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Permanent Magnet Future Electron Ion Colliders at RHIC and LHeC*

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ABSTRACT: We present a new 'green energy' approach to the Energy Recovery Linac (ERL) and Recirculating Linac Accelerators (RLA) for the future Electron Ion Colliders (EIC) using single beam line made of very strong focusing combined function permanent magnets and the Fixed Field Alternating Linear Gradient (FFA-LG) principle. We are basing our design on recent very successful commissioning results of the Cornell University and Brookhaven National Laboratory ERL Test Accelerator.

Background

A new Electron Ion Collider proposal (EIC) at Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) is based on the very successful commissioning of the 'CBETA'-**C**ornell University **B**NL **E**nergy Recovery Linac **T**est **A**ccelerator [1, 2, 3, 4, 5]. The 'CBETA' showed 4 accelerating and 4 decelerating electron passes through the Main Cryo-Module Linac using a single **F**ixed **F**ield **A**lternating **L**inear **G**radient - **FFA-LG** beam line made of permanent combined function magnets. In the CBETA project the injector provided 6 MeV energy electrons and with 36 MeV superconducting linac the beam was successfully accelerated to the maximum energy of 150 MeV. After the first pass through the Main linac electrons reached energy of 42 MeV, following the second pass 78 MeV, the third 114 MeV and the last pass fourth pass electrons reached energy of 150 MeV. The full energy recovery was shown after the 6 MeV decelerated beam was passed to the dump at the same position and the same beam profile as the electrons coming from the injector with energy of 6 MeV with the zero voltage of the Main Linac.

The main element of the new design is 1.5 GeV superconducting linac. It uses the RF frequency of 1.31369 GHz as the Cornell University Linac 14th harmonic of the future RHIC bunch frequency of 93.835 MHz This RF frequency is matched to the 1200 bucket distribution around the RHIC tunnel of 275 GeV energy proton beam. There are 1150 bunches occupying 1200 available buckets leaving 50 buckets for the abort gap. The maximum 18 GeV energy of electrons is achieved after 12 passes though the Main 1.5 GeV superconducting linac starting with 1.5 GeV.

There are multiple advantages of the proposal with respect to the existing CD0 and CD1 EIC at RHIC proposal implementing solutions from the exiting EIC design: like using the interaction regions (IR) design, the same bunch frequencies and abort gap during the collisions, use of the Crab Cavities in the IR's, the same geometrical conditions during the collisions, identical betatron functions β_x^* and β_y^* at IR, the same magnets required for the IR's, electron bunch replenishments method (although with much shorter scale), RHIC ion beam upgrade, electron and ion vacuum pipe designs, and so on. Properties of the ERL-RLA proposal are:

1. This is a real 'green' accelerator as there is no need to use electrical power for the accelerator/storage ring as the fixed field permanent magnets are used and the energy is recovered from the superconducting.

2. The Low Risk ERL-RLA design, based on the existing technologies of superconducting RF and already proven permanent magnet technology used at CBETA, provides a straight path to high luminosities of the order of 10^{34} cm^{-2}s^{-1}.

3. As the CD0 and CD1 EIC at RHIC design the beam starts from the polarized electron source with 400 kV D.C gun. There are two possible modes of operation: one with 7.5 nC electron bunches and the other with 28 nC per bunch if the polarized electron source can produce such a high intensity and electron current bunches. Most of the proposal is focused on the operation with the lower 7.5 nC polarized electron ion source.

