ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPC68

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2024). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

SINGLE LINE ERL PERMANENT MAGNET FFA ACCELERATOR FOR LHeC*

D. Trbojevic†, S. Brooks, J.S. Berg, F. Méot, BNL, Upton, NY, USA
G. Hoffstaetter, Cornell University – CLASSE, Ithaca, New York, USA
A. Bogacz, JLAB, Newport News, Virginia, USA

Abstract

We present a Fixed-Field-Alternating (FFA) permanent magnet racetrack electron accelerator with energy range between 10-60 GeV for the future LHeC. Electron beam is brought back to the linac by the single beam line without requiring electric power reducing estimated wall power of 100 MW in the present LHeC design to a negligible power for arcs as the permanent magnets are used. The design is based on experience from the very successful commissioning of the Cornell University and Brookhaven National Laboratory Energy Recovery Test Accelerator – 'CBETA'. The proposal supports sustainability efforts for LHeC by making a 'green' accelerator. It is an energy recovery linac with 99.9% energy efficiency and reduces the power consumption by using small permanent magnets. The FFA non-linear gradient design is a racetrack shape, where, as in the CBETA, the arcs are matched by adiabatic transition to the two (LHeC) or multiple straight sections. Two 10 GeV superconducting linacs are placed on both sides of the Interaction Region (IR) significantly reducing the power of synchrotron radiation loss.

INTRODUCTION

Sustainability and saving in energy represent a major concern today. We are updating our previous work on the LHeC design using the Fixed Field Alternating Gradient (FFA's) concept as in the case of Energy Recovery Linacs (ERL) a change of the energy is too fast to use variable magnetic field magnets. Usually, separate multiple arcs are used to allow multiple passages through the linac with necessary adjustments of the time of flight and momentum dependence parameter M_{56}. We present the single FFA's permanent magnet beam line to allow multiple passes of accelerating and decelerating electron beams returning them back to the superconducting linac. The design is based on a successful commissioning of the Cornell University and Brookhaven National Laboratory Energy Recovery Test Accelerator – 'CBETA'[1-6]. We emphasize few advantages of this alternate design with respect to the existing LHeC design:

- The synchrotron radiation loss is reduced allowing 15% higher luminosity.
- This LHeC proposal significantly reduces the overall cost in the lengths of the linacs and in the power consumption as the previous three electrical magnet arcs are replaced with a single permanent magnet line.
- Very small dispersion function and two orders of magnitude smaller dispersion action ***H*** reduces significantly values of the Sands radiation integrals and emittance dilution.

Electron beam is brough back to the linac by a single beam line made of permanent magnets. The FFA linear gradient design is a racetrack shape, where, as in the CBETA, the arcs are matched by adiabatic transition to the two linacs with two straight sections. Two 8.5 GeV superconducting linacs are placed on both sides of the Interaction Region (IR) replacing the two 10 GeV linacs in the previous LHeC designs. This reduces the power of synchrotron radiation loss as the maximum electron energy in collisions to 50 GeV. In the recent updates of the LHeC and publications [7, 8] there are few possibilities considered for reducing the size and maximum energy of the LHeC from the previous 60 GeV to 50 GeV. There are other options [8] with maximum energies in the arcs before the loss of synchrotron radiation with energies of 54.2, 49.1 or 45.2 GeV with corresponding circumferences of 1/3, 1/4, 1/5 or 1/6 of the present LHC.

Accomplishments from the CBETA Project

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.

Options Considered for the LHeC

The LHeC design assumed previously two superconducting linear accelerators each producing energy gain of more than 10 GeV. Other options with smaller linac energy gains are considered [8] like 8.1 GeV per linac with three acceleration passes and three deceleration passes as shown in Fig. 1. The 50 GeV beam is brought into collision with one of the LHC hadron beams. It assumed electron beam intensity of 20 mA. The racetrack shaped electron accelerator can therefore lie tangentially to the existing LHC machine. Details of the considered options for LHeC are

*This manuscript has been authored by employees of Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy and for A. Bogacz work is supported by Jefferson Sciences Associates, LLC under contract No. DE-AC05-06OR23177.
†dejan@bnl.gov

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPC68

shown in reference [8]. We will compare our alternate FFA LHeC design with a single arc with the 50 GeV maximum collision energy LHeC option. There always will be synchrotron radiation loss to be compensated with separate RF system. Reducing LHeC energy from 60 to 50 GeV reduces the luminosity. The maximum electron collision energy in our proposal is 60 GeV keeping the value of original luminosity and assuming electron current of I_e=20 mA.

