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High luminosity electron-hadron collider eRHIC

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DISCLAIMER

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 on adding 20 (potentially 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 with a 10 mrad crab crossing. We report on the progress of important eRHIC R&D such as the high-current polarized electron source, the coherent electron cooling, ERL test facility and the compact magnets for recirculation passes. A natural staging scenario of step-by-step increases of the electron beam energy by building-up of eRHIC's SRF linacs is presented.

INTRODUCTION

The Relativistic Heavy Ion Collider, RHIC, has been operating for more than a decade, providing heavy ion as well as polarized proton collisions for several experiments. The impressive scientific results produced by RHIC range from the discovery and detailed exploration of the superfuild primordial substance, called quark-gluon plasma, to uncovering the gluon contribution to the proton spin. The future plans of RHIC facility consider adding the electron accelerator to provide the experiments with electron-proton and electron-ion collisions. The new collider, named eRHIC, will present a high-resolution microscope for exploration of the internal structure of nucleons and nuclei, including the nucleon spin content. Compared with the only other existing electron-hadron collider, HERA, eRHIC will use polarized proton (and ^{3}He) beams for collision with the polarized electrons, and will provide considerably higher luminosity (10^{33}-10^{34} cm^2s^{-1} versus $5 \cdot 10^{31}$ cm^2s^{-1} at HERA). The experiments using the polarized beams intend to resolve the nucleon spin puzzle by studying the contributions from the different partons to the spin of the nucleon, as well as from the gluon and quark orbital momenta. The experiments with electron-heavy ion collisions will explore the states of high gluon densities inside nucleons, including the gluon saturation regime. The high luminosity of eRHIC will for the first time allow experimentalists to take 3-D tomographic images of the nucleon in impact and transverse momentum space., Such a diverse physics program warrants the interest of the physics community to this collider. However, the cost factor for such a machine is very important. eRHIC will take advantage of the existing RHIC ion complex and will keep its modification to minimum.

The design choice for the electron accelerator presented an interesting dilemma between storage ring and linear accelerator options. Initially, the main eRHIC option (the so-called ring-ring, RR, design) was based on an electron ring, with the linac-ring (LR) option as a backup. In 2004, the “eRHIC 0th-Order Design Report” [1] was published describing the RR design (for a 10 GeV electron ring). However, the luminosity of that design was moderate (few units of 10^{32} cm^2s^{-1}) and had been fundamentally limited by the beam-beam effects and synchrotron radiation power losses.

The LR design has a potential to reach the luminosity 10-100 times higher than in the RR. Also, the LR design can extend the reach of electron energies beyond 10 GeV, which is essential for the electron- heavy ion physics program. With the LR option there is a simple way of staging the electron energy by increasing the linac length. Last, but not least, the LR design provides simpler treatment of the polarized electron beam, eliminating problems related with the spin resonances and simplifying the spin orientation control in the experimental locations. An initial cost estimate showed that the design cost of both LR and RR options was comparable. Thus the LR design was selected as the primary choice and has been developed in recent years. Further in this paper we briefly describe the present status of the LR eRHIC design.

GENERAL LAYOUT

The layout of high luminosity LR eRHIC is shown in Figure 1. The cost-effective design contains most of the electron accelerator components inside the existing RHIC tunnel. In order to achieve high average electron beam current (50 mA) the energy recovery linacs (ERLs) are used for electron acceleration. Two ERLs (200m long and 2.45 GeV energy gain each) are placed in two straight sections in the RHIC tunnel. The electrons from the polarized source injector are accelerated to the top energy,

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first, by a 600 MeV pre-accelerator ERL, and then by passing six times through the main ERLs. After colliding with the hadron beam in up to three experimental detectors, the e-beam will be decelerated in the same linacs and dumped. The system of vertically arranged recirculation passes, based on compact magnets, runs around circumference of the RHIC tunnel.

