Accelerator Design of High Luminosity Electron-Hadron Collider eRHIC

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Abstract. The design of future high-energy high-luminosity electron-hadron collider at RHIC called eRHIC is presented. We plan adding energy recovery linacs to accelerate the electron beam to 20 (potentially 30) GeV and to collide the 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} sec^{-1} can be achieved in eRHIC using the low- beta interaction region with a 10 mrad crab crossing. The important eRHIC R&D items include the high- current polarized electron source, the coherent electron cooling and the compact magnets for recirculating passes. A natural staging scenario is based on step-by-step increases of the electron beam energy by building-up of eRHIC's SRF linacs.

Keywords: energy recovery, recirculation, SRF, polarized beams
PACS: 29.20.-c

ERHIC CONCEPT AND LAYOUT

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} sec^{-1} thus overcoming the luminosity of the previous electron-proton collider HERA by 2-3 orders of magnitude.

The layout of high luminosity collider 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, 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.

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 [1]. 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. 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 [2].

The luminosity depends strongly ($\sim E_p^3$) on the proton energy because of the space charge limit. The transverse and longitudinal cooling of the hadrons is required to reach shown luminosities. The coherent electron cooling method is

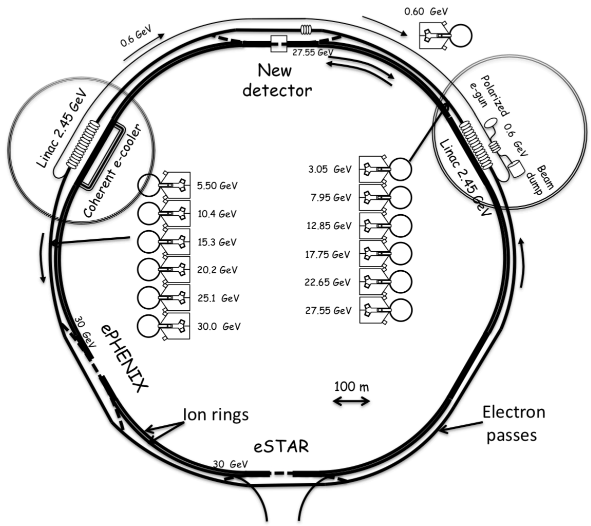

FIGURE 1. eRHIC layout. Vertically stacked electron passes will be put on in the RHIC tunnel on the outside of the existing two ion rings.

TABLE 1. Projected eRHIC luminosity (in 10^{33} cm^{-2} sec^{-1}) for polarized electron-proton collisions.

Electrons \ Protons	100 GeV	130 GeV	250 GeV	325 GeV
5 GeV	0.62	1.4	9.7	15
10 GeV	0.62	1.4	9.7	15
20 GeV	0.62	1.4	9.7	1.5
30 GeV	0.15	0.35	2.4	3.8

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 (10 MW).

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 [3, 4]. 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 [5]. 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 [6].

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) [7]. 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 [8]. The dedicated feedback scheme against kink instability is under development, using the control of the electron beam position at the collision point.

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 [9] . 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. The design of 180 MHz crab-cavity based on the quarter wave resonator has been developed [10] . 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[11] .

Conclusions

We have developed a well advanced design of the future electron-ion collider eRHIC. The conceptual tests for important R&D 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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