4. The electron storage ring in the present CD0-CD1 EIC at RHIC design is replaced with the **single** FFA-LG Energy Recovery or Recirculating Linear Accelerator **used at the same time as a storage ring.** Electron bunches with required collision energy are stored for a short time of 16 ms at the chromatically corrected highest energy orbit. The electron energies for the collision with ion are selected by the positions of the extraction magnets of the of stored electron beam. They are in the range between 6 and 18 GeV. The sextupole and octupole multipole components are added in the combined function permanent magnet design allowing the chromaticity to be corrected for the whole energy range between 6 and 18 GeV in the main Fifty electron bunches arrive to the single FFA-LG beam line after the 1.5 GeV linac every 14 RHIC turns in CW mode. A time distance between the 10 bunches is equal to the RHIC collision frequency of 93.835 MHz or 10.657 ns. The electrons are stored in the selected orbit as the fast kickers take them away from the Main linac. Ten electron bunches of selected energy, for example with the highest energy of 18 GeV bypass the main 1.5 GeV linac and remain circulating until the full 1160 bunches fill the whole ring with the 40 unfilled buckets for the abort gap. After fourteen turns in RHIC the next ten bunches are added to the previous one in the storage orbit. The storage orbit is filled after 1624 RHIC turns. When the next ten bunches arrive to the collision FFA-LG orbit the last ten bunches are not kicked out around the linac but put back to the 1.5 GeV linac entering with the opposite 180 degrees phase and their energy is taken away after each turn and the process continues sequentially.

5. The **electron polarization is preserved** as the beam is accelerated within 7.2 ms and the electron bunches are replenished in the storage mode every 540th RHIC turns or 20.768 ms with respect to the 2 minutes in the present CD0-CD1 EIC design. Time of electrons to get to the highest energy is equal to the sum of required time to merge 4 bunches into a single bunch (180 ms) four turns in the small racetrack (1.7 ms), plus three turns in the large racetrack 6.394 ms, and 9 turns in the RHIC FFA-LG line (115.1 ms).

6. The tune dependence on energy shows a very small difference in both horizontal and vertical tunes per cell for the whole energy range between 6-18 GeV.

