ERHIC CONCEPTUAL DESIGN*

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Abstract

The conceptual design of the high luminosity electron-ion collider, eRHIC, is presented. The goal of eRHIC is to provide collisions of electrons (and possibly positrons) with ions and protons at the center-of-mass energy range from 25 to 140 GeV, and with luminosities exceeding 10^{33} cm^{-2} s^{-1}. A considerable part of the physics program is based on polarized electrons, protons and He^3 ions with high degree of polarization. In eRHIC electron beam will be accelerated in an energy recovery linac. Major R&D items for eRHIC include the development of a high intensity polarized electron source, studies of various aspects of energy recovery technology for high power beams and the development of compact magnets for recirculating passes. In eRHIC scheme the beam-beam interaction has several specific features, which have to be thoroughly studied. In order to maximize the collider luminosity, several upgrades of the existing RHIC accelerator are required. Those upgrades may include the increase of intensity as well as transverse and longitudinal cooling of ion and proton beams.

ERHIC GENERAL LAYOUT

Brookhaven National Laboratory plans to build eRHIC to study intricate details of nuclear matter in collisions of electrons with protons and ions. The eRHIC design takes advantage of the existing RHIC complex, which presently operates with light and heavy ions (D, Au) and polarized proton. The range of species provided by RHIC for eRHIC will include polarized protons (up to 250 GeV), polarized He^3 ions (up to 167 GeV/nucleon) and gold ions (up to 100 GeV/nucleon). RHIC is the only machine in the world accelerating polarized protons to energies above 25 GeV without significant polarization loss [1].

The electron accelerator is designed to provide high energy electron beam for collisions with protons or ions. The eRHIC electron accelerator is a multi-pass superconducting energy recovery linac (ERL). The collision energy of electrons will be in 3-20 GeV range. The ERL design allows luminosities above 10^{33} $cm^{-2}s^{-1}$ in multiple interaction points and provides high polarization and great configuration flexibility. A layout of the 10 GeV option of ERL-based eRHIC is shown in Figure 1. The ion or proton beam circulates in one of the existing RHIC rings. The electron beam produced by a polarized electron gun, is first accelerated in a 500 MeV pre-accelerator linac, also designed to be the energy recovery linac. After that the beam is transported to the main ERL, where it is accelerated at the rate of 1.9 GeV per pass. Five passes are designed to accelerate the electron beam up to 10 GeV. One low-energy recirculation pass can be positioned locally near the main ERL location, while the remaining recirculation passes are located inside the present RHIC tunnel. The highest energy electron beam pass will intersect the ion ring in the locations of existing interaction regions. Up to four e-ions interaction points can be accommodated in this design, if the existing RHIC experiments, PHENIX and STAR, are preserved.

The principle of the energy recovery [2] allows achieving high average electron beam current in eRHIC at a reasonable power consumption. In this scheme, following the collisions, the electron bunch is decelerated passing again the main linac five times and once the pre-accelerator linac. While decelerating, the bunch returns the energy into the RF cavities, and this energy can be reused in the acceleration of other bunches.

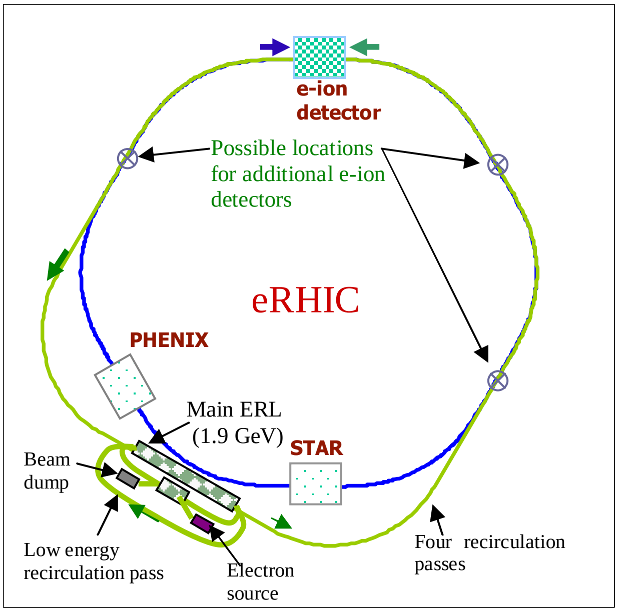

Figure 1. Layout of ERL-based design of eRHIC.

