Accelerator Design of High Luminosity Electron-Hadron Collider eRHIC

Vadim Ptitsyn on behalf of the eRHIC Accelerator Design team
BNL, Upton, NY 11973, USA

DOI: http://dx.doi.org/10.3204/DESY-PROC-2012-02/125

The accelerator 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} s^{-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 re-circulating 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.

1 eRHIC Design

Relativistic Heavy Ion Collider (RHIC) has been operating at BNL (USA) for more than decade, producing either polarized p-p collisions (with the proton energy up to 250 GeV) or unpolarized heavy ions collisions (with ions up to U and the ion energy up to 100 GeV/u). The future electron-ion collider eRHIC will take advantage of the existing RHIC ion complex. The layout of the future accelerator is shown in Figure 1. In order to keep the modifications to minimum, eRHIC will add an electron accelerator inside the present RHIC tunnel. 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 recirculations are realized with vertically stacked recirculation passes (the beam lines), which run along the RHIC circumference. The recirculation passes are composed from compact size magnets to minimize the construction and operation costs. Highest luminosity is achieved with the electrons at (or below) 20 GeV energy. In addition to ion species used in present RHIC, eRHIC will include also polarized $^3He^{++}$ ions.

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 of RF electromagnetic field. 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

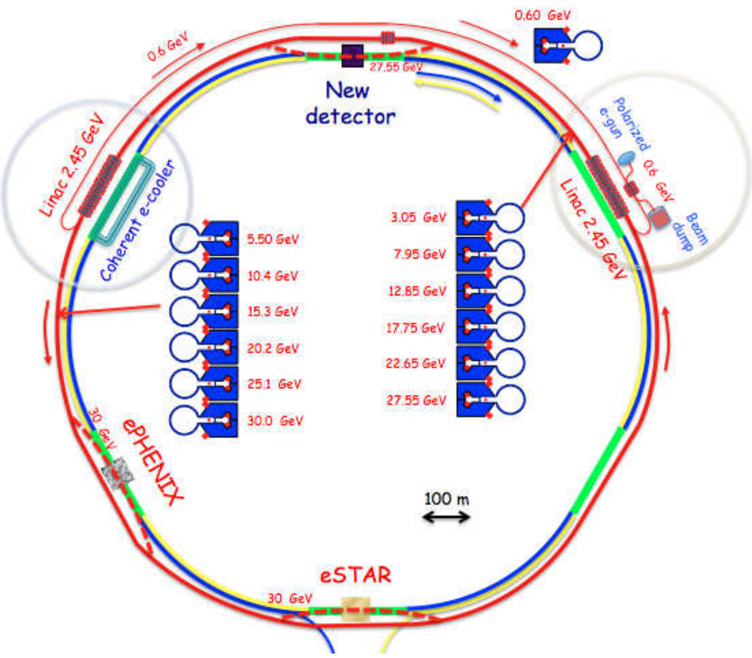

Figure 1: eRHIC Accelerator Layout.

average acceleration gradient reaching up to 12.3 MeV/m. The attractive feature of the eRHIC design is that the staging of this machine can be easily arranged. It is planned that, on the first stage, eRHIC will have shorter length ERLs and the maximum electron energy of 10 GeV. On later stages the linacs will be enlarged by adding SRF cavities, ultimately reaching 30 GeV energy of electrons. 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 (9.4 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 luminosity of collisions of 20 GeV electrons and 250 GeV protons reaches $2.7 \cdot 10^{34}$ cm^{-2} s^{-1}. Because of the space charge limit the luminosity would drop as the cube of the proton energy. In order to prevent this sharp drop of the luminosity with the proton energy, the space charge compensation (the electron columns) is utilized in the design. With the space charge compensation the luminosity decreases proportionally to the proton energy. The transverse and longitudinal cooling of the hadrons is required to reach high design luminosities. Above 20 GeV electron energy the luminosity decreases as $1/E_e^4$ due to the synchrotron radiation power limit (7 MW at 20 GeV). Further information on the beam parameters and the luminosities can be found on the eRHIC accelerator webpage [2].

