RECIRCULATING ELECTRON LINACS (REL) FOR LHEC AND ERHIC*

D. Trbojevic, J. Beebe-Wang, Y. Hao, V. N. Litvinenko, V. Ptitsyn, D. Kayran, and N. Tsoupas, Brookhaven National Laboratory, Upton, Long Island, New York, 10973-5000

Abstract:

We present a design of a CW Electron Recovery Linacs (ERL) for future electron hadron colliders eRHIC and LHeC. In eRHIC, a six-pass ERL would be installed in the existing tunnel of the present Relativistic Heavy Ion Collider (RHIC). The 5-30 GeV polarized electrons will collide with RHIC's 50-250 GeV polarized protons or 20-100 GeV/u heavy ions. In LHeC a 3-pass 60 GeV CW ERL will produce polarized electrons for collisions with 7 TeV protons. After collision, electron beam energy is recovered and electrons are dumped at low energy. Two superconducting linacs are located in the two straight sections in both ERLs. The multiple arcs are made of Flexible Momentum Compaction lattice (FMC) allowing adjustable momentum compaction for electrons with different energies. The multiple arcs, placed above each other, are matched to the two linac's straight sections with splitters and combiners.

INTRODUCTION

The eRHIC project has selected an ERL design as it has multiple advantages: higher luminosities and the electron energy recovery. It would be extremely difficult to dump 60 (30) GeV electron beam after collisions into solid-state targets. After collisions, electron energy is reduced down to their initial value, by multiple passes through the linacs at the negative side of the sinusoidal RF voltage. The electron energy in the dump is equal to the injection value. The time of flight of electrons is the most important parameter in this process allowing them to reach the sinusoidal voltage function at the right time:

$$L_p = -\frac{dL}{dp} = M_{5,6}, \quad [1]$$

$$X_{out} = M\, X_{in}, \; X = (x, x', y, y', -ds, \frac{\delta p}{p}, 1). \quad [2]$$

The recirculation passes should be isochronous to provide complete energy recovery for off-momentum electrons and to relax the tolerances on RF system. To ensure the isochronous condition the lattice has to be flexible to adjustments of the M_{56} parameter, if needed. The equation of the longitudinal synchrotron motion is:

$$\frac{\delta T}{T_o} = \left(\alpha - \frac{1}{\gamma^2}\right)\frac{\delta p}{p}, \quad [3]$$

where γ is the relativistic factor, and α is the momentum compaction. The momentum compaction α is defined as:

$$\alpha = \frac{1}{C_o}\int \frac{ds}{\rho} \approx \frac{1}{C_o}\sum_i \overline{D}_i\, \theta_i, \quad [4]$$

where γ_T is the transition energy, θ_i is a bending angle of the dipole *"i"*, $\overline{D}_i$ s average dispersion through the dipole *"i"*, and the C_o is the circumference of the accelerator. A lattice design method to avoid the transition crossing where the momentum compaction $\alpha < 0$ had been previously presented [1]. To produce $M_{5,6} \cong 0$ can be achieved if the total sum of the horizontal dispersion through dipoles is equal to zero: $\Sigma_i D_i \theta_i \cong 0$. The method is best explained by the Floquet transformation and "normalized dispersion" function [2].

$$\chi = D'\sqrt{\beta} + D\frac{\alpha}{\sqrt{\beta}} \quad \xi = \frac{D}{\sqrt{\beta}}, \quad [5]$$

where a vector $\chi = D_x' \sqrt{\beta}$ or $\chi = \theta \sqrt{\beta}$ represents the dipole effect on the dispersion function. These vectors need to be equally distributed on the ξ axis making the overall sum equal to zero or $M_{5,6} = 0$. The normalized dispersion space for the eRHIC arc basic module is shown in Fig. 1.

