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ELECTRON ACCELERATOR LATTICE DESIGN FOR LHeC WITH PERMANENT MAGNETS*

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Abstract

We present a new 'green energy' approach to the 60 GeV electron Energy Recovery Linac (ERL) of LHeC using a single beam line made of combined function permanent magnets, using a Fixed Field Accelerator (FFA) design with very strong linear gradients. We are basing our design on recent successful commissioning results of the Cornell University and Brookhaven National Laboratory ERL Test Accelerator "CBETA" in 2019-20 [1-6].

INTRODUCTION

- Future Electron Ion Colliders (EICs) could be 'green energy colliders' as Energy Recovery Superconducting Linacs (ERLs) can be used to make energy fully recovered.
- Electron beam is brought back to the linac by a single permanent magnet beam line without requiring electric power, reducing the estimated wall power of 100 MW in the present LHeC design to a negligible power for arcs.
- The single beam line transports all electron energies at once using the Fixed Field Alternating Gradient (FFA) principle with very strong focusing.
- The design is based on experience from the successful commissioning of the **C**ornell University and **B**rookhaven National Laboratory **E**nergy Recovery **T**est **A**ccelerator – '**CBETA**'.
- The green EIC of the CERN Large Hadron Collider - LHeC is presented, as well as an alternative design for the PERLE ERL.
- The FFA non-linear gradient design is a racetrack shape, where, as in CBETA, the arcs are matched by an adiabatic transition to the two straight sections. • Two 8.57 GeV superconducting linacs, replaced the 10 GeV linacs in the previous design, are placed on both sides of the Interaction Region (IR) to reduce the power of synchrotron radiation loss significantly.

PREVIOUS CBETA EXPERIENCE

The Energy Recovery Linac CBETA built with a single permanent magnet beam line was successfully commissioned in 2019-2020 showing a perfect transport of electrons passing 4 times in acceleration and three with energy recovery with an energy range between 42 to 150 MeV. One of the major new achievements during the commissioning was full energy recovery and proof of principle for the FFA large momentum transport and arc to straight adiabatic orbit merging achieved for the first time in the history of fixed field accelerators. The same principle is proposed for the LHeC lattice. We are basing our confidence in this proposal on the previous FFA experimental confirmation and on the well-established new permanent magnet technology in CBETA.

PRESENT AND PROPOSED LHEC

The LHeC design assumed two superconducting linear accelerators, each being capable of an acceleration of 10 GeV, and three accelerating and three decelerating passages through both linacs for the electron beam with a racetrack layout with a maximum electron beam energy of 60 GeV. This proposal replaces the three arcs for accelerating and decelerating electron passes, with a single line FFA arc. The two 10 GeV linacs are replaced with two 51.72 GeV linacs but at the same side of the racetrack with interaction region. This reduces the synchrotron radiation loss in the arcs as the maximum electron energy in the arcs is reduced from 60 GeV to 51.72 GeV. The 60 GeV beam is brought into collision with one of the LHC hadron beams. The racetrack shaped electron accelerator can therefore lie tangentially to the existing LHC machine as shown in Fig. 1 [7].

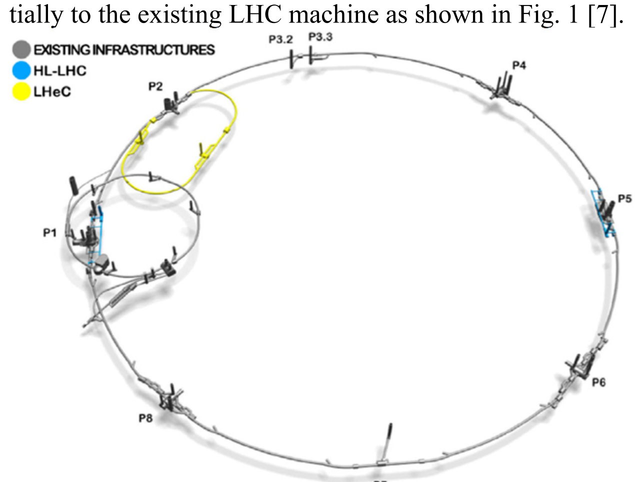

Figure 1: Proposed layout of the LHeC at CERN [7].

