

THE ERL-BASED DESIGN OF ELECTRON-HADRON COLLIDER eRHIC*

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Abstract

Recent developments of the ERL-based design of future high luminosity electron-hadron collider eRHIC focused on balancing technological risks present in the design versus the design cost. As a result a lower risk design has been adopted at moderate cost increase. The modifications include a change of the main linac RF frequency, reduced number of SRF cavity types and modified electron spin transport using a spin rotator. A luminosity-staged approach is being explored with a Nominal design ($L \sim 10^{33} \text{ cm}^{-2}\text{s}^{-1}$) that employs reduced electron current and could possibly be based on classical electron cooling, and then with the Ultimate design ($L > 10^{34} \text{ cm}^{-2}\text{s}^{-1}$) that uses higher electron current and an innovative cooling technique (CeC). The paper describes the recent design modifications, and presents the full status of the eRHIC ERL-based design.

MAIN FEATURES OF ERL-BASED ERHIC

The key goal of the eRHIC accelerator design is to achieve a required high-energy, high-luminosity performance at a realizable machine construction cost. For the hadron part of the machine, eRHIC takes advantage of the existing RHIC accelerator complex, including the full suite of injector systems for polarized protons and fully-stripped heavy ions. The new electron accelerator, based on an energy-recovery linac (ERL) is achieved through a cost-effective design, taking advantage of significant recent advances in accelerator technology.

As shown in Figure 1 the ERL-based eRHIC design uses one of the RHIC hadron beams (the clockwise-moving “blue” beam), with a high energy electron beam counter-rotating in the same tunnel, and collisions occurring in two intersection regions occupying the present experimental areas detectors. The full range of RHIC hadron beams is thus available for eRHIC, up to 250 GeV for polarized protons and 100 GeV/u for Au ions.

The accelerated electrons originate in a new, high-current polarized source and are accelerated to 20 MeV for injection into a 1.665 GeV Energy Recovery Linac. Using recirculating rings inside the RHIC tunnel the electrons make multiple passes through the ERL, and ultimately

can be accelerated up to 20 GeV. The electron beam can be extracted at an energy of choice into a high energy transport beamline which brings electrons into collision with the hadron beam. The spent electron beam is then recirculated back through the ERL, returning its energy to the superconducting RF structure of the linac, after which the decelerated electrons are dumped.

In our design work on the ERL-based eRHIC two variants of recirculating pass lattice have been developed. One of them is based on conventional approach using individual beamlines for each recirculation [1,2], while another employs FFAG beamlines, capable of recirculating electrons in wide energy range [3]. Lately, in the process of eRHIC cost optimization, the FFAG beamline approach has been thoroughly investigated. It could allow to realize large number of re-circulations at moderate cost. For instance, only two FFAG beamlines are required to realize 11 re-circulations in the eRHIC layout shown in Figure 1.

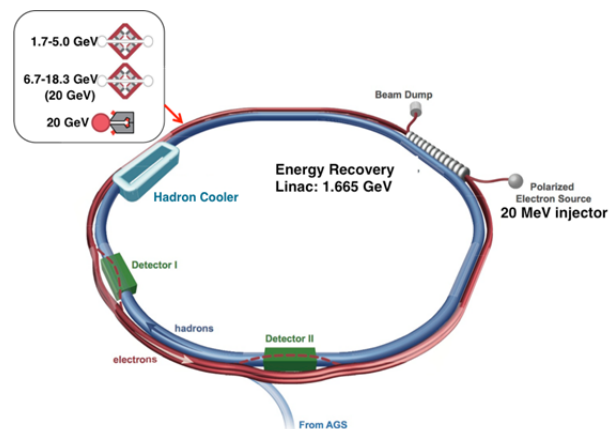


Figure 1: The layout of ERL-based eRHIC collider.

The luminosity staging can be realized with the Nominal design stage reaching the luminosity $\sim 1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ and then with a later Ultimate design pushing the luminosity to $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ level. This staging scenario relies mostly on improving the hadron cooling strength. A cooling device in the IR10 region of the RHIC tunnel will be used for longitudinal and transverse cooling of the proton

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and ion beams. In the Ultimate design the device will employ the Coherent electron Cooling (CeC) technique [4] for strong cooling in both longitudinal and transverse planes. The Nominal design requires weaker cooling and the possibility of magnetized electron cooling is being considered, although the cooling also can be realized by the CeC with relaxed electron current requirements.

