ERL BASED ELECTRON-ION COLLIDER ERHIC *

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Abstract

In this paper we describe eRHIC design based on the RHIC hadron rings and 10-to20 GeV energy recovery electron linac. RHIC requires a very large tunability range for c.m. energies while maintaining very high luminosity up to 10^{34} cm^{-2} s^{-1} per nucleon. The designs of this future polarized electron-hadron collider, eRHIC, based on a high current super-conducting energy-recovery linac (ERL) with energy of electrons up to 20 GeV, have a number of specific requirements on the ERL optics.

Two of the most attractive features of this scheme are full spin transparency of the ERL at all operational energies and the capability to support up to four interaction points. We present two main layout of the eRHIC, the expected beam and luminosity parameter, and discuss the potential limitation of its performance.

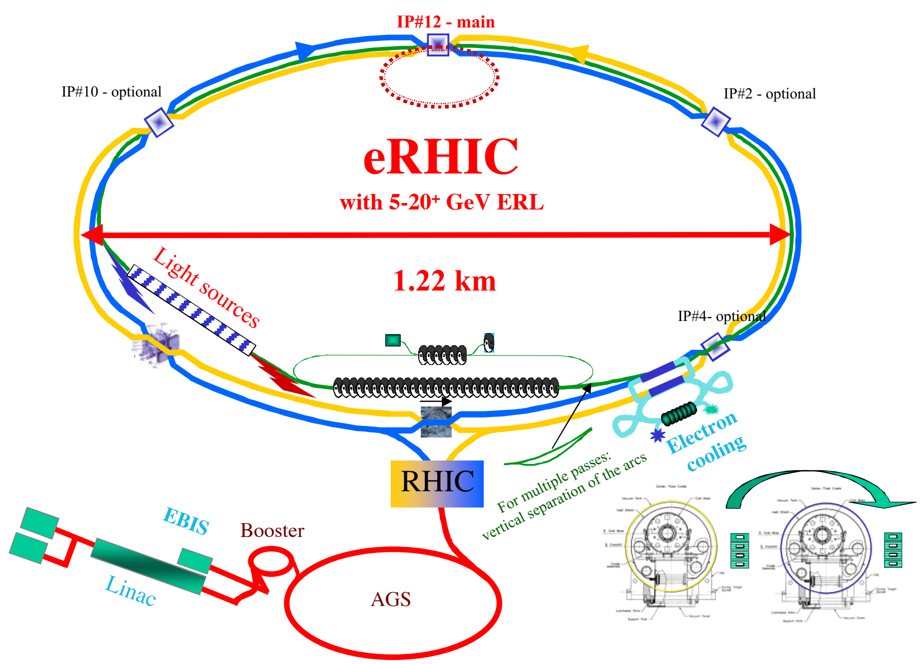

Fig.1. Main layout of ERL based eRHIC with up to four IPs and possible 5 GeV polarized positron storage ring. Polarized electrons are generated at a strained GaAs photocathode, accelerated in a multi-pass ERL, used in one –to-four collisions with the hadrons contra-rotating in the RHIC blue ring, decelerated and finally dumped.

INTRODUCTION

A Twenty-Year Outlook DoE document on "Facilities for the Future Science" [1] includes a new electron-hadron collider at BNL, based on the Relativistic Heavy Ion Collider (RHIC) and a new electron accelerator. The main goal of the eRHIC is to explore the physics at so-called "low-x", and the physics of color-glass condensate in electron-hadron collisions [2]. In response, the Collider-Accelerator Department at BNL in collaboration with Bates Laboratory at MIT issues the eRHIC ZDR (0th–order design report), which includes 76-page long a linac-ring eRHIC design based on 10-to-20 GeV ERL [3]. The design is based on CW linac with high current super-conducting RF (SRF) 5-cell cavities, which are under construction at BNL [4,5] and a polarized photo-injector using a dedicated 2 kW circularly polarized FEL [3]. The description of the eRHIC design based on electron storage ring can be found elsewhere [6].

Main parameters of the ERL based eRHIC are summarized in Table 1.

