HIGH LUMINOSITY ELECTRON-HADRON COLLIDER ERHIC*

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Abstract

We present the design of a future high-energy high-luminosity electron-hadron collider at RHIC called eRHIC. We plan adding 20 (30) GeV energy recovery linacs to accelerate and to collide polarized and unpolarized electrons with hadrons in RHIC. The center-of-mass energy of eRHIC will range from 30 to 200 GeV. The luminosity exceeding 10^{34} cm^{-2}s^{-1} can be achieved in eRHIC using the low-beta interaction region which a 10 mrad crab crossing. A natural staging scenario of step-by-step increases of the electron beam energy by building-up of eRHIC's SRF linacs. We discuss the progress of eRHC R&D projects from the polarized electron source to the coherent electron cooling.

INTRODUCTION

The future plans of RHIC facility in Brookhaven National Laboratory consider adding the electron accelerator to provide the experiments with electron-proton and electron-ion collisions. The new collider, named eRHIC, will explore the internal structure of nucleons and nuclei. In order to study the content of nucleon spin the polarized electrons will collide with polarized proton (and ^{3}He) beams, taking advantage of existing capability of RHIC complex to accelerate the polarized proton beams to 250 GeV. The luminosity goal of eRHIC is 10^{33}-10^{34} cm^{2}s^{-1}, thus overcoming the luminosity of the previous electron-proton collider HERA by 2-3 orders of magnitude.

The linac-ring design was preferred over the ring-ring design option due to its potential reach to higher luminosities and higher electron energies. The linac-ring design also provides simpler treatment of the polarized electron beam, eliminating depolarizing problems from spin resonances. The design is based on one of the RHIC's hadron rings and a multi-pass energy-recovery linac (ERL) to accelerate electrons. During last two years we have developed the detailed design of ERL-based eRHIC with the electron accelerator placed completely in the RHIC tunnel. The main features of this design are described in this paper. The work is started on thorough evaluation and the optimization of the machine cost.

CONCEPT OVERVIEW

The layout of high luminosity ERL-based eRHIC is shown in Figure 1. Major layout features are:

- Injection complex, which includes the high-current polarized beam injector and 600 MeV pre-accelerator ERL, is located near IR2
- Acceleration of the electrons (up to 30 GeV max) is done by the energy recovery linacs (ERLs) placed in IR2 and IR10.
- The system of vertically arranged recirculation passes, based on compact magnets, runs around circumference of the RHIC tunnel.
- The collisions can be arranged in up to 3 interaction regions.

The current eRHIC design focuses on electron-hadron collisions. If justified by the physics goals, we would add a 30-GeV polarized positron ring with full energy-injection from eRHIC ERL. This addition to the eRHIC facility provide for positron-hadron collisions, but at a significantly lower luminosity than those attainable in the electron-hadron mode.

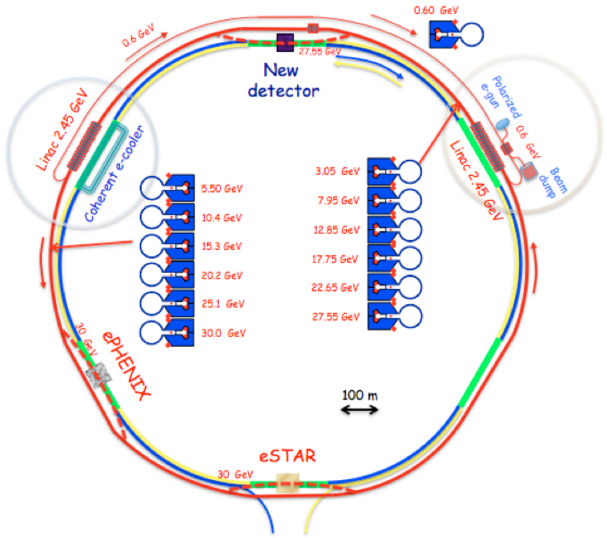

Figure 1: eRHIC layout. Blue and Yellow are existing RHIC hadron rings. Red curve presents vertically stacked electron beam lines.

As a novel high-luminosity EIC, eRHIC faces many technical challenges, such as generating 50 mA of polarized electron current. eRHIC also will employ coherent electron cooling (CeC) for the hadron beams.

One of the important advantages of the linac-ring design approach is a convenient staging scenario. The six-pass magnetic system with small-gap magnets will be installed already on the first stage. The main linacs on the first stage will be ~40 m long and will provide the

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electron acceleration on 6 accelerating passes at least to 5 GeV. On further stages the each linac length will be increased to 200 m to finally reach 30 GeV beam energy with ~20.4 MeV the energy gain per cavity. Pre-accelerator linac length will be also increased from 10 m on first stage to 60 m in full staged design.