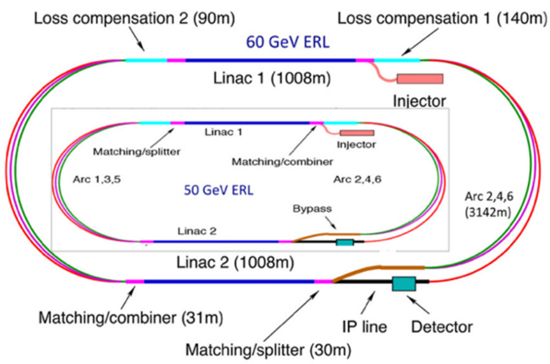

Figure 1: Proposed options of the LHeC at CERN [8].

The alternate single line FFA LHeC proposal is shown in Fig. 2.

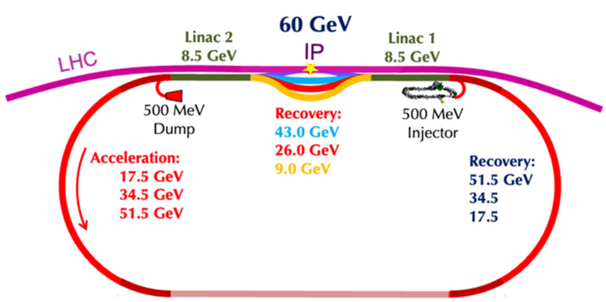

Figure 2: The FFA Arc Lattice Design.

A total power consumption for six arcs in the LHeC option with 8.1 MeV linac is **2.1 MW** [8]. The single FFA line proposal requires significantly lower electrical power due to permanent magnets. It requires only very small power for correction magnets. compared to Two 8.5 GeV linacs replace two 10 GeV or in the first option by 8.1 GeV linacs. The electron beam is brought from 500 MeV injector to the first 8.5 GeV linac (dark green color) upstream of the IR and continues from the first pass (beige) transfer line to the second 8.5 GeV linac (dark green) getting to the FFA transition (dark red) from the straight to the arc (red) with energy of 17.5 GeV. After the first adiabatic merging (dark red) reaches the straight section (light brown). From the straight section and second adiabatic transition (dark red) it reaches the second arc (red) and the fourth adiabatic merge (dark red) and it is matched to the linac for the second pass. The second pass through the arc has energy of 34.5 GeV while the third pass reaches energy of 51.5 GeV. After passing the third time the first linac the electron beam reaches the energy of 60 GeV. The 60 GeV beam is extracted by the separate beam line (purple) to collide with LHC beam. After the collision the beam reaches the second linac at the opposite phase and energy is recovered by 8.5 GeV leaving the linac with 51.5 GeV. This process continues until the energy is reduced to 500 MeV where the beam is brought to the dump. The lattice design of the single FFA arc is optimized to reduce the synchrotron radiation. The reference energy E_C of the FFA lattice has circular orbits within the combined function magnets.

Lattice Synchrotron Radiation Loss

The optimum value of the reference energy E_C to produce the lowest synchrotron radiation loss was found to be 42 GeV. The synchrotron radiation power loss in the electron storage or acceleration rings occurs when electrons are bent in the magnets:

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

The synchrotron radiation loss in the LHeC option with maximum energy 54.2 GeV is shown in Table 1.

Table 1: Synchrotron Radiation Loss in #1 CERN Option

Section	Beam Energy (GeV)	ΔE(MeV)
Arc one	8.62	3
Arc two	16.73	25
Arc three	24.85	80
Arc four	32.96	229
Arc five	41.08	383
Arc six	49.19	836
		1.556 GeV

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 combined function FFA arc permanent magnets have open gaps in the horizontal aperture allowing synchrotron radiation to be adsorbed outside.The optimum lattice properties to obtain the smaller synchrotron radiation overall power loss are shown in Table 2.

Table 2: Synchrotron Radiation Loss in FFA

Section	Beam Energy (GeV)	ΔE(MeV)
FFA #1	17.5	507.4
FFA#2	34.5	171.2
FFA#3	51.5	842.6
		1.521 GeV

For similar radiation power loss this proposal makes collisions at 60 GeV instead at 50 GeV.