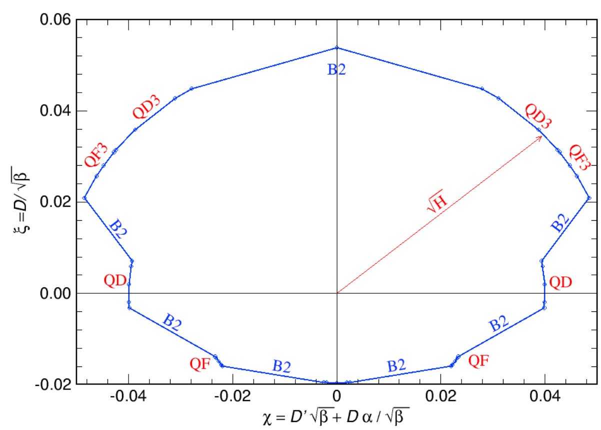

Figure 1: The normalized dispersion space for the basic module of the eRHIC arc. The *B2* dipole vectors $\chi = \theta\sqrt{\beta}$ shown are placed symmetrically with respect to the zero of the ξ axis making for the presented module the momentum compaction equal to zero (α=0).

ERL COLLIDERS PARAMETERS

The lattice design for the future LHeC and eRHIC has the same arc structure and multiple passes. The LHeC design is a racetrack with two linacs placed at opposite sides in the zero dispersion straight sections with three arcs placed above each other connected to the linacs by the splitters and combiners. The eRHIC magnets are placed inside of the existing RHIC tunnel. The arcs follow the shape of the tunnel while the two linacs are in the 10 and 2 o'clock straight sections. The synchrotron radiation in the arcs presents significant concern. An average radius of the arcs for the LHeC is 1000 m, while the eRHIC average tunnel radius is 381.23 m. Geometry of arc lattice

*Work performed under Contract Number DE-AC02-98CH10886 with the auspices of the US Department of Energy.

needs to follow the average radius. The basic cell of the arc lattice is very similar for both LHeC and eRHIC. It has one and a half FODO cells on both sides and two doublet quadrupoles for a "π" flip in phase of the dispersion function in the middle. It has strong focusing, good compaction, low values of betatron and dispersion functions, and tunable momentum compaction. Tuning is achieved by the doublet quadrupoles. The LHeC electron-proton collider will collide 90% polarized electrons with energy of 60 GeV and protons presently at 7 GeV, with expected luminosity of 1×10^{33} cm^{-2} s^{-1}. Other LHeC parameters are shown in Table 1. The eRHIC should provide collisions between polarized electrons with maximum energy of 30 GeV and 250 GeV polarized protons or heavy ions with a maximum luminosity of $\sim1\times10^{34}$ cm^{-2} s^{-1}, at electron energy of 20 GeV and proton energy at 250 GeV. Six arcs in the eRHIC collider, are assumed to be vertically above each other with the same arc elements, but with scaled down with energies of magnet excitations.

Table 1: Lepton Beam Parameters for LHeC

Electron energy at IP [GeV]	60
Luminosity [cm^{-2}s^{-1}]	1.01×10^{33}
Polarization (%)	90
Bunch population [10^9]	2.0
e− bunch length [μm]	300
Bunch interval [ns]	50
Transverse emittance. $\gamma\varepsilon_{x,y}$ [μm]	50
Rms IP beam size [μm]	7
Hourglass reduction H_{hg}	0.91
Crossing angle θ_c	0
Repetition rate [Hz]	CW
Average current [mA]	6.6
ER efficiency η	94
Total wall power [MW]	100

The eRHIC will collide polarized proton and ^{3}He beams, and heavy ions with the polarized electrons. The eRHIC beam parameters are shown in Table 2:

Table 2: Beam Parameters for eRHIC

	Protons	Electrons
Energy [GeV]	250	20
#of bunches/bunch freq. MHz	166	14.08
Bunch intensity $\times10^{11}$	2.0	0.22
Bunch charge [nC]	32	3.5
Beam current [mA]	415	50
Rms normalized emittance μm rad	0.18	20
Rms emittance nm rad	0.52	0.52
β^* [cm]	5	5
Beam-beam parameter/disruption	0.015	27.1
Rms bunch length [cm]	4.9	0.2
Polarization [%]	70	80
Luminosity [cm^{-2} s^{-1}]	1×10^{34}	

Connections to the two linacs are provided with spreaders or mergers at the ends of the arcs.