As can be seen in Figure 1, space is available for an upgrade of the main linac to higher energy to achieve a 20 GeV electron beam energy .

The ERL-based design provides a number of advantages. Since the allowed beam-beam force acting on the electron beam can be considerably larger in an ERL as compared to an electron beam circulating in a storage

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ring, higher ion beam intensity and/or smaller beam emittances can be used. This opens the way to a higher luminosity. The Table 1 shows the main beam parameters for the case of electron-proton collisions. It is assumed that the maximum achievable beam-beam parameter for the proton beam is 0.015, which is based on the experience at RHIC with proton-proton collisions. Based on the experience of HERA [3], the precise matching of the colliding beam sizes is important to minimize the strength of the beam-beam interactions. The luminosity of electron-ion collisions is about the same as for the e-p collisions, if one considers it as the electron-nucleon luminosity.

For a polarized electron beam the longitudinal polarization at the collision point can be achieved by a slight readjustment of the energy gains in the pre-accelerator and main ERL linacs.

Table 1: Beam parameters for two modes of the electron-proton operation

	p	e	p	e
Energy, GeV	50	3	250	10
Bunch frequency, MHz	14.1		14.1	
Bunch intensity, 10^{11}	2	1.2	2	1.2
Beam current, A	0.42	0.26	0.42	0.26
rms emittance, nm	18.8	13.2	3.8	3.9
β^*, cm	26	37	26	25
Beam size at IP, x/y, μm	70/70		31/31	
Beam-beam parameter	0.015	0.58	0.015	0.59
Rms bunch length, cm	20	1	20	1
Polarization, %	70	80	70	80
Peak Luminosity, 10^{33} cm^{-2}s^{-1}	0.53		2.6	
Average Luminosity, 10^{33} cm^{-2}s^{-1}	0.18		0.87	
Luminosity integral /week, pb^{-1}	105		530	

MAIN R&D ITEMS

Most important R&D items are related to the electron beam. One of the key items is the development of the ERL technology for high power beams. Development of the state-of-art design for main element of the ERL, a superconducting 703.75 MHz 5-cell SRF linac, is pursued at C-AD, BNL [4]. The cavity design has efficient damping of the HOM to operate with higher beam currents. A test energy recovery linac, which is under construction at BNL, will verify various aspects of the ERL technology at high beam currents [5].

A very high intensity polarized electron source needs to be developed to produce continuous polarized electron beam for eRHIC. An R&D program has been started to design a large cathode gun. It will operate with existing current densities (50 mA/cm^2) and use large cathode area to reach the required high current [6].

The design of multiple recirculating passes in 3.8 km-long RHIC tunnel is a crucial factor for the minimization of the project cost. The development of compact magnets for the recirculation passes is under way. The small transverse sizes of electron beam allows for the use of a compact magnet with 5-10 mm aperture [7]. The design, prototyping and test of prototypes of the small aperture magnets are planned to be completed in 2009. Recirculation pass design based on FFAG principle has also been studied [8].

For the proton beam, important R&D takes place in the area of transverse and longitudinal cooling. Beam parameters shown in the Table 1 assume pre-cooling at the injection energy (22 GeV) with subsequent acceleration to the top energy. However, the transverse cooling at the top energy would be also very beneficial. If one could maintain the transverse emittance of the protons at the store at lower values than shown in the Table 1, then the required intensity of the electron beam current can be correspondingly reduced. Many aspects of the electron accelerator design would benefit from lower electron beam intensity, including the polarized source development, harmful effects of beam interaction with surroundings, beam loss tolerances, to mention a few. In addition, an effective longitudinal cooling of high energy protons would allow us to reduce the design β^* values with corresponding gain in the luminosity.

The scheme of FEL-based coherent electron cooling may open a way to cool high energy protons efficiently [9]. Active studies of this scheme are underway. Possible proof-of-principle test of the concept at RHIC is under consideration.