Lattice Functions in the Single FFA Arcs

The orbits in the FFA cell are shown in Fig. 3. While the orbits, betatron and dispersion functions are shown in Fig. 4. As shown in the orbit display the maximum orbit offsets within the combined function magnet apertures are

© Content from this work may be used under the terms of the CC BY 4.0 licence (© 2024). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

15th International Particle Accelerator Conference,Nashville, TN JACoW Publishing
ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPC68

© Content from this work may be used under the terms of the CC BY 4.0 licence (© 2024). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

x_{max}<1.5 mm and x_{min}< -5.25 mm. This significantly reduces the combined function magnets' size. The FFA's properties are very strong focusing reflected in small values of betatron functions and producing very small dispersion function as shown in Fig. 4. The small dispersion function reduces the value of the dispersion action <***H***> significantly reducing the Sands' radiation integrals. This reduces the emittance growth during acceleration.

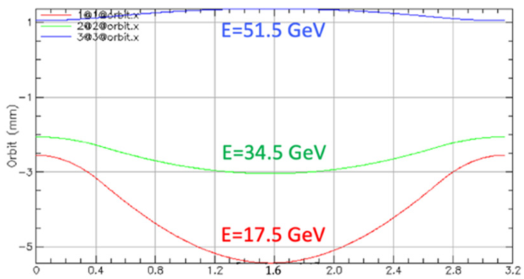

Figure 3: Electron beam orbits in the FFA cell.

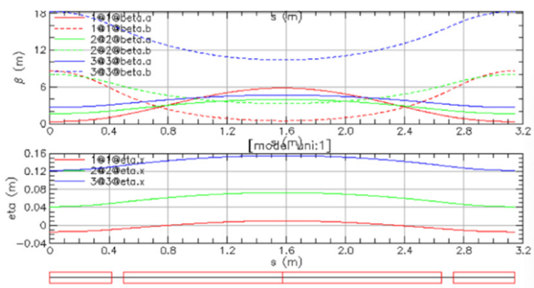

Figure 4: Betatron functions (upper part) and dispersion function dependence on energy in a single FFA cell.

Time of Flight and M₅₆ Dependence on Energy

The path length difference with respect to the reference energy E_C, momentum compaction α_C, and values of momentum dependence on time M_{56} in the FFA arcs are shown in Fig. 5 and in the Table 3.

Table 3: Path Length, M_{56}, γ_t and α_c Dependence on Energy

E (GeV)	Δs(mm)	M_{56}(cm)	γ_t	α_C
17.5	-12.67	-6.27	631.3	-9.9e-6
34.5	-14.92	3.68	413.4	5.85e-6
51.5	7.93	8.38	273.8	1.33e-5

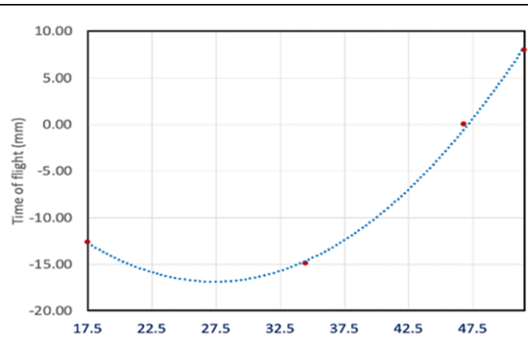

Figure 5: Time of flight dependence on energy

Reduction of the Emittance Dilution

Advantages of the alternate FFA solution comes from the small dispersion function, as shown in Fig. 5, and of small average curly <***H***> function reducing the Sands radiation integrals. A comparison of the two averaged <***H***> function values in the present LHeC 50 GeV design, one with a value of 3.62x10^{-3} for isochronous solution, or the other with TME mode [8] with of 5.9x10^{-4} with a value of the FFA design solution of 5.3x10^{-5} shows the clear FFA design advantage. The <***H***> function values for energy of 51.5GeV is <***H***>=4.69x10^{-5}, for 34.5 GeV <***H***>=2.506x10^{-5} and for 17.5 GeV <***H***>=5.235x10^{-5}. The Sands radiation integrals are shown in Table 4.