We considered several IR designs for eRHIC. The latest one, with a 10 mrad crossing angle and β^*=5cm, employs a very special design of IR magnets [1].

The acceleration in the main linacs, as well as in the pre-accelerator ERL, will be done by using 5-cell 704 MHz SRF cavities, developed in BNL [2, 3]. The cavity has been designed for high current applications, with the attention to minimizing and damping of high-order modes. In order to achieve the required beam acceleration in ~200 m straight section of the RHIC tunnel the cavity cryo-module will be as compact as possible, with the average acceleration gradient reaching up to 12.3 MeV/m.

Several physics and practical considerations influenced our choice of beam parameters for eRHIC. Some of these limitations, such as the intensity of the hadron beam, the space charge and beam-beam tune shift limits for hadrons, come from experimental observations at RHIC or other hadron colliders. Some of them, for example $\beta^* = 5$ cm for hadrons, are at the limits of current accelerator technology, while others are derived either from practical- or cost-considerations.

For example, from considering the operational costs, we limit the electron beam's power loss to about 10 MW. Above 20 GeV, the electron beam's current will decrease in inverse proportion to the fourth power of energy, and will be restricted to about 12 mA at energy of 30 GeV.

Since the ERL provides fresh electron bunch at every collision, the electron beam can be can be heavily distorted during collision.

Assumed limits and parameters:

- Bunch-intensity limits:
  - For protons: $2\ 10^{11}$
  - For Au ions: $1.2\ 10^{9}$
- Electron-current limits:
  - Polarized current: 50 mA
- Minimum $\beta^* = 5$ cm for all species
- Space-charge tune shift for hadrons: ≤ 0.035
- Proton (ion) beam-beam parameter: ≤ 0.015
- Bunch length (with coherent electron-cooling):
  - Protons: 8.3 cm at energies below 250 GeV,
  - 4.9 cm at 325 GeV
  - Au ions: 8.3 cm in all energy ranges
- Collision rep-rate = 14.1 MHz.

The luminosity depends strongly ($\sim E_p^3$) on the proton energy because of the space charge limit [4]. The transverse and longitudinal cooling of the hadrons is required to reach shown luminosities. The luminosity decrease above 20 GeV electron energy is related with the beam power loss limit (< 10 MW). The luminosity for various operation modes of polarized electron-proton collisions is shown in the Table 1.

Table 1: Projected eRHIC luminosity (in $\mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$) for polarized electron-proton collisions.

Protons Electrons	100 GeV	130 GeV	250 GeV	325 GeV
5 GeV	$0.62 \cdot 10^{33}$	$1.4 \cdot 10^{33}$	$9.7 \cdot 10^{33}$	$15 \cdot 10^{33}$
10 GeV	$0.62 \cdot 10^{33}$	$1.4 \cdot 10^{33}$	$9.7 \cdot 10^{33}$	$15 \cdot 10^{33}$
20 GeV	$0.62 \cdot 10^{33}$	$1.4 \cdot 10^{33}$	$9.7 \cdot 10^{33}$	$15 \cdot 10^{33}$
30 GeV	$0.15 \cdot 10^{33}$	$0.35 \cdot 10^{33}$	$2.4 \cdot 10^{33}$	$3.8 \cdot 10^{33}$

MAJOR R&D ITEMS

The list of major eRHIC R&D items includes:

- High average polarized current source
- Efficient high energy cooling of hadron beams
- High power energy recovery linacs
- Beam-beam effects for linac-ring collision scheme
- Compact magnets of electron recirculation passes
- Polarized ^{3}He production and acceleration
- Crab crossing and crab-cavities
- The design of high gradient interaction region magnets

The polarized electron source capable of producing 50 mA average current is needed for achieving the high design luminosity in eRHIC. A "Gatling gun" design of the polarized source is under development in BNL where the electron currents extracted from many small size cathodes are merged in a special RF field combiner [5,6]. After developing the engineering design of the "Gatling gun" the gun prototype will be constructed.

An efficient high-energy hadron cooling, in both transverse and longitudinal dimensions, should maximize the luminosity by shrinking the hadron beam down to the space charge and beam-beam parameter limits. The novel technique of coherent electron cooling (CeC) has been pursued [7]. According to analytical calculations the CeC should be able to cool the beam on the scale of tens of minutes. To confirm the analytical predictions the proof-of-principle experiment for the CeC method is under preparation at RHIC [8].

