AN ALTERNATE RING-RING DESIGN FOR eRHIC

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Abstract

I present here a new ring-ring design of eRHIC. It utilizes high repetition rate colliding beams and is likely able to deliver the performance to meet the requirements of the science program with low technical risk and modest accelerator R&D. The expected performance includes high luminosities over multiple collision points and a broad CM energy range with a maximum value up to 2×10^{34} $cm^{-2}s^{-1}$ per detector, and polarization higher than 70% for the colliding electron and light ion beams. This new design calls for reuse of decommissioned facilities in the US, namely, the PEP-II high energy ring and one section of the SLAC linac as a full energy injector.

INTRODUCTION

A polarized electron-ion collider (EIC) in a CM energy range up to 100 GeV/n is envisioned as a future facility for nuclear science research in the US [1]. Presently, both BNL and JLab are engaged in design studies for this future collider [2,3,4,5]. Since the beginning in 2001, the EIC design studies have been focused on achieving superior performance. The EIC science program [1] requires high luminosity (above 10^{33} $cm^{-2}s^{-1}$ per detector) over a broad CM energy range with a wide array of fully stripped ion species up to lead or uranium, and high polarization (>70%) for both colliding electron and light ion beams. Both ring-ring and linac(ERL)-ring collider scenarios have been adopted respectively for MEIC (the JLab design [4,5]) and eRHIC (the BNL design [3]).

The MEIC design is based on a very high bunch repetition rate for both colliding beams and strong final focusing to achieve a luminosity close to 10^{34} $cm^{-2}s^{-1}$ per detector [6]. The design concept was formulated more than 10 years ago and is still considered the best approach for MEIC. Recently, the reuse of the PEP-II high energy ring for the MEIC electron collider ring has been integrated into the present baseline [5].

eRHIC started with a ring-ring collider design [2] and advanced to the present ERL-ring collider design [3] around 2007 to maximize luminosity. This design is very innovative and introduces a set of new and advanced concepts and schemes, and relies on several yet-to-be-demonstrated technologies [3]. These include a high current polarized electron source based on a multi-cathode Gatling gun; high energy high current multi-pass ERL based on FFAG-type recirculation beam lines; space charge compensation; and coherent electron cooling. While these concepts and technologies are expected to improve the eRHIC performance, they do require R&D effort for development and proto-typing, and for proof-of-principle demonstrations.

In this paper I propose an alternate eRHIC design based on a ring-ring scenario and the same luminosity concept used in the MEIC design. This design has the potential to reach high luminosities and polarization while requiring modest accelerator R&D. I also include a discussion on implementation issues and the required accelerator R&D.

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DESIGN CONCEPT

Design Strategy

I choose a ring-ring collider scenario as the basis of this alternate eRHIC design since it is technically a conservative approach compared to an ERL-ring design but still able to deliver very high luminosities. The design supports simultaneous operation of multiple detectors, thus increases science productivity. This is different from an ERL-ring design where an electron bunch is allowed to collide only once (at one of the detectors) due to a large beam-beam disruption, so the detectors can only be operated alternately.

The strategy for high luminosity has been demonstrated already in the B-factories [6] and has been adopted for the MEIC design since 2002 [4]. The concept involves specific design choices of colliding beams, interaction region (IR) and beam cooling. Namely, (1) both colliding beams have a high bunch repetition rate, very small bunch lengths, bunch charges and transverse emittances; (2) the IR has very strong final focusing to attain very small beam spots at collision points; it also has an implementation of crab crossing of colliding beams to support high bunch repetition; (3) electron cooling is responsible for reduction of the proton or ion beam six-dimensional emittances.

New Design Baseline

The following key elements are proposed as the new ring-ring eRHIC baseline

- *Electron collider ring*: the PEP-II high energy ring;
- *Ion collider ring*: one of the RHIC rings;
- *Electron full energy injector*: a section of the SLAC warm linac;
- *Ion injector*: the RHIC ion complex

Reuse of the PEP-II high energy ring includes the entire magnet set and the vacuum chamber as well as the RF system. This results in a 476 MHz bunch repetition rate of the electron beam in the collider ring. Following this approach, no major new facility is required.

RHIC Upgrade

I further propose to upgrade RHIC and its injectors

- To support high bunch repetition rates;
- To support multi-phased electron cooling;
- To improve the RHIC polarized ion beam operation.

To match bunch structure of the electron beam, the RF system of RHIC (and part of AGS) should be rebuilt to support 476 MHz frequency. This provides an

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opportunity to implement the high luminosity concept based on a high bunch repetition rate discussed above.

Besides a new RF system, the RHIC upgrade needs two electron cooling facilities, namely, a DC cooler installed in the AGS and a bunched beam ERL based cooler installed in the RHIC ring. More Siberian snakes will be installed in the RHIC ring as already planned in the present eRHIC design [3].

