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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.

INTRODUCTION

Two new Electron Ion Colliders proposals (EIC) at Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL) and for the LHeC at CERN are based on the very successful commissioning of the 'CBETA'- **C**ornell University **B**NL **E**nergy Recovery Linac **T**est **A**ccelerator [1-5]. The schematic of the two designs is shown in Fig. 1 and 2.

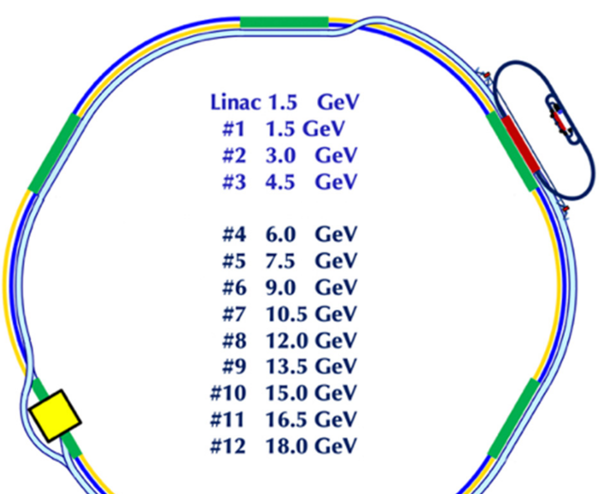

Figure 1: Layout of the large Fixed Field Alternating Linear Gradient accelerator with the 1.5 GeV superconducting linac. The beam is accelerated from 6 to 18 GeV with a total of 12 passes through the linac where the first three are using the racetrack with $C_{RHIC}/6$ length.

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. The main element of the new design in RHIC has 1.5 GeV superconducting linac while in LHeC two 10 GeV linacs are replaced with two 5 GeV linacs. The 1.5 GeV linac has the RF frequency of 1.31369 GHz, as the Cornell University Linac, making the 14th harmonic of the future RHIC bunch frequency of 93.835 MHz's.

The 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.

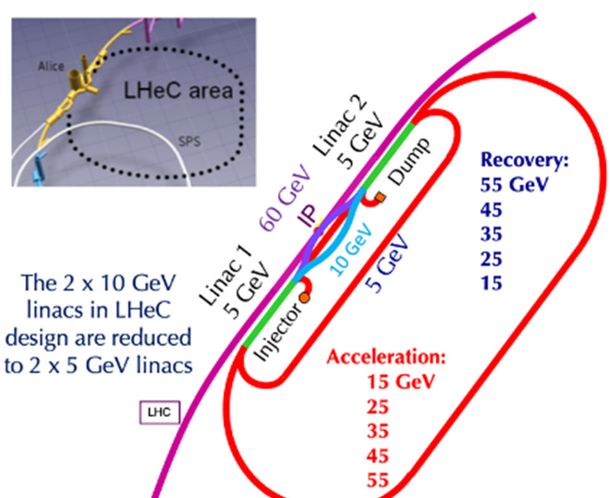

Figure 2: The LHeC two 10 GeV linacs are replaced with the two 5 GeV linacs placed on opposite side of the Interaction Collision region.

The proposal assumes the same interaction regions as in the present (IR) design, the same bunch frequencies, and abort gap during the collisions, uses the crab cavities in the IRs with the same geometrical conditions during the collisions with the same β_x^* and β_y^* using the electron bunch replenishments method (although in a much shorter time scale). It follows the RHIC ion beam upgrade, electron, and ion vacuum pipe designs, and so on. Properties of the ERL-RLA proposal are:

1. It 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 cavities in the linac.

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2. It is a low risk ERL-RLA design as it is based on already used superconducting linac technology and a single permanent magnet beam line during the CBETA very successful commissioning. It provides a straight path to very high luminosities of ~ 10^{34} cm^{-2}s^{-1}. Electron beam starts from the polarized electron source with 400 kV D.C gun. The 7.5 nC charge per bunch had been already produced by the polarized electron ion source.

3. The single FFA-LG Energy Recovery or Recirculating Linear Accelerator ERL is used at the same time as a storage ring. Electron bunches with required collision energy are stored for a short time of the order of ~21 ms at the corrected chromaticity. The electron energies for the collision with ion are selected by radial positions of the extraction magnets of the of stored electron beam. Sextupole and octupole multipole components are added in the combined functions permanent magnet designs, shown in Fig. 3, allowing the chromaticity to be corrected for the whole energy range between 6 and 18 GeV, as shown in the tune dependence on energy in Fig. 4.