With the ERL test facility built in BNL we plan to explore effects associated with the energy recovery of high average current electron beam (the current up to 0.5 A) [9]. The ERL facility will also verify the operation of 704 MHz SRF cavity, which is the basic component of the eRHIC energy recovery linacs. The initial tests on the ERL facility are scheduled at the end of this year.

The beam-beam interactions have been the subject of thorough studies. All diverse features of the beam-beam effects were explored: electron beam disruption, proton kink instability, and electron beam parameter fluctuations. [10, 11] The dedicated feedback scheme against kink instability is under development, using the control of the electron beam position at the collision point [12].

In order to minimize the machine cost the magnets of recirculation passes with the magnet gap as small as 8mm are considered. The R&D program to design and build the prototypes of the small-gap magnets and the corresponding vacuum chamber has been carried out at BNL [13]. The field of the dipole magnet prototypes close to satisfying eRHIC tolerances has been achieved.

While RHIC produces highest energy polarized protons, eRHIC would also need polarized ^{3}He beams. The issues related with the production, the acceleration and the polarization measurement of the polarized ^{3}He ions are being considered. The depolarizing resonances are about twice stronger for ^{3}He than for the protons, presenting a challenge for the polarization preservation during the acceleration through the injector chain as well as in RHIC itself.

eRHIC interaction region design employs the 10 mrad crossing angle and the crab-crossing scheme [1]. The design of 180 MHz crab-cavity based on the quarter wave resonator has been developed [14]. The main advantages of such crab-cavity design are its compactness and large separation of the fundamental mode from unwanted HOM modes. The present crab-crossing system for hadrons includes also higher harmonic cavities, which compensate for longitudinal nonlinearities induced by the main crab-cavities. The comprehensive study of the beam dynamics with the crab-crossing is underway.

Another important R&D item is the design of large aperture superconducting magnets of the eRHIC interaction region. The magnets not only should produce the adequate focusing of the hadron beam for $\beta^*= 5$ cm optics, but also have to provide a good experimental acceptance and separate neutrons and off-momentum charged particles from the outgoing hadron beam. The initial design of the IR quadrupoles, with the electron beam going through the low field area has been evaluated. The implementation of Nb_3Sn conductor technology has been considered for IR magnets, following successful commissioning of Nb_3Sn quadrupoles [15].

DESIGN HIGHLIGHTS

The lattice of eRHIC includes many components: recirculation passes, splitters/mergers, detector by-pass lines, the interaction regions and the path lengthening insertion. The lattice of recirculation passes is based on an isochronous cell, with minimized synchrotron radiation and the possibility of flexible tuning of R_{56} parameter [16]. One of design challenges originates in the wide energy range of hadron beam in eRHIC. Since the electron and hadron bunch frequencies have to be matched, the path lengthening insertion is required to vary the length of the electron recirculation passes at different hadron energies. The present path lengthening insertion design allows the variation of the path length up to 15 cm.

The major beam dynamics effects have been evaluated. The beam break-up simulations confirmed the ability of eRHIC to operate with the 600 mA average electron current passing through the main linacs [17].

The considerable energy losses are incurred by the electron beam not only because of the synchrotron radiation but also due to the interaction of short electron bunches with the surrounding impedances (resistive wall, cavity wake, …). The Figure 2 demonstrates the corresponding beam power loss pattern. To compensate for these energy losses the insertion of 2nd harmonic (1.4 GHz) cavities is implemented in the IR12 straight section. The compensation scheme for the energy spread, induced by the same interactions, has been considered. The compensation involves the special optics of 600 MeV energy line to realize a proper longitudinal transformation before the deceleration to 10 MeV, the energy of the beam dump line [18].

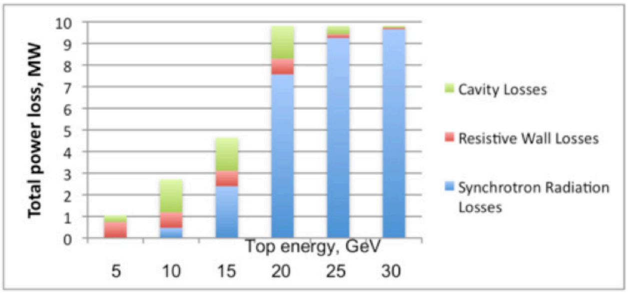

Figure 2: Beam power loss pattern at different electron beam energies. 5 GeV energy pattern is shown for the first stage of eRHIC.

CONCLUSIONS

We have developed a well advanced design of the future electron-ion collider eRHIC. The conceptual tests for important R&S items: coherent electron cooling and the high current energy recovery, are in preparation. The work has started on the detailed estimate of the machine cost.

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