IMPLEMENTATION ISSUES

PEP-II Ring in the RHIC Tunnel

Both RHIC and PEP-II rings have six-fold symmetric footprints, however, their circumferences are different, namely, 3834 m for RHIC and 2199 m for PEP-II [7]. There are two ways to fit the PEP-II high energy ring into the RHIC tunnel. The first way is by reducing the dipole packing factor of the arc cells to stretch the PEP-II arc length while preserving the dipole bending angle, therefore, no new magnet is required. The second way is by adding extra arc cells to cover the RHIC arc. This will reduce the dipole bending angle and increase the bending radius, leading to reduction of synchrotron radiation (SR) power and beam emittance. Table 1 lists the number of electron arc cells in each sextant (~399 m) of the RHIC ring, the corresponding dipole bending radius and SR power using these two methods. The PEP-II vacuum chambers have a limit of 10 kW/m for the SR power density. Thus in the high energy region, the electron current must be adjusted to satisfy this limit.

Table 1: Fitting the PEP-II arc cells into one sextant of the RHIC tunnel; the third row shows stretched PEP-II arc cells; the fourth row utilizes more PEP-II type arc cells.

Cells per arc	Packing factor	Bending radius	Cell length	Current @10GeV	SR power
		m	M	A	MW
16	0.43	165	24.9	1.93	10
26	0.71	268	15.2	3	5.9

Injection from the SLAC Linac

The SLAC warm linac was used as a full energy injector to the PEP-II collider rings. The currents of stored high energy electron and low energy positron beams reached 2.1 A and 3.2 A respectively during the last run of the PEP-II program [8]. To support eRHIC, a pulsed polarized electron source is required. To match the PEP-II injection performance, this source should be able to deliver a beam with a 60 to 120 Hz pulse repetition rate, (0.1 to 3)$\times 10^{10}$ electrons per pulse, and polarization higher than 70%. Such a source was developed at SLAC for Stanford Linear Collider operations in the early 90s [9]. It delivered 7×10^{10} electrons per pulse, and had a 4-day QE lifetime. With this source and the SLAC pulsed linac, the eRHIC electron ring can be filled in a similar time as the PEP-II rings, as low as 2 minutes.

Top-off injection was performed in PEP-II in 30 min interval and took 3 minutes to bring the stored current from 80% to 100%. Such a top-off injection scheme is useful and also sufficient to maintain a satisfactory beam current and polarization in eRHIC. Since the synchrotron radiation is low due to a larger dipole bending radius, the depolarization time is on the order of hours even at very high energies.

If it is decided that the SLAC linac will not be used for eRHIC, a new warm linac may be considered. Recirculation of up to three to four passes of the linac may reduce the linac energy substantially.

COLLIDER PERFORMANCE

The main features of this alternate ring-ring eRHIC design can be summarized below

- Multiple detectors and simultaneous operation;
- Ion species: proton to uranium, fully stripped; proton and helium-3 ions are polarized;
- Electron energy range: 3 to 15 GeV;
- Proton energy range: up to 250 GeV;
- Ion energy range: up to 100 GeV/u
- Electron beam current: 3 A nominal value, reduced at high energies;
- Proton beam current: 0.415 A nominal value, same as the RHIC operation current;
- Bunch repetition rate of colliding beams: 476 MHz;
- Electron polarization: >70%, with longitudinal polarization at collision points (IPs)
- Proton and helium-3 polarization: ~70%, with both longitudinal or transverse polarization at IPs

The PEP-II high energy ring, which is inherited from the PEP project, can support 18 GeV electrons [7]. If more PEP-II like arc cells are packed into the RHIC tunnel, the ring can accommodate an electron beam with energy up to ~30 GeV.

The SLAC linac has a total energy of 50 GeV. It is divided into three sections, with one section used as a driving linac for the LCLS X-FEL source; the second section is used for experimental research of plasma acceleration of charged particles. The third section is scheduled to be dismantled to make the space available for a new SRF linac for the LCLS-II project. This last section can accelerate electron to 15 GeV. Studies showed it can reach 30 GeV by installing twice many klystrons.

The nominal electron current for this ring-ring eRHIC is 3 A; however, it must be scaled down proportionally when beam energies are above 9 GeV if only the existing PEP-II magnets are used, in order to meet the SR power limit (10 kW/m) of the PEP-II vacuum chambers [7]. On the other hand, if more PEP-II like arc cells are used to fill the RHIC tunnel, the SR power is reduced due to a larger dipole bending radius, then a 3 A nominal current can be maintained up to 11.2 GeV electron beam energy.

The nominal current of the eRHIC proton beam is set to 0.415 A, which has already been achieved in RHIC operations. Due to the high bunch repetition rate (up to 476 MHz), the proton bunch charge is very small, i.e., 5.4×10^{9} protons per bunch, which is roughly 56 times smaller than that of the ERL-ring eRHIC design (3×10^{11} protons per bunch [3]).