The interaction region has to satisfy demanding requirements for detector acceptance of forward collision products like neutrons and scattered protons. It also has to deal with challenging protection of detector area from direct and backscattered synchrotron radiation produced by electron beam. Studies showed that it will be extremely difficult to satisfy the detector acceptance and SR protection requirements without crossing angle [5]. The present IR design is based on 10 mrad crossing angle. Crab cavity system is used to prevent loss of luminosity due to the crossing angle [6]. Simulations exploring the crab-crossing together with beam-beam interactions have started [7]. The IR hadron superconducting magnets employ a “sweet spot” concept to arrange for passage of the electron beam through the field-free (sweet spot) area between the superconducting coils [8]. The Nominal design calls for hadron and electron $\beta^* = 16$ cm, while the Ultimate design requires β^* as low as 7 cm.

One of strong points of the linac-ring design is straightforward delivering of high polarization of electron beam. In the absence of spin resonances, typical for storage rings, the electron polarization of 80%, or even more, produced at the source, is easily preserved during the acceleration. Latest design revision includes modified spin transport. Previously the spin transport was realized by allowing the electron spin to precess in the horizontal plane, similar to CEBAF. Lately we have switched to accelerate the electrons with vertically aligned spins and employ a spin rotator [9] near an interaction region to produce the longitudinal beam polarization at the detector. As the result of this approach, tolerances on the electron beam energy spread were considerably relaxed thereby eliminating the need for dedicated SRF systems to compensate the energy spread.

LUMINOSITY

The ERL-based design approach is related to the linac-ring collision scheme that overcomes fundamental luminosity limitation by beam-beam effects of the standard “ring-ring” scheme. The luminosity of the “linac-ring” scheme can be written as a function of the hadron beam parameters:

$$L = f_c \xi_h \frac{\gamma_h}{\beta_h^*} \frac{ZN_h}{r_h} H_{hg} H_p,$$

where $r_h = Z^2 e^2 / Mc^2$ is the hadron classical radius, ξ_h is the hadron beam-beam parameter, β_h^* is the hadron beta-function at the interaction point, N_h is the hadron bunch intensity, γ_h is the hadron relativistic factor and Z is

the hadron charge. f_c is the collision frequency (or the bunch repetition rate).

The geometric loss factor H_{hg} arises from luminosity loss due to the hour-glass effect and the crossing angle. With a crossing angle as large as 10 mrad the crab-crossing technique is employed to prevent luminosity loss. The H_p parameter represents the luminosity enhancement resulting from the pinching of the electron beam size at the collision point caused by the hadron beam focusing force. Typical luminosity enhancement by the pinching is on the scale of 15-30%.

The major limits assumed for the beam and accelerator parameters are:

- Polarized electron average current: $I_e \leq 50$ mA
- Hadron space-charge tune shift: $\Delta Q_{sp} \leq 0.06$
- Hadron beam-beam parameter: $\xi_h \leq 0.015$
- Electron synchrotron radiation power: $P_{SR} < 2.5$ MW

Determined by these limits the luminosity dependence on the center-of-mass energy is shown in Figure 2. For the Ultimate design the space charge compensation is assumed at lower energies to satisfy the declared space charge limit.

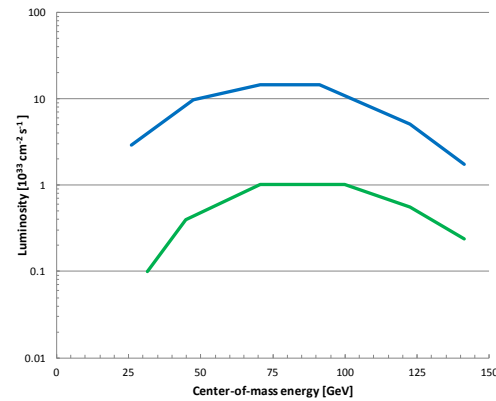


Figure 2: The ERL-based eRHIC luminosity versus center-of-mass energy. Blue curve – Ultimate design, Green curve - Nominal design.

As described before, the Ultimate and Nominal design stages mostly differ by the strength of the hadron cooling system. We should also note that no cooling case produces peak luminosity up to $8 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ which may be acceptable for an initial operation of eRHIC.