The initial goal of the LHeC assumes a total wall plug power consumption of 100 MW for the electron beam. This proposal significantly reduces the wall plug power using the permanent magnets reducing the total installation cost as the three arcs are replaced with one. The updated LHeC design has a peak current from the source of 20 mA and total currents within the SRF cavities of more than 120 mA with accelerating 3 × 20 mA and decelerating 3 × 20 mA. A comparison between the previous LHeC design and this proposal is shown in Figs. 2 and 3.

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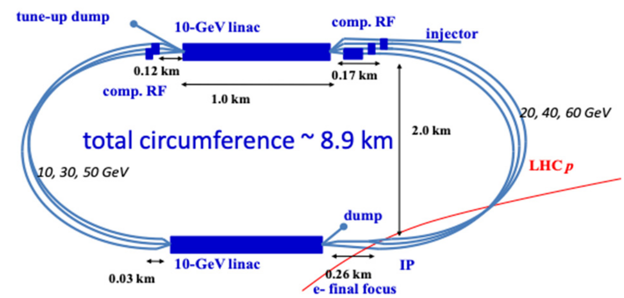

Figure 2: Present LHeC design layout.

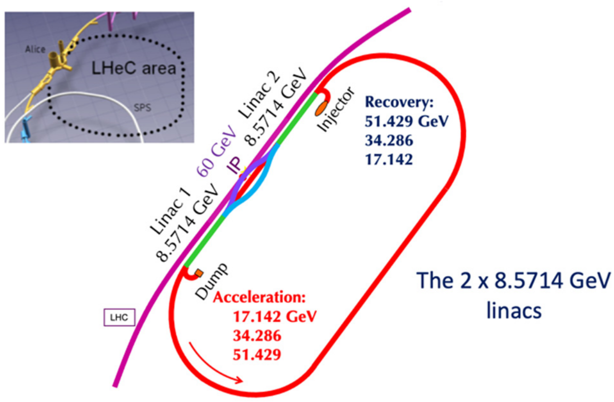

Figure 3: The FFA's LHeC proposal layout.

The electron beam is brought from injector to the first 8.57 GeV linac upstream of the IR and continues from the first pass to the second 8.57 GeV linac getting to the FFA transition from the straight to the arc with energy of 17.143 GeV. At the same place after the second pass the electron beam energy is 34.286 GeV and after the third pass 51.429 GeV.

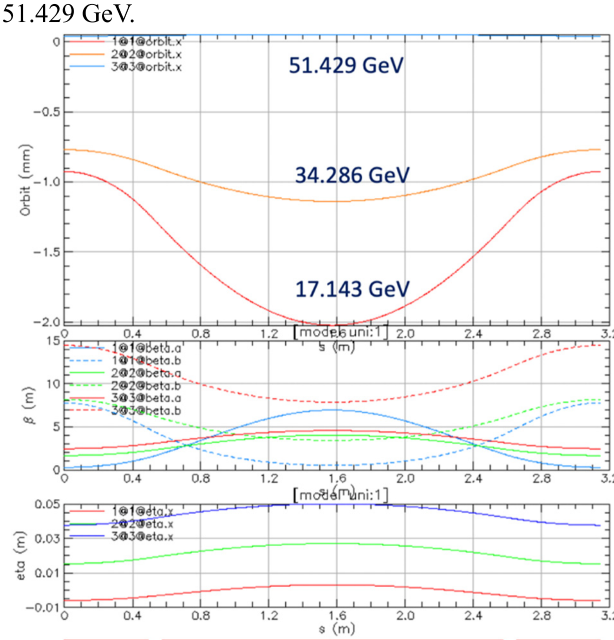

Figure 4: The FFA Arc Lattice Design.