The acceleration of polarized He^3 ions presents another R&D item. Large value of the anomalous magnetic moment of He^3 ions leads to an about 56% higher spin precession rate than that for the protons. The positive side of this effect is that the Siberian Snakes and spin rotators used at RHIC for the control of the proton polarization will work well for He^3 too. On the other hand, the sensitivity to the spin resonances is also increased as well as the number of the resonances. Detailed studies are needed to explore the polarization preservation of polarized He^3 ion through the whole injector chain and during the acceleration at RHIC.

The bunch frequency listed at the Table 1 is 50% higher than presently used in RHIC operation. For eRHIC the number of bunches in RHIC will be increased to 166 (111 bunches are used at present). The increase will need modification of the injection kicker system to provide faster kicker rise time. The beam dynamics issues of the higher intensity beam also need development, especially problems caused by the electron cloud. For instance, the achievable ion beam intensity in RHIC is presently limited by the transverse instability happening at the transition where electron clouds lower the instability threshold [10].

An important R&D item, concerning both electron and proton beams, is the exploration of the beam-beam interactions and their impact on the accelerator design and beam parameters. The beam-beam effects for a beam circulating in a ring and colliding with another beam from a linac have specific features, which are quite different from a ring-ring collision. Furthermore, there has been no practical experience with linac-ring colliders. Thus, the beam-beam effects in eRHIC must be thoroughly studied. We studied the electron beam disruption by the collisions, which should be minimized in order to simplify consecutive electron beam transfer and deceleration [11,12]. For the protons (and ions) the kink instability has been also thoroughly studied [11,12]. The instability is driven by the head-tail effect in the proton beam caused by the interactions with electrons. The beam-beam simulations were done including the effects of synchrotron oscillations, nonlinear beam-beam force, hourglass effect and machine chromaticity. Figure 2, summarizing the results, shows proton beam emittance growth rate due to the kink instability. It was shown that sufficiently large chromaticity suppresses the instability. The tune spread caused by the nonlinear beam-beam force also plays a role in the suppression. On the basis of studies of electron beam disruption and the proton beam incoherent emittance growth enhancement by the electron pinch effect the interaction region, we optimized the lattice and modified the IR design.

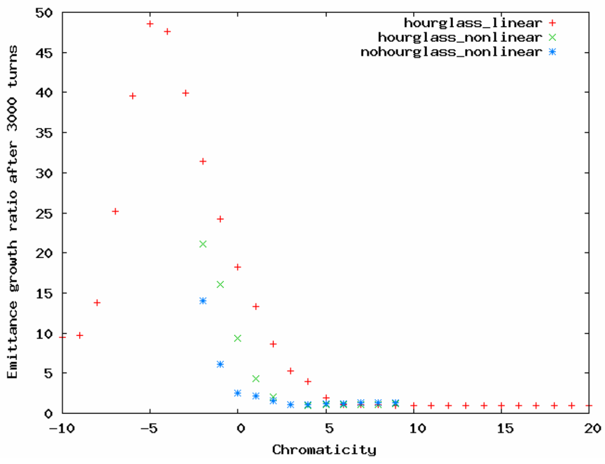

Figure 2: Transverse emittance growth, caused by the kink instability, versus the chromaticity. Shown cases include linear and nonlinear beam-beam force, with and without hourglass effect.

IR DESIGN

Figure 3 shows layout and lattice of eRHIC IR. Figure 4 shows a 3-D view of the IR in the vicinity of a collision point. The small emittance of the electron beam produced by the linac simplifies the IR design. The round beam collisions geometry also benefits the luminosity. One of main goals for the IR design is to avoid the parasitic collisions, which may happen away from the design collision points. No crossing angle is used in the current design. Fast beam separation is done with the help of the dipole field superimposed with the detector solenoidal field [13].

All magnets involved in the final focusing of both ion and electron beams are warm magnets. The closest quadrupole to the collision point is placed at 3m from the collision point, providing sufficient space for the detector. Hadron beam passes through the final focusing electron triplet. Septum quadrupoles, similar to the HERA design of a half-quadrupole, are used for the hadron beam focusing where the electron and ion beam trajectories are close to each other.