The eRHIC bunch frequency is 9.4 MHz which is equal to the bunch frequency of the present RHIC hadron beam. The eRHIC hadron bunch intensity in the Nominal design is similar to that used in RHIC operation (up to $N_h = 2 \cdot 10^{11}$ for protons). For the Ultimate design besides the strong cooling the proton intensity will be increased to $3 \cdot 10^{11}$ protons per bunch.

MAIN LINAC

The main SRF linac is placed in a 200 m long straight section of the RHIC tunnel. The use of energy recovery technology in the main accelerator linac is essential to reach a high value (50 mA) of electron average current. The RF frequency of main linac was reconsidered, giving

preference to the 647 MHz frequency. Major advantage of this frequency choice is that the technology for 650 MHz SRF cavities has been under successful development in Fermilab. The baseline 5-cell cavity gradient for eRHIC is 18 MV/m at $Q_0 \sim 2 \cdot 10^{10}$ [10]. Copper and niobium cavity prototypes will be built and used for cavity performance and HOM damping studies. HOM damping of main linac cavities uses combination of ridge waveguides and beam pipe absorbers to damp several kW power in full HOM spectrum [11,12].

An additional set of cavities operating at 1.3 GHz (2nd harmonic of main linac) will be used to compensate for synchrotron radiation losses.

RECIRCULATING PASSES

For the recirculating passes two possible designs have been worked out. The first is based on conventional approach using individual transport beamlines for each recirculation energy [2]. Compact electromagnet design for these transport beamlines has been developed [13]. The second design is based on FFAG beamlines, capable of recirculating electrons in wide energy range [3]. The basic FFAG cell of a high-energy FFAG is shown in Figure 3. It is capable of transporting beams in the energy range from 6.7 GeV to 20 GeV.

A spreader and a combiner are placed on either side of the ERL for proper distribution and matching of the electron beams of different energies between the ERL and FFAG beamlines. The spreader/combiner arms also are used for optics matching and path length correction (to make one turn transport completely isochronous and achromatic), as well as for fine tuning of pathlength and R_{56} parameter.

R&D FOR ERL-BASED DESIGN

The Pre-Project R&D Program is underway which aims at various elements of the Linac-Ring eRHIC. This includes numerical simulation and theory of the multiple aspects of the eRHIC Linac-Ring design. Items considered as high-risk are being addressed by experimental programs: R&D on highly-damped Superconducting RF (SRF) accelerating cavities; R&D of SRF crab cavities and testing the performance of crab cavities in a high-energy hadron machine; R&D of high-current polarized electron gun; R&D of FFAG multi-pass ERL; R&D of strong hadron cooling, in particular magnetized electron cooling and Coherent electron cooling. These R&D programs have been funded so far by BNL R&D funds. According to present schedule these R&D studies will be realized on the scale of 2-3 years.

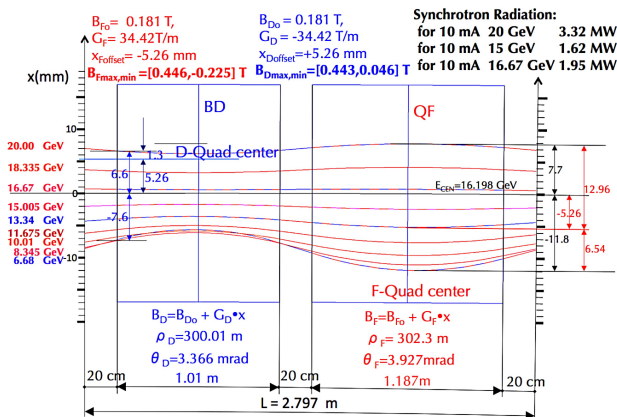


Figure 3: Basic cell of high-energy FFAG beamline.

The BD and QF magnets are quadrupole magnets having a horizontal offset (max 10.5 mm) between their center axes. Such an arrangement provides at the same time both bending and focusing necessary to transport beams of very different energies. A remarkable feature is that all lattice elements (arcs, detector bypasses, straight and matching sections), can be realized on the basis of this FFAG cell by using different horizontal offsets. To save on operational cost we consider for BD and QF magnets a design based on permanent magnet material (NdFeB or SmCo).

The main idea behind using the FFAG recirculating pass approach and the permanent magnet technology is to lower machine construction and operation costs. The operation of FFAG recirculation beamline will be demonstrated at a Cornell—BNL ERL FFAG test facility which is presently under construction in Cornell University [14].

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