7. The beam-beam effect is reduced as the electron ion collisions do not repeat after 1624 turns.

8. The electron energy at the dump is 100 MeV and the energy from the linac is recovered.

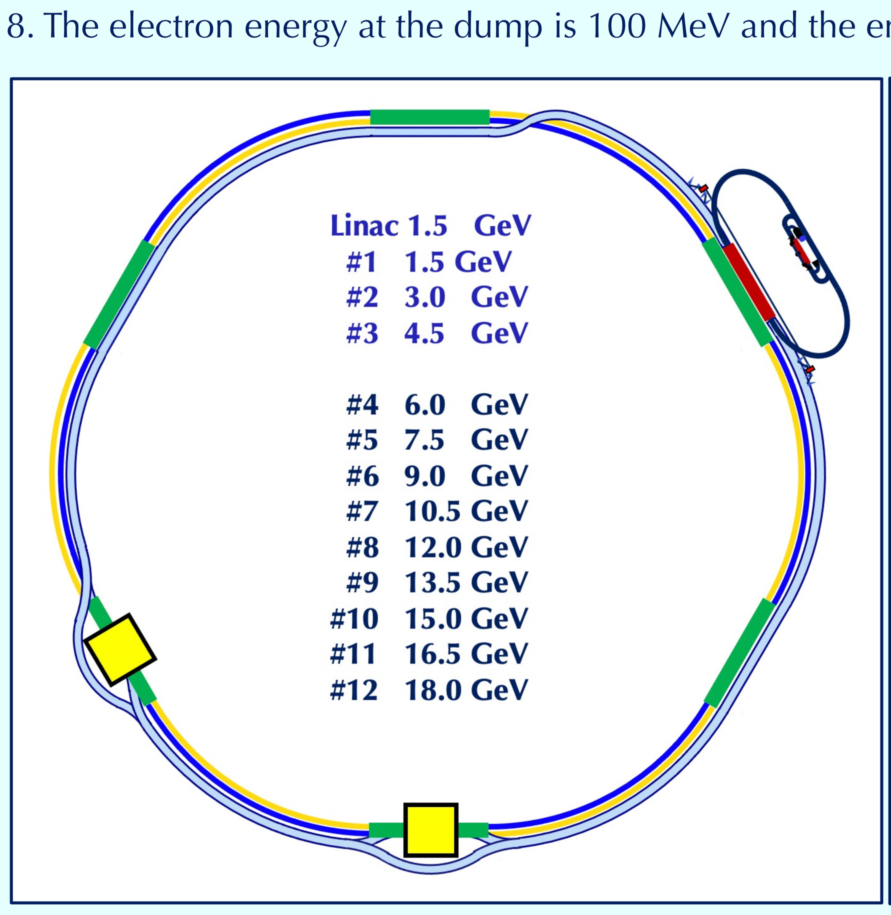

Figure 1: Layout of the large Fixed Field Alternating Linear Gradient accelerator with the 1.5 GeV superconducting linac. The beam is accelerated from 6 to 18 GeV with a total of 12 passes through the linac where the first three are using the racetrack with $C_{RHIC}/6$ length. When the beam reaches 18 GeV it is stored for ~200 turns in the ring bypassing the 1.5 Main linac. Electron beams with energies in a range 6-16.5 GeV bypass the detectors. The colliding electron energy can be selected between 6-18 GeV by adjusting the radial position of the septum dipole.

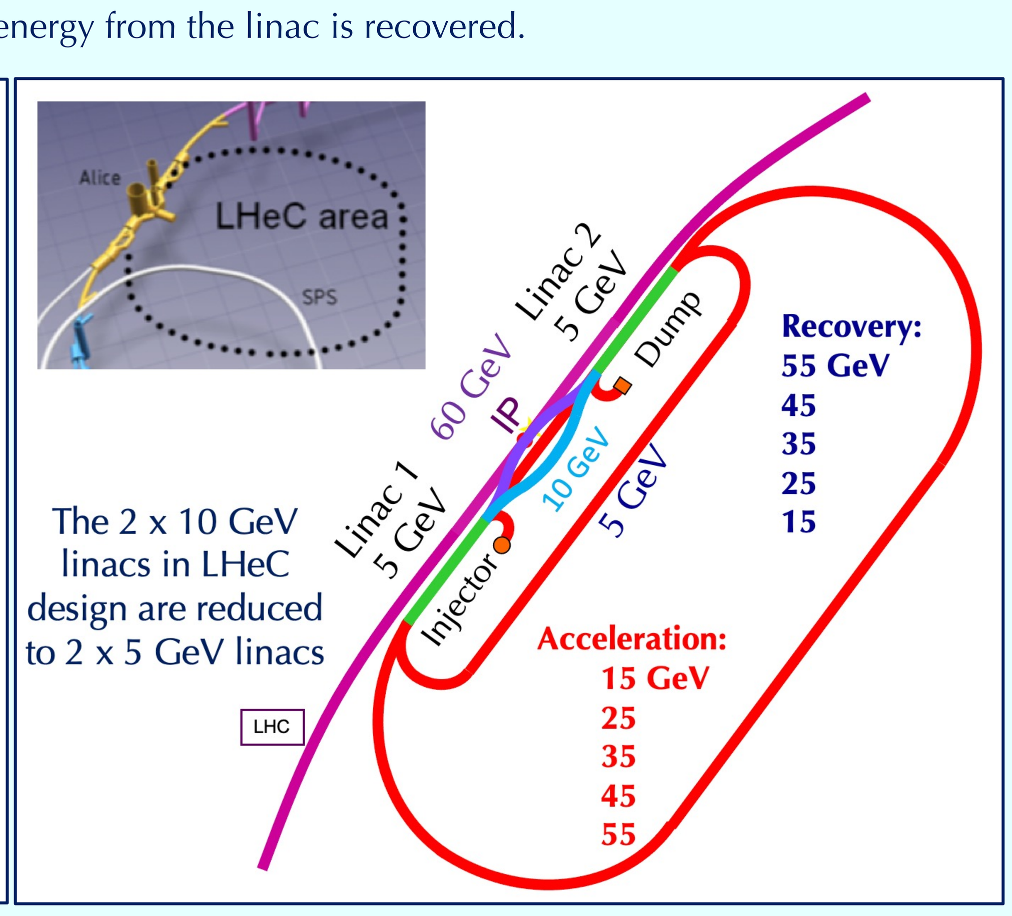

Figure 2: The LHeC two 10 GeV linacs are replaced with the two 5 GeV linacs placed on opposite side of the Interaction Collision region. The main Fixed Field combined function permanent magnet single loop is the same size as presented in the present design but there are 5 electron beam passes through it: 15, 25, 35, 45, and 55 GeV. After the beam passes through the 5 GeV linac it gains energy reaching 60 GeV and collides with ions. After the single collision, the beam return the energy to the linacs and reaches the initial energy.

