of beam sizes at the interaction point and r_i, r_e are the classical radii of the ion and the electron, respectively. In order to minimize the destructive effects of beam-beam interactions, the beam sizes for ions and electrons have to be matched at the interaction point: i.e., $\sigma_{xe}=\sigma_{xi}$ and $\sigma_{ye}=\sigma_{yi}$.

According to equation (1) the luminosity is greatest at maximum values of the beam-beam parameters. For protons (and ions) a total beam-beam parameter limit of 0.02 was assumed following experience and observations from other proton machines as well as initial experience from RHIC operation. With three beam-beam interaction points (two for p-p and one for e-p collisions) the proton beam-beam parameter from e-p collisions should not exceed 0.007.

The electron beam-beam parameter limit of 0.08 at 10 GeV has been defined by scaling ξ_e from B-factory design values, taking into account the larger (by a factor 3) radiation decrement in the eRHIC electron ring. This choice of the beam-beam parameter has been confirmed also by simulations [7].

The available magnet apertures in the interaction region also put a limit on the achievable luminosity. The studies for the interaction region design revealed considerable difficulties in obtaining an acceptable design for collisions of round beams. Thus the current IR design, provides a beam size ratio K=1/2 at the interaction point. The main aperture limitation comes from the septum magnet, which leads to a limiting value of $\sigma'_{xp} \approx 90\ \mu\text{rad}$.

Table 1 shows design luminosities and beam parameters for the high energy setup of e-p or e-gold ion collisions.

Table 1: Luminosities and main beam parameters for high energy collisions in the ring-ring eRHIC design option.

	e-p mode		e-Au mode	
	p	e	Au	e
Energy, GeV	250	10	100	10
Bunch intensity, 10^{11}	1	1	0.01	1
Number of bunches	360	120	360	120
96% normalized ion emittance, π mm.mrad	15		6	
rms emittance, nm, x/y	9.5/9.5	53/9.5	9.5/9.5	54/7.5
β*, cm, x/y	108/27	19/27	108/27	19/34
Beam-beam parameters, x/y	0.0065 /0.003	0.03/ 0.08	0.0065 /0.003	0.022/ 0.08
rms bunch length, cm	20	1.2	20	1.2
$\kappa=\varepsilon_y/\varepsilon_x$	1	0.18	1	0.14
Luminosity, 1.e32 $cm^{-2}s^{-1}$	4.4		0.044	

Higher luminosity (up to 10^{33} $cm^{-2}s^{-1}$ for the e-p mode) might be achieved in a dedicated operation mode with only e-p collisions (no p-p collisions at other RHIC IPs). More studies are planned to explore the feasibility of such operation which involves higher electron beam intensity.

ION RING UPGRADES

In order to reach higher luminosities in eRHIC, several improvements and upgrades should be made in the ion rings.

While the single bunch ion current in eRHIC is at the level of that used for current RHIC operation, the total beam current should be increased by a factor of six. This can be achieved by increasing to 360 the number of ion bunches in the ion ring. An injection system upgrade will be required to manage the beam injection with a short distance (36ns) between bunches. Other important areas of study deal with vacuum pressure rise, effects from electron clouds, an upgrade of the abort system and a precise evaluation of heat load in the cryogenic beam pipe of the ion rings.

Longitudinal proton polarization at the interaction point will be provided by helical spin rotators, identical to those already used in two existing RHIC p-p interaction regions. The eRHIC design also considers the use of polarized beams of other ion species, with $^3He^{+2}$ as best possible candidate.

Beam cooling would be required to reach high luminosities for electron collisions with gold ions and lower (<150 GeV) energy protons. The electron cooling technique would be applied to reduce and maintain the transverse emittances at the required level. Cooling can also be used to shorten the ion bunch rms length to 20 cm or less. The electron cooling system [8] is an essential part of the RHIC upgrade, RHICII, for higher luminosity in ion-ion collisions.

LINAC-RING OPTION

Another possible electron accelerator design option has been described in detail in the ZDR Appendix [1] (see also Ref. [9]). This design considers the use of a high current polarized electron beam accelerated to collision energies by a superconducting energy recovery linac (ERL). In this case the electron beam is delivered to an interaction point directly from the linac.

Figure 2 shows the schematic layout of one of the two linac-ring designs considered for eRHIC. The electron beam uses a major portion of the length of the RHIC tunnel and provides a possibility for more than one collision point.

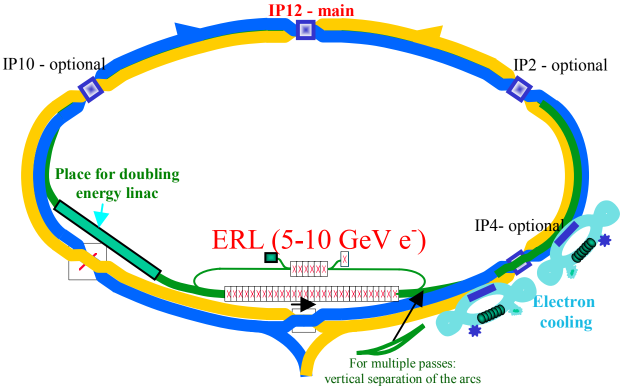

Figure 2: Design based on an energy recovery electron linac.

Assuming that a polarized electron current of a magnitude similar to that in the electron ring design (~0.5A) can be provided and accelerated by an energy recovery linac, the linac-ring option leads to higher luminosity and has several advantages. One of them is that the beam-beam tune shift for the electron beam does not limit the luminosity, since each electron bunch experiences only one collision. The handling of electron polarization and the interaction region design are simpler in the linac-ring option. An IR design with round beam collisions can be realized in this case. The disadvantage of the linac-ring option is the exclusion of positron beams.

An e-p luminosity beyond 10^{33} $cm^{-2}s^{-1}$ might be achieved in this design, with the luminosity limit coming from the maximum achievable proton (ion) beam intensities, as defined by electron cloud related effects and the heating of ion ring cryogenic vacuum pipe. In a dedicated mode, with only e-p collisions, 10^{33} $cm^{-2}s^{-1}$ luminosity can be reached with 120 bunches in the proton beam. If an energy upgrade were required a location for an additional linac would be available (see Fig.2).

The major challenge for the linac-ring design is to achieve high, polarized, electron currents of several hundred milliamps from the polarized injector and the ERL. This requires intense R&D to develop and to test technologies for high-current polarized electron sources and high power energy recovery linacs.

CONCLUSIONS

We have presented two options for the eRHIC design. They are described in more detail in the eRHIC ZDR [1]. The main design option, ring-ring, uses conventional technology for electron rings, and for critical design aspects utilizes experience and achievements from existing B-factories. The linac-ring option requires developing energy recovery technology and has a larger uncertainty in the estimate of performance and cost involved, but may pave a way to higher luminosities. Work on both options for eRHIC will continue in the foreseeable future, until the final construction timescale requires freezing the design and technology.

Important R&D items in the ion ring for eRHIC are vacuum pressure rise and electron cloud effects, beam-beam limits, the development of electron cooling and injection system upgrade.

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