Careful studies of the IR region geometry, the magnet arrangement and their strength have been done to eliminate the possibility of synchrotron radiation hitting surfaces at the detector area. Simulations also explored possible background effects originating from the backscattering of synchrotron radiation photons from the absorber at the septum quadrupole [14].

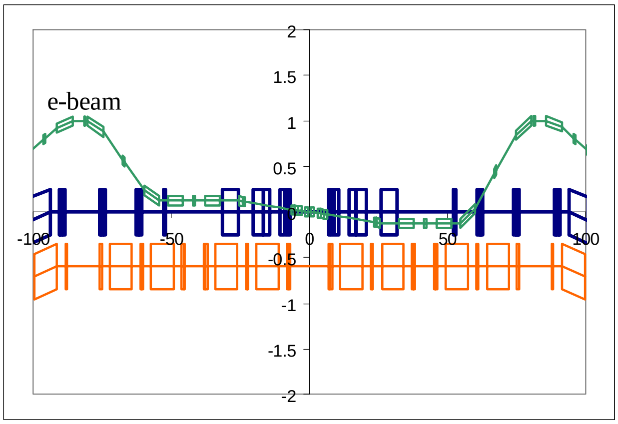

Figure 3: The layout of the interaction region section. The both horizontal and vertical axis shows the distance in meters.

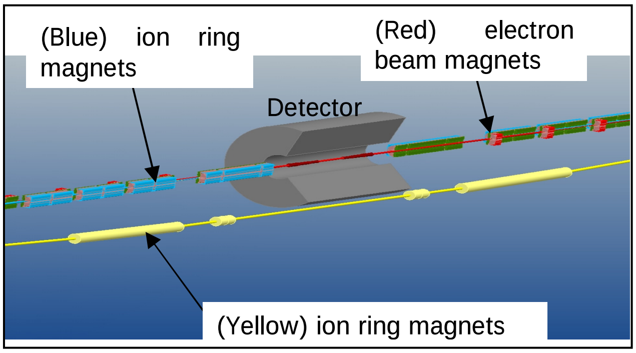

Figure 4: Details of the interaction region straight in the vicinity of the detector.

OTHER DESIGN OPTIONS

While the eRHIC scheme shown in the Figure 1 is considered as the base design, there are other design options under development. One of the eRHIC design options places the electron accelerating linacs inside the RHIC tunnel [15]. This scheme promises a considerable cost saving. The ERL design with sufficiently higher average acceleration rate (8-10 MeV/m) is also under consideration [16]. It makes the option with the ERLs inside the RHIC tunnel more feasible. Using the RHIC tunnel for the ERL makes the electron acceleration up to 30 GeV energy and the extension of the center-of-mass energy region to 170 GeV possible.

The option of an electron-ion collider at RHIC operating with medium energy electron beam (up to 3 GeV) is under consideration. All components of the electron accelerator for such a collider can be placed locally inside the RHIC tunnel within one or two RHIC sextants. Since the main components of the electron accelerator will be essentially identical to that of the high energy eRHIC, the medium energy machine elements can be reused in the high energy eRHIC.

The ring-ring design of eRHIC with 10 GeV electron storage ring was considered in details few years ago [17]. The average luminosities of such a ring-ring scheme are limited to 10^{32} $cm^{-2}s^{-1}$ level by the beam-beam effects. Presently the ring-ring design is considered as a backup option.

CONCLUSIONS

Development of various aspects of the ERL-based design of eRHIC is continuing at BNL. eRHIC aims to provide average luminosity at or above 10^{33} $cm^{-2}s^{-1}$ level for e-p collisions. Major R&D projects, such as the polarized source development, ERL test facility and compact magnet design, are in progress and have financial support.

Modifications of the existing RHIC for eRHIC will include new interaction region(s) and increase in the number of the hadron bunches.

We are considering the possibility of an effective cooling of hadrons at the collision energy to increase luminosity. reduce the requirements on the electron beam intensity and simplify the design of the electron accelerator.

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