LHEC ARC LATTICE

A 180-degree arc (with average radius of 1000 m) consists of 113 asynchronous arc cells 27.8 m long. m. The filling factor in this lattice is 69.7%, the bending radius is 697 m and the maximum bending field is 0.287 T in the 60 GeV arc. The arc contains 782 dipoles and 1017 quadrupoles. Four quadrupole families are fed in series. The synchrotron radiation integrals [3] for the 360-degrees are as follows: I_1 = 0.190 10^{-1}, I_2 = 0.891 10^{-2}, I_3=0.126 10^{-4}, I_4 = 0.38 10^{-7}, I_5= 0.103 10^{-7}. The horizontal normalized emittance growth, during the acceleration of the beam to 60 GeV, is 8.59 μm rad and its RMS energy spread adds 15.98 MeV.

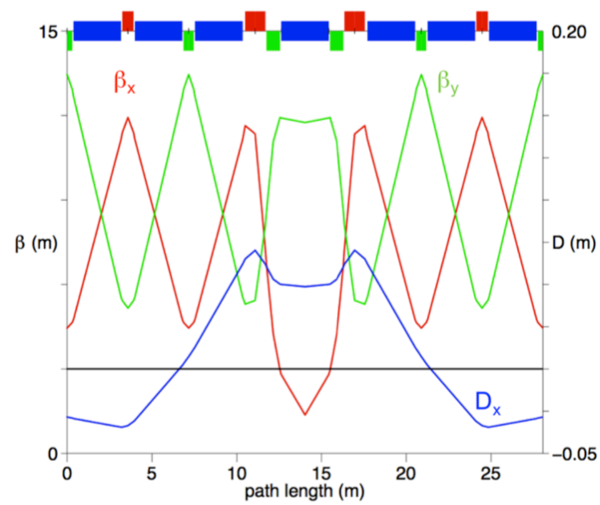

Figure 2: Betatron and dispersion functions in the basic LHeC arc cell.

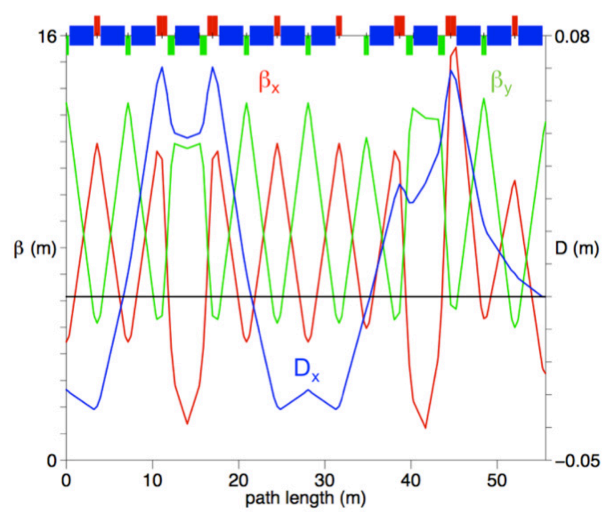

Figure 3: The achromatic LHeC cell at the end of arc.

The total normalized emittance growth from the moment of injection to its ejection measures 36.53 μm rad. The *rms* energy spread adds to 35.24 MeV, i.e. the beam is ejected with 11.7% energy spread. The betatron functions and dispersion in the basic arc module of the LHeC are shown in Fig. 2. The achromatic cells at the end of the arcs are designed either by the missing dipole method or by [4] using two basic module cells but with different gradients of the quadrupoles. The missing dipole achromatic cell is shown in Figure 3.

ERHIC ARC CELLS

Two linacs and six arcs of the future electron ion collider will be placed inside of the existing RHIC tunnel. The six arcs, vertically separated, are made of compact small aperture magnets. The lattice of the eRHIC arc cell is very similar as the one already presented for the LHeC. The achromatic cells at the end of the arcs are presented in Fig. 4.