4. 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.

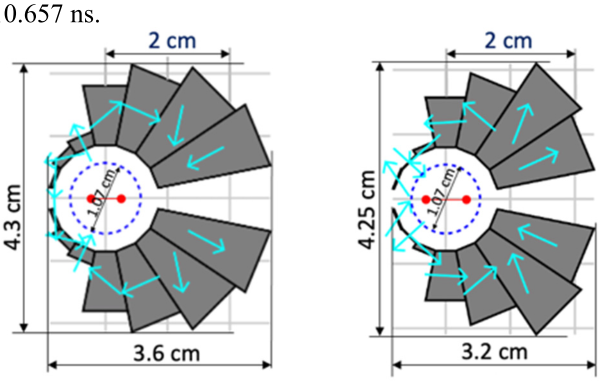

Figure 3: RHIC EIC defocusing (left): L_{BD}=0.816 m, G_D=73.95 T/m, B_D=-0.104525 T, S_{XD} = 9401.4 T/m^2, O_{XD}= 2.510^4 T/m^3, R_{BD}=357.419 m and focusing (right) permanent magnets: L_{QF}=0.92 m, G_{QF}=-82.79T/m, B_F=-0.104525 T, S_{XF}= -7407.9 T/m^2, O_{XF}=1.68*10^5 T/m^3, R_{QF}=357.419 m, R_{QF} = 357.419 m.

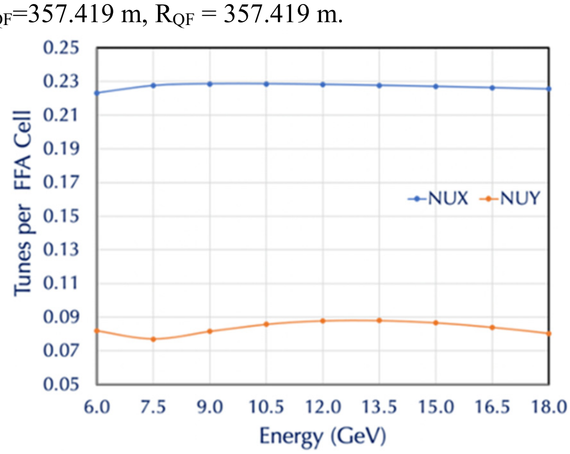

Figure 4: Tune dependence on energy in the large FFA ring and the time-of-flight difference in one arc.

The electrons are stored in the selected orbit as the fast kickers make them bypass 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 50 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 of 1150 circulating 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. 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 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 beam-beam effect is reduced as the electron ion collisions do not repeat after 1624 turns. The electron energy at the dump is 100 MeV and the energy from the linac is recovered.

The lattice functions in the large electron FFA-LG ring in the RHIC EIC are shown in Fig. 5.

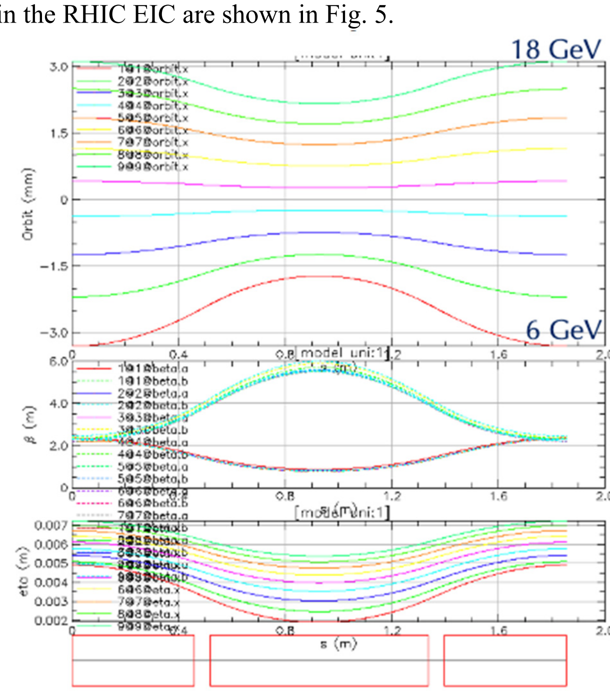

Figure 5: Lattice functions in the large RHIC ring.