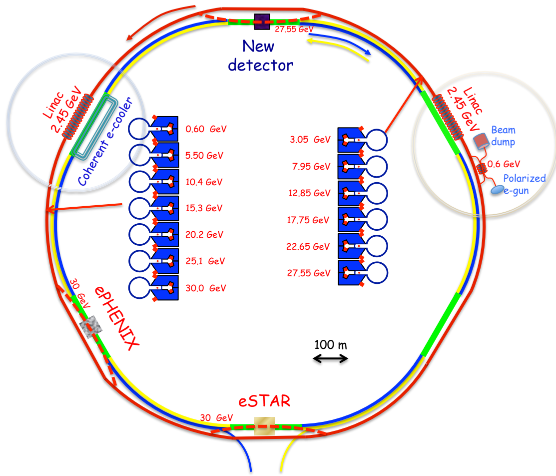

Figure 1: eRHIC layout. Blue and Yellow are existing RHIC rings. Red curve presents vertically stacked electron beam lines.

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 cryomodule will be as compact as possible, with the average acceleration gradient reaching up to 12.3 MeV/m. Figure 2 shows the transverse cross section of the RHIC tunnel with the main ERL and RHIC magnets.

In the cost optimized staging approach, the electron energy of eRHIC will come up from 5 GeV to 30 GeV in several stages. This energy increase will be done in steps by increasing the lengths of the ERLs, while all recirculation passes will be put in the tunnel already during the first stage. In the full staged design the collider will be able to do experiments in a wide range of center mass energies: from 30 to 200 GeV.

With the bunch repetition rate defined by the present RHIC hadron beam the electron beam has relatively low bunch frequency (14 MHz) and high charge per bunch (3.5 nC). The main luminosity limiting factors are the hadron space charge tune shift (<0.035), hadron beam-beam parameter (<0.015), the achievable value of the polarized electron current (50 mA) and synchrotron radiation power losses. The resulting luminosity for polarized electron-proton collisions, as function of the beam energies is shown in Table 1. Further information on the beam parameters and the luminosities can be found on the eRHIC accelerator webpage [4].

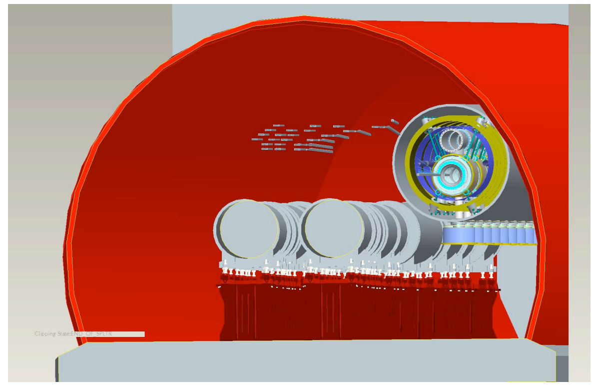

Figure 2: The main ERL cryostat and the RHIC superconducting magnets in the RHIC tunnel. Small magnets above the RHIC magnet cryostats are the magnets for the electron beam lines (the beam splitter).

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

Protons / Electrons	100 GeV	130 GeV	250 GeV	325 GeV
5 GeV	$0.62\cdot10^{33}$	$1.4\cdot10^{33}$	$9.7\cdot10^{33}$	$15\cdot10^{33}$
10 GeV	$0.62\cdot10^{33}$	$1.4\cdot10^{33}$	$9.7\cdot10^{33}$	$15\cdot10^{33}$
20 GeV	$0.62\cdot10^{33}$	$1.4\cdot10^{33}$	$9.7\cdot10^{33}$	$15\cdot10^{33}$
30 GeV	$0.12\cdot10^{33}$	$0.3\cdot10^{33}$	$1.9\cdot10^{33}$	$3\cdot10^{33}$

The luminosity depends strongly ($\sim E_p^3$) on the proton energy because of the space charge limit [20]. The transverse and longitudinal cooling of the hadrons is required to reach shown luminosities. The coherent electron cooling method is presently considered as a very promising technique to realize the high energy cooling. The luminosity decrease above 20 GeV electron energy is related with the synchrotron radiation power limit (~7 MW at 20 GeV).

DESIGN DEVELOPMENTS

All lattice components of the electron accelerator have been created. The lattice of recirculation passes is based on a low-emittance near-isochronous cell, which allows a flexible tuning R_{56} parameter and has a large dipole filling factor to minimize synchrotron radiation. The four splitters/mergers provide the transition between the beam line in the linacs and six vertically arranged recirculation passes in the arcs. The by-pass lines around the experimental detectors are provided for all recirculation passes except the top energy pass. The variants of by-pass lines with 3 to 5 m transverse excursion have been developed. In order to match the electron and proton bunch frequencies at different proton energies we plan to use both the path length variation of the electron recirculation passes and the electron beam RF harmonic changes. The present solution for the electron optics in the ERLs does not include any quadrupole magnets, still providing reasonably low beta-functions. More details on the electron optics can be found in [5].