The 1160 electron bunches fill the available 1200 buckets with 40 empty buckets for the abort gap. A distance between the electron bunches in RHIC is equal to the Δs_{BUNCH} = 3833.8450/1200 m = 3.19486 m or 10.6569 ns. The length of the RF cycle is 761.2146 ps. The 1.5 GeV superconducting linac accelerates and decelerates electrons 12 times: three times after they arrive from the injection racetrack gaining the energy from 1.50 GeV up to 4.50 MeV and additional 9 passes where electrons gain energy in a range between 6 to 18 GeV in the RHIC ring.

This design allows all conditions set by the present CD0-CD1 EIC at RHIC design to be fulfilled. The present CD0 or CD1 assumes that the total electron current is **2.5 A**, with **1160 bunches,** the electron current is **2.155 mA** per bunch with a total charge of **27.55 nC** per bunch. The previous ERL design was based on the polarized electron gun providing an electron current of **50 mA** with **5.3 nC per bunch or 26 mA** assuming **the single collisions between electrons and protons/ions with 112 bunches**. If this kind of polarized electron gun is available, it could still be used it this design.

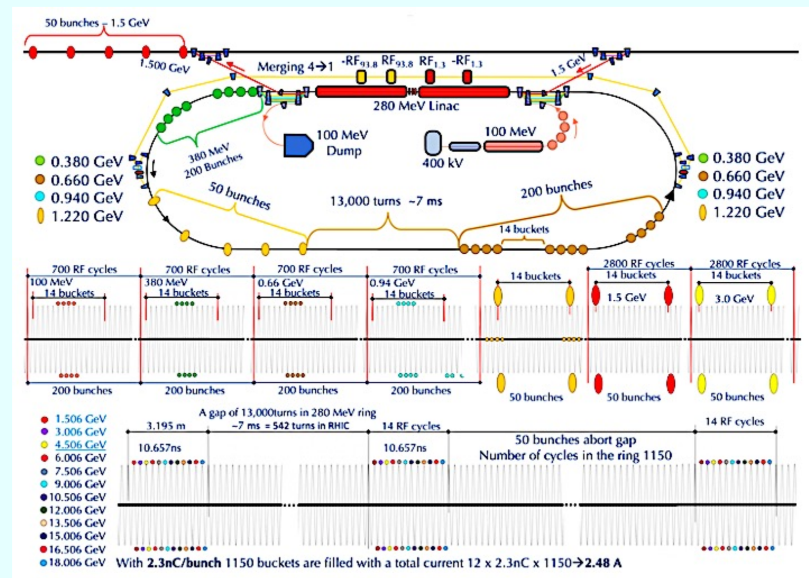

Figure 3: The 280 MeV superconducting 1.3137 GHz linac 127.795 m racetrack FFA-LG single return beam line. When the beam reaches 1.220 GeV energy at the outside orbit the beam is extracted in the middle of the arc bypassing the linac. It goes sequentially through the three RF cavities with ¼ RF frequency 328.423 MHz and ½RF frequencies of 656.845 MHz and the main frequency cavity with 1.31369 GHz. After 13,000 turns four bunches merge into the two bunches first and then into a single bunch ramping up and lowering down voltages in cavities with half frequency ½ RF and with quarter ¼ frequency as shown later in Fig. 4.