FFA-LG INJECTOR RACETRAC

The 280 MeV superconducting 1.3137 GHz linac is placed in one of two straight sections. Injector linac starting with the 400 kV electron D.C. gun provides electrons with 100 MeV energy. When the beam reaches 1.220 GeV energy at the outside orbit the beam is extracted in the middle of the racetrack arc bypassing the linac. After

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13,000 turns four bunches merge into the two bunches first and then into a single bunch.

Lattice Functions in the Small Racetrack

The 100 MeV electrons arrive from the injector like the CBETA injector starting with the 400 kV D.C. gun. The racetrack circumference is $C_{SMALL}=C_{RHIC}/24=159.7435$ m. A time for 1.22 GeV electrons ($\gamma_{REL}=2387.48$) to travel around the small racetrack is equal to $\tau_{SMALL}=532.847$ ns. The harmonic number is equal to $h=700$, as there are 700 available buckets of linac RF frequency of $f_{MAIN}=1.31369$ GHz around the C_{SMALL} circumference. The combined function permanent magnet designs for the injector racetrack, are shown in Fig. 6, allow the chromaticies to be corrected for the whole energy range between 380 MeV and 1.22 GeV, as shown in the tune dependence on energy in Fig. 7. Electrons are extracted from the polarized electron source using laser filling pattern with four buckets in the middle of the 14 sequential buckets. Fourteen buckets of the main frequency f_{MAIN} make a distance of: $\Delta\tau_{RHIC}=10.657$ ns between the colliding bunches in the RHIC. With this filling pattern 200 bunches will circulate around the racetrack from the 700 available buckets.

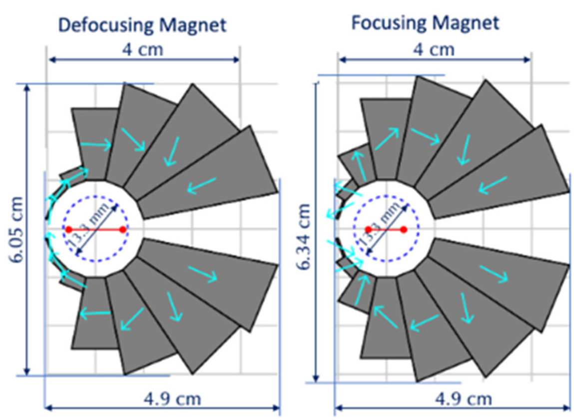

Figure 6: Defocusing and focusing permanent combined function magnet for the small injector racetrack with the good field region @ R=6.67 mm

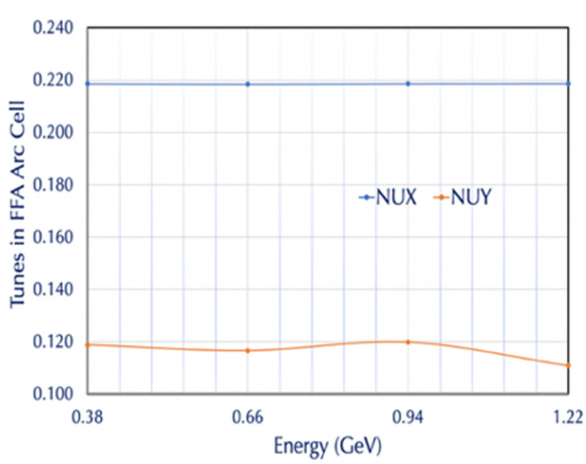

Figure 7: Tune dependence on energy in the small FFA-LG racetrack for the range of 380 MeV < ΔE < 1.22 GeV.

A time gap equal to do the required merging of (4 to1) four-to-one bunches is added to the filling pattern. A time to merge 4 to 1 bunch into is Δτ=13000*532.847, ns = 6.927ms. A distance between bunches of the four buckets is equal to the RF cycle or τ_{RF} = 761.21 ps. The FFA-LG permanent magnet racetrack accelerates 100 MeV electrons with the 280 MeV linac. After the first pass through the linac electrons reach energy of 380 MeV, the second 660 MeV, the third 940 MeV and after the fourth pass they reach the energy of 1.220 GeV. The lattice is designed allows energy range of 3.947. The merging of the 4 bunches into a single bunch in the small racetrack is done using the fast RF kicker [6] (method developed in Jefferson Lab) in the FFA arc upstream of it making it as a storage ring.