Table I. Parameters of ERL eRHIC

Ring circumference [m]	3834
Number of bunches	360
Beam rep-rate [MHz]	28.15
Beam energy [GeV]	26 - 250
Protons per bunch (max)	$2.0 \cdot 10^{11}$
Normalized 96% emittance [μm]	14.5
RMS Bunch length [m]	0.2
Beam energy [GeV/u]	50 - 100
Ions per bunch (max)	$2.0 \cdot 10^{9}$
Normalized 96% emittance [μm]	6
Electrons:	
Beam rep-rate [MHz]	28.15
Beam energy [GeV]	2 – 20
γ, Relativistic factor	$3.9\ 10^{3}$ - $3.9\ 10^{4}$
RMS normalized emittance [μm]	5- 50
Beam emittance @ 20 GeV [Å]	1.25-12.5
RMS Bunch length [psec]	30
Electrons per bunch	0.1 - $1.0 \cdot 10^{11}$
Charge per bunch [nC]	1.6 -16
Average e-beam current [A]	0.45

The list of the advantages provided by the ERL-based eRHIC compared with the ring-ring scenario [6] is rather long:

- usage of a fresh electron beam and absence of the memory in the e-beam practically waves the limitation on the tune shift in the IP and increase in the intensity of proton/ion beam;
- increase in luminosity by 2-to-10 fold;
- larger β* for e-beam and simplified IP geometry;
- smaller e-beam emittance;
- smaller angular divergence in IP;
- smaller aperture for e-beam;
- no-need for e-beam quads in the detector area;
- possibility to focus e-beam after separating it for protons/ions;
- simplified IP geometry;
- reduced number of coupled bunch instability modes;
- spin-transparency of the system at all energies;
- high (80%+) degree of e-beam polarization at all energies;
- absence of "prohibited" energies for the e-beam;
- no need of preserving beam qualities (polarization, emittance…) after the IP(s);
- simple geometry of the return pass;
- absence of spin-resonances;
- possible multiple Ips;
- usage of the linac (ERL) geometry;
- easy adjustment the e-beam rep-rate to the beam rep-rate in the RHIC which significantly depends on the ion energy (equivalent change in circumference is ~ 30m);
- easy future e-beam energy upgrades;
- possibility of using multiple energy collisions;
- possibility of γ-hadron collider with ERL-based Compton source of γ-rays.

LUMINOSITY

In the ERL-based eRHIC we pan to collide two round beams of equal size to maximize the luminosity. The main distinctive feature here is that the attainable luminosity is defined in practice by the energy and intensity of the proton or ion beam in RHIC:

$$L = f_c \cdot \xi_h \cdot \frac{\gamma_h}{\beta_h^*} \cdot \frac{Z \cdot N_h}{r_h} \qquad (1)$$

i.e., by the intensity N_h (number of hadrons per bunch), repetition rate f_c, the energy of the ion or proton beam, $\gamma_h = E_h / Mc^2$, its charge $q = Ze$, its classical radius $r_h = Z^2 e^2 / Mc^2$, and the allowable beam-beam tune shift ξ_h in the eRHIC IP(s). The linac-ring eRHIC's luminosity is independent of the electron beam's energy and linearly proportional to the energy of the proton or ion beam.

Table 1. Luminosities for e-p collisions for various energies in the ERL- based eRHIC: 360 bunches with $2 \cdot 10^{11}$ protons per bunch.

Luminosity in 10^{33} cm^{-2}sec^{-1}	*Protons 26 GeV*	*Protons 50 GeV*	*Protons 100 GeV*	Protons 250 GeV
Parallel mode with RHIC collider	0.285	0.548	1.097	2.74
Dedicated eRHIC mode	0.978	1.88	3.76	9.40

This means that that the same center of mass energy, (*given that there is no preferred energy ratio*), can be reached using higher energy protons (ions) and lower energy electrons; hence, the high luminosity in contrast with ring-ring scenario [6], where electron beam beam-beam tune shift limits the attainable luminosity. Details on the eRHIC IP design can be found in [7].

For the linac-ring collider, the beam-beam effect on the electron beam is better described not by a tune shift but by a disruption parameter, i.e. an additional betatron phase advance caused by the ion beam during the interaction. As seen in Fig.2 above, the electron beam can survive very violent collisions with hadrons. The real limitation of the ERL base eRHIC may be limited by kick instability of the proton beam [8,9]. The proton beams in RHIC are rather long (~ 1 nsec) and we plan to develop a transverse feed-back system to suppress the lowest modes of this instability.