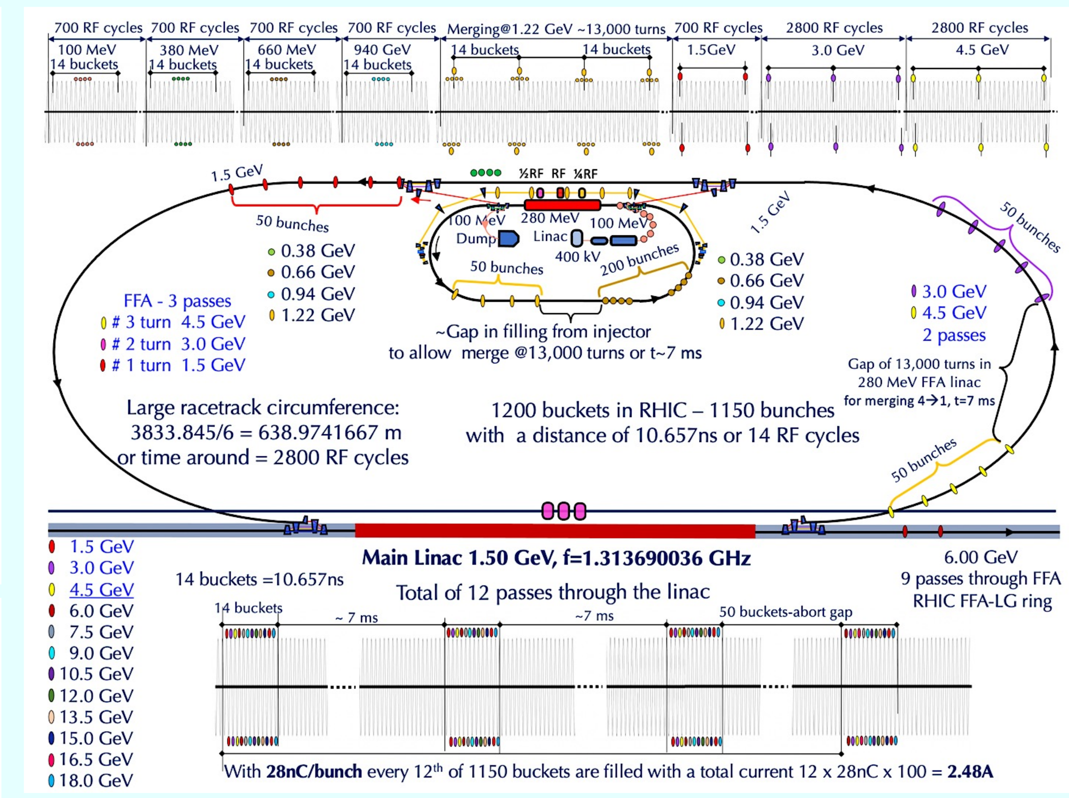

Figure 4: Large Racetrack with the energy range of 1.5 – 4.5 GeV. The Main 1.3137 GHz superconducting linac is ~160 m long and has a total of 12 passes of the electron beam through.

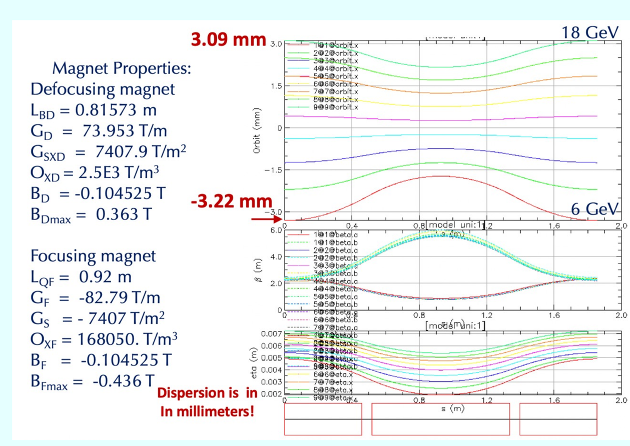

Figure 5: The Main FFA-LG arc cell properties with maximum orbit offsets -3.09 mm < x_{MAX} < 3.22 mm with combined function permanent magnets.

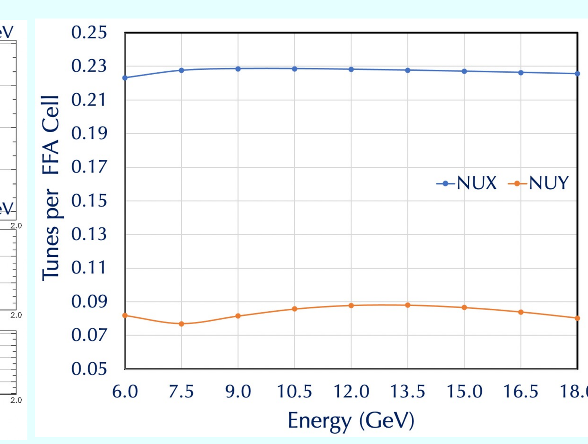

Figure 6: Tune dependence on momentum on energy for the energy range between 6 and 18 GeV.