The electron beam from the second arc passes the first linac exiting with 60 GeV energy and it is extracted towards IR for the collisions with the proton beam. The lattice design of the FFA arc for transferring three energies 17.14 GeV, 34. 29 GeV, and 51.43 GeV is shown in Fig. 4. The combined function FFA arc permanent magnets have open gaps on both sides of the horizontal aperture, as shown in Fig. 5, allowing synchrotron radiation to be adsorbed outside.

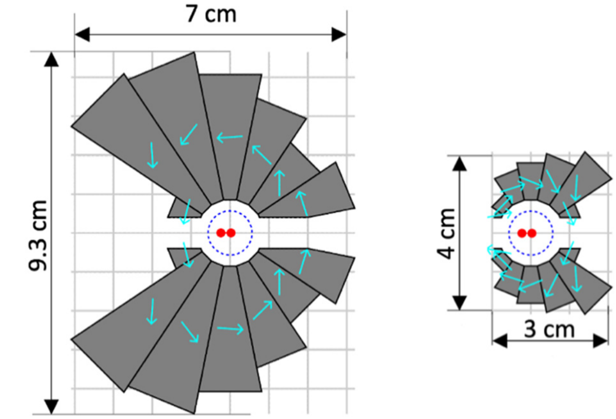

Figure 5: Defocusing (left) and focusing (right) combined function magnet for the FFA LHeC arc with beams in the middle.

Table 1: Magnet Properties

Parameter	Defocusing magnet	Focusing magnet
L (m)	0.696	2
G (T/m)	106.6	-61.92
B (T)	-0.163	-0.163
B_{max}(T)	-0.532	0.272
Area(cm^2)	34.8	5.89

Lattice Optimization Towards Reduction of the Synchrotron Radiation Loss

The synchrotron radiation power loss in the electron storage or acceleration rings occurs when electrons are bent in the magnets:

$$P_o = \frac{ec}{6\pi\varepsilon_0} \cdot \gamma^4 \, N_{cell} I_B \left(\frac{L_{QF}}{R_{QF}^2} + \frac{L_{BD}}{R_{BD}^2}\right) \quad (1)$$

Where *'e'* is the elementary charge, e_0 is the vacuum permittivity, γ is the relativistic factor, N_{cell} is the total number of cells in the arcs, L_{QF} and L_{BD} are the lengths of the focusing and defocusing combined function magnets, respectively, and the R_{QF} and R_{BD} are the bending radii in the magnets calculated from the average of the magnetic fields in the magnets as $R_{QF}=BRHO/\langle B_{QF}\rangle$, and I_B is the beam current $I_{B\text{-}QF} = ecN / L_{QF}$ or $I_{B\text{-}BD} = ecN/L_{BD}$. The optimum lattice properties to obtain the smaller synchrotron radiation overall power loss are shown in Table 2. The electron current in the LHeC previous design of 6.6 mA produced the limitation on the synchrotron radiation power loss of 15 MW.

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Table 2: Synchrotron Radiation Power Loss for 6.6 mA

Electron Energy (GeV)	R@QF	R@BD	Power loss in QF	Power loss in BD	Total Power loss
51.43	-682.1	-535.1	5.511	0.046	5.56
34.29	746.8	-277.8	0.059	2.32	2.38
17.14	447.4	-117.1	0.160	0.814	0.97
					8.92

As shown in the Table 2 the total synchrotron radiation power loss in the FFA design for the same current of 6.6 mA is less than 15 MW Po=8.92 MW mostly due to the reduction of the highest energy fin the arcs from 60 to 51.43 GeV. For the new LHeC limit of 20 mA with the maximum power lost due to synchrotron radiation loss of 45 MW is reduced by this FFA proposal to 27 MW! Gain in luminosity is 1.68.

PERLE Design with the FFA as in CBETA

The present design of the PERLE, a **P**owerful **E**nergy **R**ecovery **L**inac for **E**xperiments, emerged from the design of the Large Hadron Electron Collider as a 3-turn racetrack configuration with a linac in each straight as shown schematically in Fig. 6.