Table 4: Sands' Radiation Integrals from FFA Passes

E	I1	I2	I3	I4	I5X	JX
51.5	0.07	0.006	0.52e^{-5}	0.011	2.1e^{-10}	-0.98
34.5	0.10	0.01	0.17e^{-4}	0.025	6.9e^{-10}	-1.09
17.5	0.20	0.05	0.11e^{-3}	0.115	5.8e^{-9}	-1.44

Permanent Magnet Design

We already have developed combined function magnets with open aperture to allow for synchrotron radiation escape tangentially outside [9]. The FFA magnets for the alternate FFA LHeC design are shown in Fig. 6.

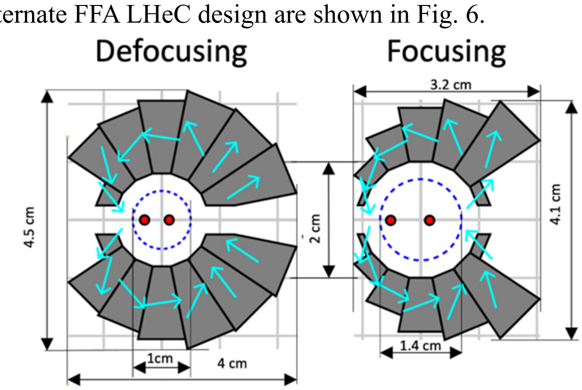

Figure 6: Defocusing and focusing combined function permanent magnets for the LHeC FFA solution.

CONCLUSIONS

Lattice solutions for a permanent magnet single FFA arcs for LHeC are presented. A new LHeC proposal with the two 8.1GeV linacs, with reduced LHeC energy of 50 GeV, and with three separate arcs is replaced with 2 x 8.5 GeV linacs placed at the opposite sides of the Interaction Point (IP). There are multiple advantages of the alternate proposal: it is a cost-effective solution as three beam lines are replaced with a single line, the energy saving is significant as the permanent magnets are used, the synchrotron radiation in arcs. The comparisons between 50 GeV LHeC option to our alternate proposal with maximum energy of 60 GeV with the same electron current of 20 mA and the similar synchrotron radiation loss of 1.556 MW for the option with 50 GeV compared to 1.521 MW for the FFA solution shows clear advantage with higher luminosity.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPC68

REFERENCES

[1] A. Bartnik *et al.*, "CBETA: First Multipass Superconducting Linear Accelerator with Energy Recovery," *Phys. Rev. Lett.*, vol. 125, no. 4, Jul. 2020. doi:10.1103/physrevlett.125.044803

[2] C. 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. 24, no. 1, Jan. 2021. doi:10.1103/physrevaccelbeams.24.010101

[3] S. Brooks, G. Mahler, J. Cintorino, J. Tuozzolo, and R. Michnoff, "Permanent magnets for the return loop of the Cornell-Brookhaven energy recovery linac test accelerator," *Phys. Rev. Accel. Beams*, vol. 23, no. 11, Nov. 2020. doi:10.1103/physrevaccelbeams.23.112401

[4] D. Trbojevic, R. Michnoff, G. Hoffstaetter *et al.,* "CBETA Project Report," CLASSE, Ithaca, New York, NYSERDA contract No. 102192, March 2020.

[5] D. Trbojevic, J. S. Berg, S. J. Brooks, W. Lou, F. Méot, and N. Tsoupas, "Multi Pass Energy Recovery Linac Design with a Single Fixed Field Magnet Return Line", in *Proc. 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. LINAC'18,* Beijing, China, Sep. 2018, pp. 702-705. doi:10.18429/JACoW-LINAC2018-THPO010

[7] O. Brüning, A. Seryi, and S. Verdú-Andrés, "Electron-Hadron Colliders: EIC, LHeC and FCC-eh," *Front. Phys.*, vol. 10, Apr. 2022. doi:10.3389/fphy.2022.886473

[8] P. Agostini *et al.*, "The Large Hadron–Electron Collider at the HL-LHC," *J. Phys. G: Nucl. Part. Phys.*, vol. 48, no. 11, p. 110501, Nov. 2021. doi:10.1088/1361-6471/abf3ba

[9] S. Brooks, "Open-midplane gradient permanent magnet with 1.53 T peak field", in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 3870-3873. doi:10.18429/JACoW-IPAC2023-WEPM128

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2024). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.