Table 2 summarizes main parameters of *e-p* collisions for this alternate ring-ring eRHIC design at four representative points. The electron current and emittance are estimated for the case that the collider ring is filled with extra PEP-II type arc cells. The luminosities are above 10^{33} cm^{-2}s^{-1} per detector at all four design points, with a highest value at 2×10^{34} cm^{-2}s^{-1} at a medium CM energy (71 GeV). Figure 1 shows the luminosity curve for the *e-p* collisions. The luminosities of *e-A* collisions can be estimated similarly, and they reach a similar high level.

Table 2: Main Design Parameters of the New EIC design at Four Representative Design Points

CM energy	GeV	31.6 (low)		70.7 (medium)		100 (high)		122.5 (high)	
		p	*e*	*p*	*e*	*P*	*e*	*p*	*e*
Beam energy	GeV	50	5	250	5	250	10	250	15
Bunch repetition rate	MHz	476		476		476		476/3=158.7	
Particles per bunch	10^{10}	0.54	3.9	0.54	3.9	0.54	3.9	1.6	3.9
Beam current	A	0.415	3	0.415	3	0.415	3	0.415	1
Polarization	%	70	70	70	70	70	70	70	70
Bunch length, RMS	cm	2	1.2	1	1.2	1	1.2	2	1.2
Norm. emit., vert./horz.	µm	0.5	11.2	0.5	11.2	0.5	90	0.5	310
Horizontal & vertical β*	cm	2	16.5	2	3.3	2	1.5	3	1.35
Vert. beam-beam parameter		0.01	0.11	0.01	0.11	0.005	0.025	0.004	0.03
Laslett tune-shift		0.036	Small	0.003	Small	0.003	Small	0.004	Small
Hour-glass (HG) factor		0.88		0.92		0.85		0.74	
Luminosity/IP, w/HG, 10^{33}	cm^{-2}s^{-1}	3.8		19.8		13.0		6.0	

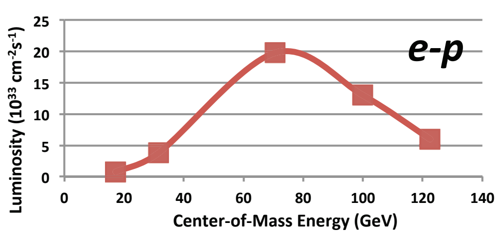

Figure 1: Luminosity of *e-p* collisions of the alternative ring-ring eRHIC design.

In the parameter table above, the luminosity reduction due to the hour glass effect is modest. An interaction region design supporting small β* and a full acceptance detector has been developed by the JLab MEIC team [5]. Because of the very small bunch charges, the proton beam space charge tune-shift is very small (less than 0.01) in the medium to high energy range. Even at 50 GeV, the proton beam space charge tune-shift can be kept modest low (0.036) after the bunch length is increased from 1 cm to 2 cm. At high electron energy (15 GeV), the electron current is reduced to 1 A. In this case, the luminosity is optimized by reducing the bunch repetition rate by a factor of 3 to boost the bunch charge.

It is clear that the design parameters in Table 2 are not fully optimized yet since the proton beam-beam parameters are far away from the commonly agreed limit (0.015 per IP). One possible optimization is reducing the bunch repetition rate by a factor of 3 or 4 (i.e., the third or fourth harmonic of 476 MHz). This could boost luminosities significantly, up to a factor of two. In addition, a reduced bunch repetition rate may also greatly ease the physics detector design.

ACCELERATOR R&D

Choosing a ring-ring design for eRHIC avoids several accelerator R&D challenges (as listed in the introduction section of this paper) associated with the present ERL-ring eRHIC design.

Due to a very small proton or ion bunch charge and modest emittances, the space charge effect is modest so space charge compensation [3] is not required. Similarly, the resistive wall effect is also much weaker than that of the present eRHIC design, there is likely no need to upgrade the RHIC vacuum chambers [3].

It is well understood that an efficient cooling mechanism must be a part of an EIC design for reaching its high luminosity goal. Since the proposed emittance (~0.5 mm mrad) of the colliding proton or ion beams is modest, the intra-beam scattering (IBS) time is not extremely short. As a consequence, conventional electron cooling with a multi-step cooling scheme [10, 11] is likely sufficient for delivering and preserving the designed beam emittances and for achieving high luminosities. This cooling scheme utilizes a DC electron cooler in the AGS for an initial cooling and a bunched beam cooler in the RHIC for final cooling and for suppressing the IBS induced emittance growth during collisions. The increased IBS time relaxes the current requirement in the bunched beam cooler to a few hundred mA, therefore, success of the required electron source R&D is likely. Strong beam cooling methods, such as coherent electron cooling [3] and bunched beam cooling driven by an ERL and a circulator ring [5], are currently under development at both BNL and JLab. These methods could further reduce the proton and ion beam emittances to reach even higher luminosities.

CONCLUSION

It seems that a ring-ring eRHIC can be constructed by reusing the decommissioned facilities (PEP-II and SLAC linac). The alternative eRHIC design holds the promise to deliver excellent performance and to require modest accelerator R&D.

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