The interaction region design went through several iterations before converging to a solution suitable both for the experiments and the accelerator. The design uses 10 mrad crossing angle, with the electrons going along the axis of the experimental solenoid, and a β*=5cm (for both electrons and protons). The large aperture high gradient (up to 200 T/m) quadrupoles in the proton triplet take advantage of recently commissioned Nb_3Sn quadrupoles [6]. The initial design of these quadrupoles, with electron beam going through the arranged field-free passage in those magnets, has been evaluated [7]. Crab cavities will be used to create crab-crossing and maximize the luminosity.

The main beam dynamics effects, which may limit the achievable beam parameters and luminosities, have been evaluated. Since there has been no collider operating with a linac-ring collision scheme the beam-beam effects have to be thoroughly explored. The simulations using the EPIC code [8, 9] studied the diverse issues of the beam-beam interactions: electron beam disruption, proton kink instability, and electron beam parameter fluctuations. To contain the kink instability the feedback scheme has been considered [10].

Simulations of beam break-up instability with the 600 mA average electron current in the main linacs established the tolerances on HMO mode values [19]. As the electron bunch peak current exceeds 100 A, various effects, leading to the energy loss and producing the energy spread, have been looked into. The experiment in the ATF electron facility in BNL provided valuable insights on the effect of coherent synchrotron radiation on the energy loss and spread in the presence of shielding [11]. Another experiment is planned to explore the effect of surface roughness of a small size extruded Al vacuum pipe on the electron beam. The results of ion trapping studies can be found in [12].

MAJOR R&D

High average polarized current (50 mA) and the longitudinal and transverse cooling of high energy protons and ions are needed to achieve the high design luminosity in eRHIC. Two variants of a high current polarized source have been under development. Both plan to achieve high current by effectively increasing the cathode area, using standard cathode materials (strained GaAs or superlattice). The polarized gun, being developed by MIT group, extracts high current from one large size cathode [13]. The BNL group is developing a “Gatling gun” design where the high current is produced by merging the electron currents extracted from several small size cathodes [14, 15]. The engineering designs of both guns have been completed and both groups are ready to build the gun prototypes.

To efficiently cool the transverse and longitudinal emittances of high-energy proton and ion beams by an order of magnitude, the novel technique of coherent electron cooling (CeC) has been considered [16]. The calculation shows the cooling rates on the scale of tens of minutes can be achieved for the high-energy proton beam, which can not be done with traditional stochastic- or electron- cooling techniques. The proof-of-principle experiment at RHIC for the CeC technique is under preparation [21]. The experiment will be done in the collaboration between scientists from BNL, Jefferson Laboratory, and Tech-X.

With the large number of electron recirculation passes more than 14000 magnets are needed to guide and focus electron beam. Making the magnets as compact as possible is a major cost saving issue for eRHIC. The R&D effort of designing and prototyping efficient and inexpensive small-gap magnets and the corresponding vacuum chamber has been underway at BNL for the last two years [17]. The magnetic measurements done with the dipole magnet prototypes (with the gap as small as 5mm) showed a field close to satisfying eRHIC requirements.

The ERL test facility has been built in BNL in order to test the key components of SRF technology (with 704 MHz BNL cavity) and energy recovery with high beam average current (up to 0.5 A) [18]. The facility plans to start first tests with the beam later this year.

The list of other important R&D items includes studies of crab-crossing and the design of crab-cavities; polarized ^3He acceleration, and the design of high gradient interaction region magnets.

SUMMARY

The design of the future electron-ion collider eRHIC has been well advanced. The electron lattice and interaction region design have been developed, and all critical beam dynamics issues have been evaluated. Considerable progress on crucial R&D items has been achieved and important conceptual tests (CeC and ERL facility) are in preparation. It is planned to complete the detailed cost estimate of all eRHIC stages by the end of this year.

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