2 eRHIC R&D program

In order to reach its luminosity and polarization objectives the eRHIC design intends to utilize advanced accelerator technologies. The list of eRHIC accelerator 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 eRHIC polarized electron source has to be able to produce the average current up to 50 mA. The high current can be achieved by effectively increasing the cathode area, using standard cathode materials (strained GaAs or superlattice). The BNL group has been developing a so-called "Gatling gun" design where the high current is produced by merging the electron currents extracted from several small size cathodes [3]. The engineering design of the "Gatling gun" has been completed. The next planned step is building the gun prototype.

To efficiently reduce 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 proposed [4]. 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 for CEC, funded by DOE NP Office of Science, is being prepared in RHIC by the collaboration of BNL, JLab and Tech-X [5]. The experiment will take place in 2014-2016. The aim of the experiment is to demonstrate the longitudinal cooling of 40 GeV/u Au ion beam.

With the large number of electron recirculation passes, several thousand 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 three years [6]. The magnetic measurements done with the dipole magnet prototypes (with the gap as small as 5mm) demonstrated a magnetic field quality close to satisfying eRHIC requirements.

The high beam power ERL technology will be used in RHIC to accelerate the high average current electron beam. The ERL test facility has been built in BNL in order to test the key components of the SRF technology (with 704 MHz BNL cavity) and the energy recovery with high beam average current (up to 0.5 A) [7]. The beam dynamics issues, specific for the energy recovery machines will be also explored, They include the beam breakup, the beam emittance growth and the beam halo formation. The facility plans to start first tests with the electron beam, produced by the SRF gun, later this year.

The beam-beam interactions for the linac-ring collision scheme have been the subject of thorough studies. All diverse features of the beam-beam effects were explored with the beam simulations as well as analytically: electron beam disruption, proton kink instability, and electron beam parameter fluctuations. The beam halo created because of the beam disruption by the collisions defines the aperture of recirculation pass magnets. It was shown also, that the dedicated broadband feedback scheme can be successfully used against the kink instability [8].

The Interaction Region design is crucial for the luminosity gains. It faces the issues of strong focusing of beams at the collision point and the fast separation of beams after the collision. The detector integration issues are important: the design has to provide the good experimental acceptance and separate neutrons and off-momentum charged particles from the outgoing hadron beam. In the same time the synchrotron radiation fan produced by electrons in the magnets has to be kept away from hitting the pipe inside and in the vicinity of the detectors and in superconducting magnets. Because of the proximity of the hadron and electron beam trajectories, special designs of IR magnets have to be developed. The application of Nb_3Sn superconductor technology is considered, following recent progress made for such magnets for the LHC luminosity upgrade. The details of the present interaction region scheme is described in [9]. It employs the 10 mrad crossing angle and the crab-crossing technique. Corresponding crab-cavity design has been developed on the basis of Quarter Wave Resonator cavity [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.

On the basis of EBIS ion source, recently built for RHIC, the polarized $^3He^{++}$ ions can be produced. The concept of such polarized $^3He^{++}$ ion source has been developed by the collaboration of MIT and BNL scientists [11]. The use of polarized $^3He^{++}$ ions is presently considered for the experiments at RHIC, that is on the time scale before eRHIC. Corresponding studies of the polarization preservation through the injector chain and at the acceleration in RHIC are underway.

The considerable progress has been already achieved on all major R&D items. Next 3-4 years will be critical for completing R&D work and finalizing the cost effective eRHIC accelerator design.

3 Acknowledgements

My acknowledgements are to scientists who contributed to various aspects of the eRHIC accelerator design: V. N. Litvinenko, S. Belomestnykh, I. Ben-Zvi, M. M. Blaskiewicz, K. A. Brown, J. C. Brutus, A. Elizarov, A. Fedotov, P. K. Feng, D. Gassner, H. Hahn, Y. Hao, P. He, L. T. Hoff, W. Jackson, A. Jain, Y. Jing, D. Kayran, R. Lambiase, C. Liu, Y. Luo, M. Mapes, G. Mahler, G. McIntyre, W. Meng, M. Minty, R. Michnoff, B. Parker, A. Pendzick, A. Pikin, I. Pinayev, T. Rao, E. Riehn, T. Roser, J. Sandberg, J. Skaritka, B. Sheehy, K. Smith, S. Tepikian, O. Tchoubar, Y. Than, C. Theisen, D. Trbojevic, E. Tsentalovich, N. Tsoupas, J. Tuozzolo, G. Wang, Q. Wu, W. Xu, A. Zaltsman, W. Zhang, A. Zelenski.

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