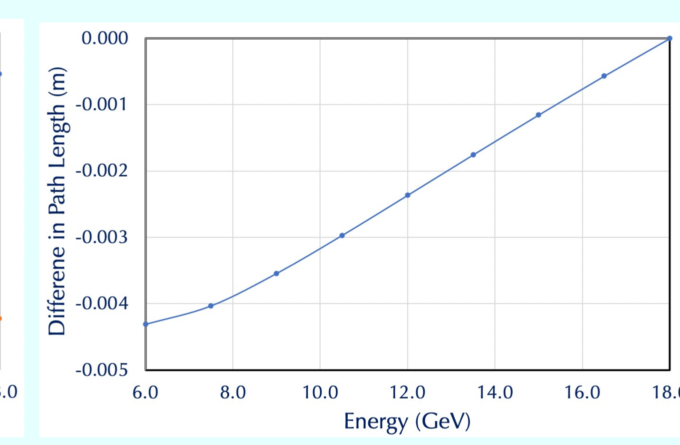

Figure 7: A difference in the path length for on the one FFA arc in the large ring for the EIC in RHIC tunnel for the lattice with sextupoles and octupole.

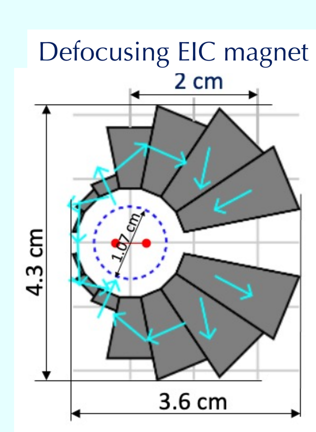

Figure 7: Good field @R_{BD}=5.33 mm maximum orbit offsets @ B_D: 2.28mm < Δx_{OFFSET} < 2.52 mm maximum field B_{DMAX}=– 0.363 T

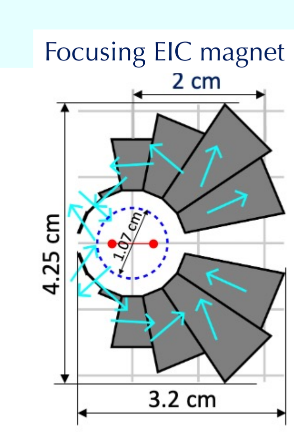

Figure 8: Good field @R_{BF} =5.33 mm Maximum orbit offsets @ Q_F: -3.22 mm< Δx_{MAX}< 3.09 mm, maximum field of B_{FMAX}=–0.436 T

For EIC@RHIC, the defocusing magnet properties are: L_{BD}=0.816 m, G_D=73.95 T/m, B_D=-0.104525 T, S_{XD} = 9401.4 T/m^2, O_{XD}= 2.510^4 T/m^3 , R_{BD}=357.419 m; while for the focusing magnet, they are: L_{QF}=0.92 m, G_{QF}=-82.79 T/m, B_F=-0.104525 T, S_{XF}= -7407.9 T/m^2, O_{XF}=1.68∗10^5 T/m^3, R_{QF}=357.419 m, R_{QF} = 357.419 m