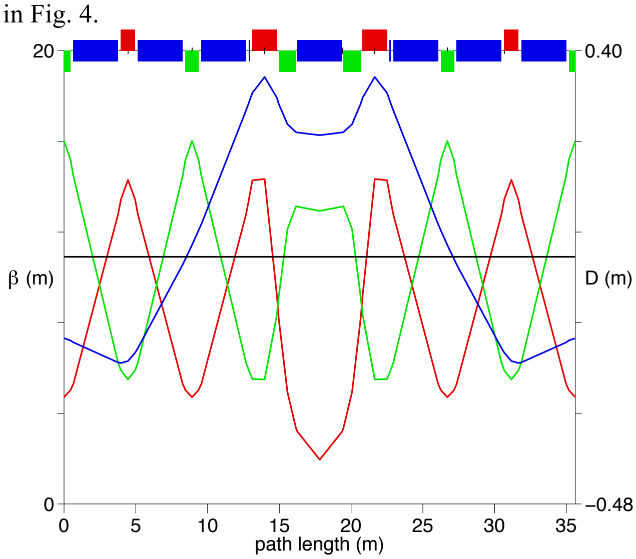

Figure 4: Newest basic block of the eRHIC arc where the elements are 2.6 times scaled up to reduce their overall number and improve on the packing factor. Dipole length is 3.12 m with a bending radius of ρ=234.2 m.

The normalized dispersion space for the achromatic cells is shown in Fig. 5.

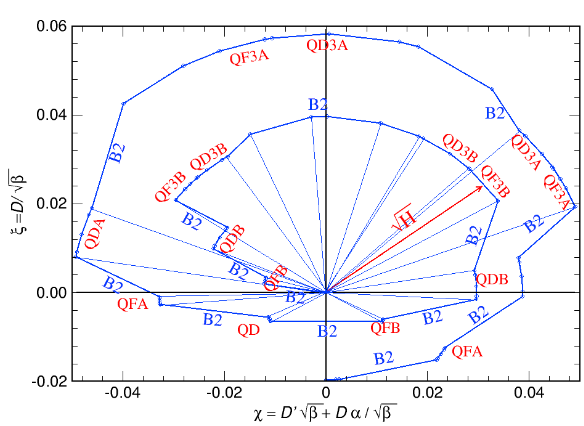

Figure 5: The achromatic cells of the eRHIC in the normalize dispersion space.

Three types of connections between the arcs and straight sections are developed: first, the special vertical cells with very small bending magnets to provide connection to the interaction region, second, spreaders and combiners to provide connection to the linacs, and third, cells which either pass parallel to the present RHIC straight section or bypass the detectors. The linacs in both examples do not have quadrupoles, as the energy range is too large for them to provide significant difference in focusing. The splitters and combiners define the betatron functions for each energy pass. The center of the linac has the minimum of the betatron functions. The combiner and spreader are shown in Fig. 6. In addition, the cavities electrical fields provide the RF focusing.

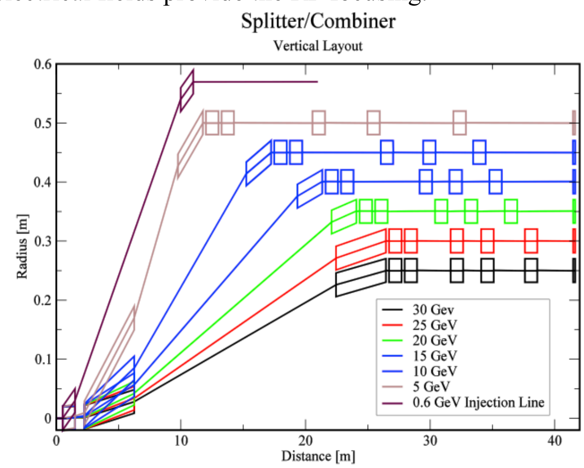

Figure 6: Splitter/Combiner define betatron functions in the linac for appropriate energies and provide connections to the arcs.

SUMMARY

Lattice design of the future lepton-hadron colliders LHeC and eRHIC based on an ERL, has been described. Multiple passage of electrons through linacs requires M_{56} = 0 from the arcs. We have encreased the magnet sizes to be able to reduce the total number of elements. The radiation integrals and emttance became larger (I_1 = -.24 10^{-5}, I_2 = 0.39 10^{-2}, I_3=0.1 10^{-4}, I_4 = 0.4 10^{-10}, I_5= 0.26 10^{-6}, ε_{PX}=3.95 10^{-6} , ε_{PXN}=0.15 10^{-2}), but a control of the momentum compaction remains the same.

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