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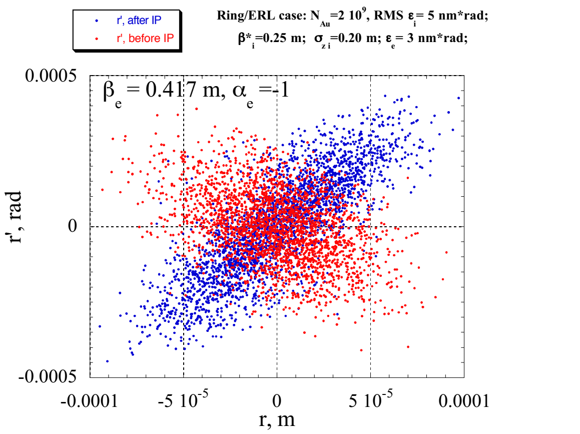

Fig. 2. Round 10 GeV electron beam from ERL with initial transverse RMS emittance of 3 nm rad passes through the IP with the disruption parameter 3.61 (tune shift ξ_{xe} = 0.6). The emittance growth is only 11%.

POLARISATION AND SPIN TRANSPERANCY

We plan to use GaAS photocathode driven by near-IR FEL for generation of longitudinally polarized beam with high degree (>80%) of polarization [10]. We illustrate the spin manipulation in ERL-based using second layout of eRHIC shown in Fig. 3.

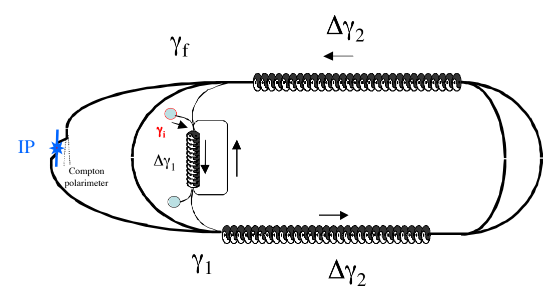

Fig. 3. A stand-alone 5-10 GeV ERL for eRHIC.

Electrons are generated in a photo-injector with longitudinal polarization exceeding 80% and the energy of $E_i = \gamma_i mc^2$. Helicity is controlled by the choice of the helicity of the photons, and can be switch from positive to negative. The electron beam is turned for the angle $\Delta\varphi_i = \pi/12$ and is injected into first stage of ERL. First stage of ERL has one linac. Electron beam passes twice through it gaining $\Delta E_1 = \Delta\gamma_1 mc^2$ at each pass and makes one 360° turns before reaching transfer energy $E_1 = \gamma_1 mc^2$ into second section of ERL. The e-beam makes $\Delta\varphi_t = \pi/2$ turn before reaching fist main acceleration section. Electron beam passes twice through each of the main accelerator sections $\Delta E_2 = \Delta\gamma_2 mc^2$ at each pass, and makes three180 turns before reaching final energy $E_f = \gamma_f mc^2$. The e-beam makes last $\Delta\varphi_t = \pi/2$ turn before reaching its goal in the IP. The spin rotation in ERL-based eRHIC is very simple – spin rotates for an angle of $\Delta\varphi_s = \Delta\varphi \cdot \gamma \cdot a$ around the vertical axis, where $\Delta\varphi$ is angle of rotation in a bend, γ is the relativistic factor and $a = g/2 - 1 = 1.1596521884 \cdot 10^{-3}$ is the anomalous magnetic moment of electron. Changing $\Delta\gamma_1$ and $\Delta\gamma_2$ (within few % range), while keeping final energy γ_f constant one can rotate spin at any desirable angle, i.e. achieve the full spin transparency at any energy.

CONCLUSIONS

The ERL based eRHIC promises to satisfy all requirements set by the nuclear physics and spin program at RHIC and, in addition, to open a number of new opportunities. It will exploit the developing technology of high current, high brightness electron beam to realize the full potential of the polarized electron-positron collider in Collider-Accelerator Department at BNL.

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