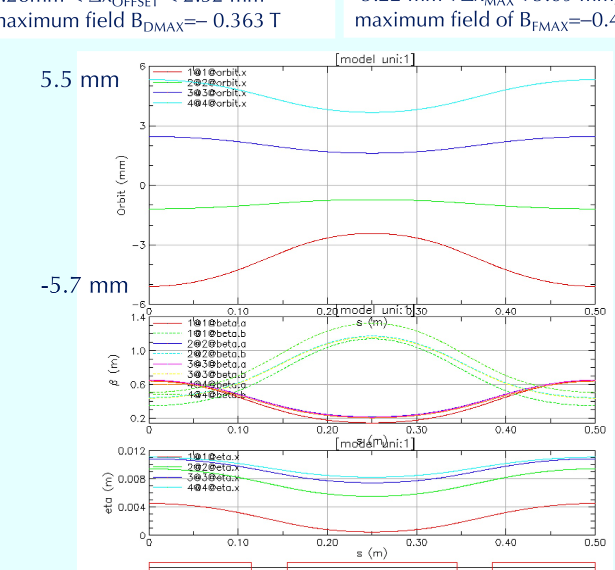

Figure 9: Lattice functions and orbits in the single arc cell of the small 159m racetrack with the permanent combined function magnet properties. Maximum orbit offsets in Q_F: -5.7 mm<Δx_{MAX}<5.5 mm or in Q_D: -3.7 mm<Δx_{MAX}<4.4 mm

Properties of the Small Racetrack 159 m circumference

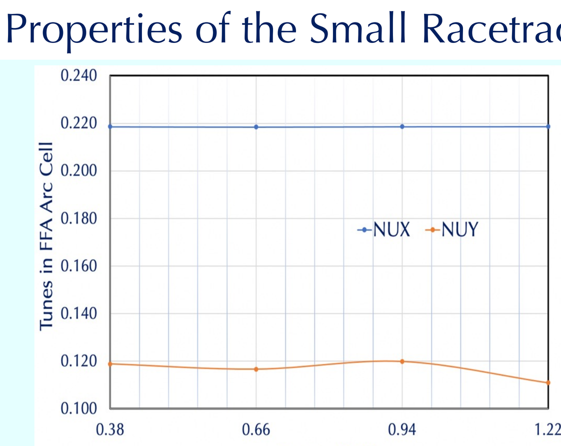

Figure 10: Tune dependence on energy in the FFA small racetrack arc within the energy range between 0.38<ΔE<1.22 GeV.

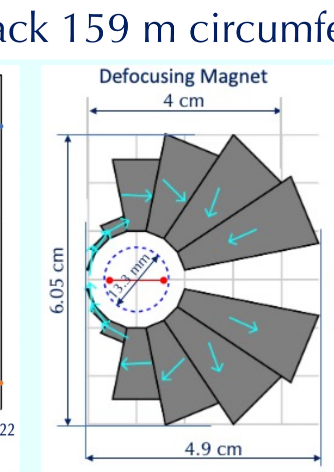

Figure 11: B_D: L_{BD}=0.170 m, B_D= -0.166 T, R_D=14.9733 m, G_D=75.71 T/m, $Sextp_D$=5.84 *10^3 T/m^2, $Octp_D$ = 2.9x10^4 T/m^3 B_{Dmax}=-0.527 T, good field @ R=6.6667 mm

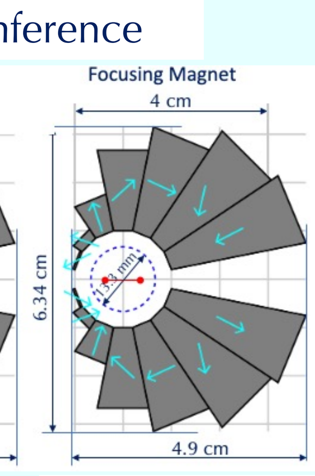

Figure 12: Q_F: L_{BF}=0.250 m, B_F=–0.166 T, R_F=14.973 m, G_F= –75.43 T/m, $Sextp_F$ = –3968.0 T/m^2, $Octp_F$=5.8x10^4 T/m^3 B_{Fmax}=–0.703 T, good field region at R=6.6667 mm

