ERL Based Electron-Ion Collider eRHIC

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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-to-20 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 layouts 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 hardrons contra-rotating in the RHIC blue ring, decelerated and finally dumped.
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 layouts of the eRHIC, the expected beam and luminosity parameter, and discuss the potential limitation of its performance.

INTRODUCTION

Table I. Parameters of ERL eRHIC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring circumference [m]</td>
<td>3834</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>360</td>
</tr>
<tr>
<td>Beam energy [GeV]</td>
<td>26 - 250</td>
</tr>
<tr>
<td>Protons: number of bunches</td>
<td>360</td>
</tr>
<tr>
<td>Protons per bunch (max)</td>
<td>2.0 \times 10^{11}</td>
</tr>
<tr>
<td>Normalized 96% emittance [μm]</td>
<td>14.5</td>
</tr>
<tr>
<td>RMS Bunch length [m]</td>
<td>0.2</td>
</tr>
<tr>
<td>Gold ions: number of bunches</td>
<td>360</td>
</tr>
<tr>
<td>Beam energy [GeV/μA]</td>
<td>50 - 100</td>
</tr>
<tr>
<td>Ions per bunch (max)</td>
<td>2.0 \times 10^{9}</td>
</tr>
<tr>
<td>Normalized 96% emittance [μm]</td>
<td>6</td>
</tr>
<tr>
<td>Electrons: Beam rep-rate [MHz]</td>
<td>28.15</td>
</tr>
<tr>
<td>Beam energy [GeV]</td>
<td>2 - 20</td>
</tr>
<tr>
<td>RMS normalized emittance [μm]</td>
<td>5 - 50</td>
</tr>
<tr>
<td>Electrons per bunch [nC]</td>
<td>0.1 - 1.0 \times 10^{11}</td>
</tr>
<tr>
<td>Average e-beam current [A]</td>
<td>0.45</td>
</tr>
</tbody>
</table>

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 (O*-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].

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

LUMINOSITY

In the ERL-based eRHIC we 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:

\[ L = \frac{f_e \cdot \varepsilon_{em} \cdot \frac{\gamma_h \cdot Z \cdot N_h}{\beta_h^2 \cdot r_h}}{r_h} \]

i.e., by the intensity \( N_h \) (number of hadrons per bunch), repetition rate \( f_e \), the energy of the ion or proton beam, \( \gamma_h = \frac{E_h}{Mc^2} \), its charge \( q = Ze \), its classical radius \( r_h = \frac{Z^2 e^2}{Mc^2} \), and the allowable beam-beam tune shift \( \varepsilon_{em} \) 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. 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].

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

<table>
<thead>
<tr>
<th>Luminosity in ( 10^{33} ) cm(^{-2}) sec(^{-1} )</th>
<th>Protons 26 GeV</th>
<th>Protons 50 GeV</th>
<th>Protons 100 GeV</th>
<th>Protons 250 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel mode with RHIC collider</td>
<td>0.285</td>
<td>0.548</td>
<td>1.097</td>
<td>2.74</td>
</tr>
<tr>
<td>Dedicated eRHIC mode</td>
<td>0.978</td>
<td>1.88</td>
<td>3.76</td>
<td>9.40</td>
</tr>
</tbody>
</table>

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 \( \varepsilon_{em} = 0.6 \)). The emittance growth is only 11%.
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. additional betatron phase advance. As seen in Fig. 2 above, the electron beam can survive a very violent collisions with hadrons. The real limitation of the ERL base eRHIC may be limited by kick instability of the proton beam [9,10]. 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.

![Fig. 3. Projected luminosity (per nucleon) and the center-of-mass energy for ERL based eRHIC compared with other electron-hadron colliders and fixed target facilities.](image)

**CONCLUSIONS**

ERL based eRHIC will exploit the developing technology of high current, high brightness electron beam to realize the full potential of the polarized electron-positron collider in Cooler-Accelerator Department at BNL.

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