LARGE RACETRACK AND RHIC RING

The timeline and the number of bunches during acceleration and merging is sketched in Fig. 8. The RF kicker is a part of the chicane, and it is placed in the middle of the arc in the small racetrack as in the large RHIC-EIC ring to allow beam merging in the small racetrack and beam starage in the large one. The RF kicker is a part of the chicane, and it is placed in the middle. The Large FFA racetrack is shown in Fig. 8.

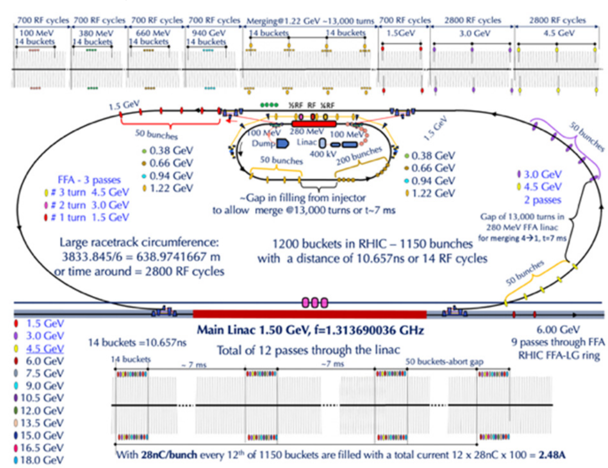

Figure 8: Large Racetrack with the energy range of 1.5 – 4.5 GeV.

SUMMARY

Major novelties in the 'green electron ion collider' is use of ERL combined with the single beam line made of permanent combined function magnets. The lattice is adiabatically matched between the FFA gradient arcs to the linac. The betatron tunes are fixed for the energy range 6-18 GeV in RHIC-EIC or in 15-45 GeV range in LHeC. There are 12 (RHIC) or 5 (LHeC) accelerating passes through the superconducting linac with the same number for energy recovery. The permanent magnets have open gaps for synchrotron radiation, and they are of miniscule sizes. The FFA arcs are used in a storage ring mode in both: the small racetrack to allow merge 4 to 1 and in the large RHIC ring, respectively. In the RHIC ring the electrons are stored but ten electron bunches are replenished every 7 ms.

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REFERENCES

[1] Adam Bartnik *et al.*, "First Multipass Superconducting Linear Accelerator with Energy Recovery," *Phys. Rev. Lett.*, vol. 125, p. 044803, Jul. 2020. doi:10.1103/PhysRevLett.125.044803

[2] Colwyn Gulliford *et al.*, "Measurement of the per cavity energy recovery efficiency in the single turn Cornell-Brookhaven ERL Test Accelerator configuration," *Phys. Rev. Accel. Beams*, vol. 4, p. 010101, Jan. 2021. doi:10.1103/PhysRevAccelBeams.24.010101

[3] Stephen Brooks *et al.*, "Permanent magnets for the return loop of the Cornell-Brookhaven energy recovery linac test accelerator," *Phys. Rev. Accel. Beams*, vol. 23, p. 112401, Nov. 2020. doi:10.1103/PhysRevAccelBeams.23.112401

[4] D. Trbojevic, R. Michnoff, *et al.,* "CBETA Project Report," *CLASSE*, Brookhaven National Laboratory (BNL), Upton, New York, March 2020, NYSERDA contract No. 102192. https://wiki.classe.cornell.edu/pub/CBETA/WebHome/CBETA_final_report_revB-V3f.pdf?_t=1585859643

[5] D. Trbojevic *et al.*, "Multi Pass Energy Recovery Linac Design With a Single Fixed Field Magnet Return Line", in *Proc. 13th International Computational Accelerator Physics Conference (ICAP'18)*, Key West, Florida, USA, Oct. 2018, pp. 191-195. doi:10.18429/JACoW-ICAP2018-TUPAF09

[6] K. E. Dietrick *et al.*, "Novel "Straight Merger for Energy Recovery Linacs," in *Proc. 29th Linear Accelerator Conf. (LINAC'18)*, Beijing, China, Sep. 2018, pp. 702-705. doi:10.18429/JACoW-LINAC2018-THPO010