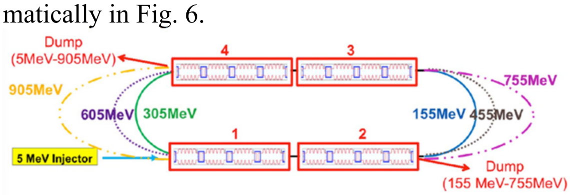

Figure 6: Schematic of the previous 'PERLE' design.

The CDR of the LHeC in 2012 assumed an electron current of 6.8 mA to reach the initial design luminosity of 10^{33} cm^{-2} s^{-1}. The default electron beam current of the LHeC is now 20 mA, and this value has now been adopted for PERLE. The multi-turn, high-current, small-emittance configuration, and the timeline of PERLE make it a central part of the European plans for the development of energy-recovery linacs.

A proposal for the FFA type like CBETA for PERLE is shown in Fig. 7.

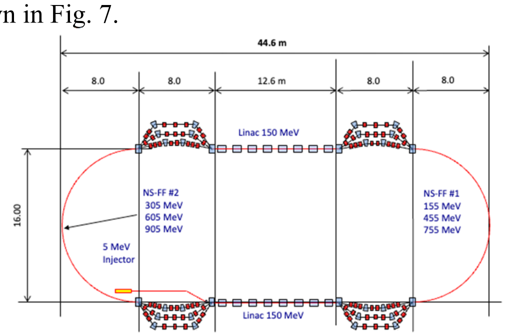

Figure 7: Schematic of the FFA PERLE design.

The left side covers energy ranges between 305 and 905 MeV with orbit offsets, betatron functions and the dispersion functions, is shown in Fig. 8, while the right-side arc covering the energy range between 155-755 MeV is shown in Fig. 9.

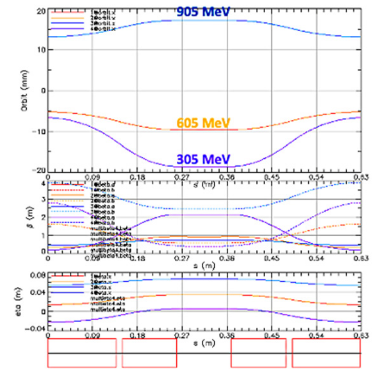

Figure 8: Orbit offsets, betatron functions and dispersion functions for electron energies of 305, 605, and 905 MeV.

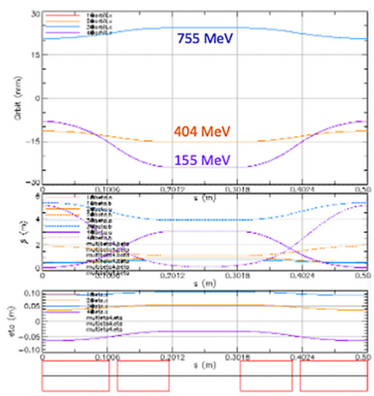

Figure 9: Orbit offsets, betatron functions and dispersion functions for electron energies of 155, 404, and 755 MeV.

New PERLE parameters for LHeC are shown in Table 3.

Table 3: New PERLE Beam Parameters [7]

Parameter	**unit**	**value**
Injection Energy	MeV	6
Electron Beam Energy	MeV	500
Average beam current	mA	20
RF frequency	MHz	801.58

CONCLUSIONS

Lattice solutions are proposed for the PERLE design with a single arc line and for LHeC. A new LHeC proposal replaces the 2 x 10 GeV linacs and three arcs, with 2 x 8.57 GeV linacs and one arc per side. This is a cost-effective solution as there are no magnet power, power supplies or cabling with a single arc to transport all three energies 14% less linac. It reduces the synchrotron radiation in arcs to 8.9MW instead of 15MW for 6.6 mA current, hence provides 1.68 times larger luminosity for the same limit on the total power loss from synchrotron radiation. At 45 MW limit, instead of 20 mA the FFA solution can provide 33.6 mA.

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