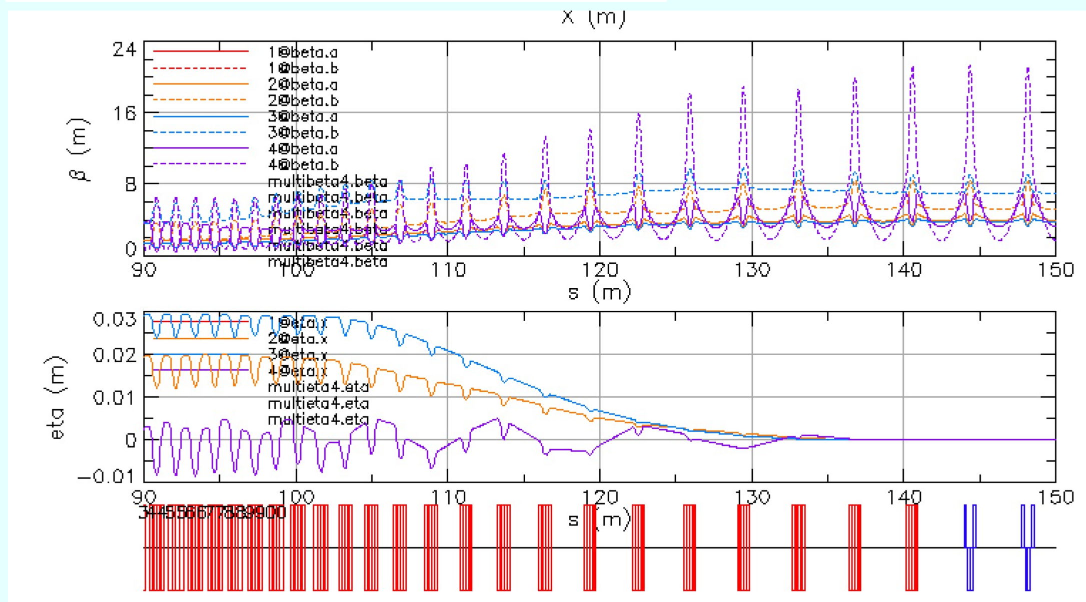

Figure 13: Adiabatic matching between the FFA arc to the linac.

Lattice Functions the LHeC Racetrack

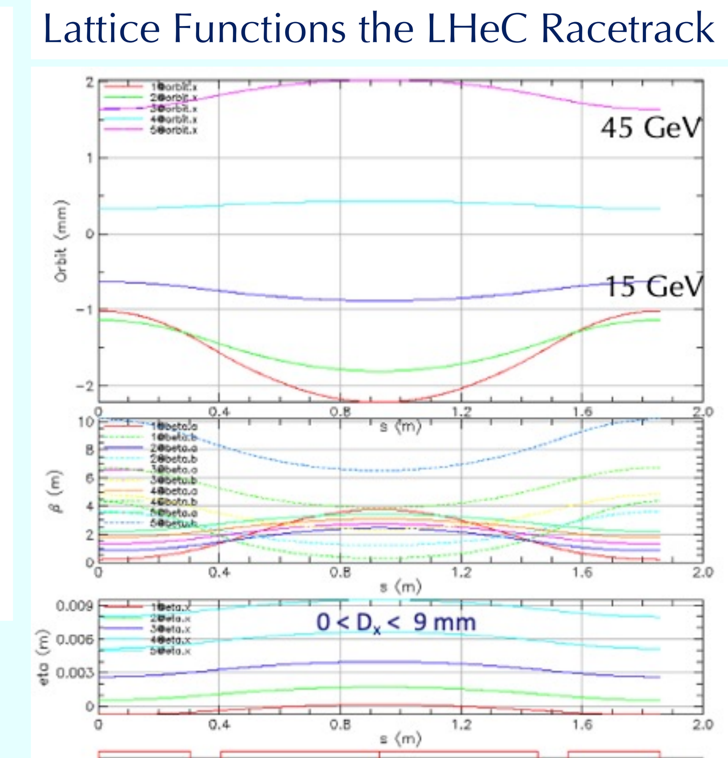

Figure 13: Betatron functions in the LHeC large FFA ring in energy range 15-45 GeV

Summary: We presented a new 'green energy' approach to the Energy Recovery Linac (ERL) and Recirculating Linac Accelerators (RLA) for the future Electron Ion Colliders (EIC) using single beam line made of very strong focusing combined function permanent magnets and the Fixed Field Alternating Linear Gradient (FFA-LG) principle. We are basing our design on recent very successful commissioning results of the Cornell University and Brookhaven National Laboratory ERL Test Accelerator. The new combined function permanent magnets have additional sextupole and octupole multipoles and this is the first time that the very small aperture non-scaling Fixed Field Alternating Gradient can transport very large energy range with the fixed horizontal and vertical tunes.