PROCEEDINGS OF SCIENCE

22 GeV CEBAF with Novel Fixed Field Alternating Gradient Design

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Extending the energy reach of CEBAF up to 22 GeV within the existing tunnel is being explored. Proposed energy upgrade can be achieved by increasing the number of recirculations, while using the existing CEBAF SRF cavity system. Presented scheme is based on an exciting new approach to acceleratie electrons efficiently with multiple passes in a single FFA (Fixed Field Alternating Gradient) beam line. Encouraged by recent success of the CBETA Test Accelerator, a proposal was formulated raise CEBAF energy by replacing the highest-energy arcs with Fixed Field Alternating Gradient (FFA) arcs. The new pair of arcs configured with FFA lattice would support simultaneous transport of additional 6 passes with energies spanning a factor of two, using the non-scaling FFA principle implemented with Halbach-derived permanent magnets - a novel magnet technology that significantly saves energy and lowers operating costs. One of the challenges of the multi-pass (11) linac optics is to provide uniform focusing in a vast range of energies, using fixed field lattice. Here, we propose a triplet lattice scaled up with increasing momentum along the linac. This would provide a stable periodic solution covering energy ratio of 1:33. The current CEBAF configured with a 123 MeV injector, makes optical matching in the first linac virtually impossible due to extremely high energy span ratio (1:175). Therefore, we envision replacement of the current injector with a 650 MeV 3-pass recirculating injector based on the existing LERF facility. Finally, the 22 GeV CEBAF would promise to deliver in 10-passes a beam with normalized emittance of 80 mm·mrad and with a relative energy spread of 1.5×10^{-3}. Further recirculation beyond 22 GeV is limited by large, 974 MeV per electron, energy loss due to synchrotron radiation.

25th International Spin Physics Symposium (SPIN 2023)
24-29 September 2023
Durham, NC, USA

[*] Speaker

PoS(SPIN2023)145

1. Energy 'Doubling' Concept

The previous energy upgrade of CEBAF, from 6 to 12 GeV, was achieved by installing additional SRF cavities in the North and South LINACs, increasing the energy gain per pass, while leaving the maximum number of passes unchanged. Recent advances in accelerator technology have made it possible to further extend the energy reach of the CEBAF accelerator up to 22 GeV within the existing tunnel footprint. In the proposed energy upgrade, the energy gain per pass remains unchanged, while the number of recirculations through the accelerating cavities is nearly doubled. Encouraged by the recent success of the CBETA project (Cornell Brookhaven Electron Test Accelerator) [1]), a proposal was formulated to increase the CEBAF energy from the present 12 GeV to about 22 GeV by replacing the highest-energy arcs with Fixed Field Alternating Gradient (FFA) arcs [2], as illustrated schematically in Fig. 1).

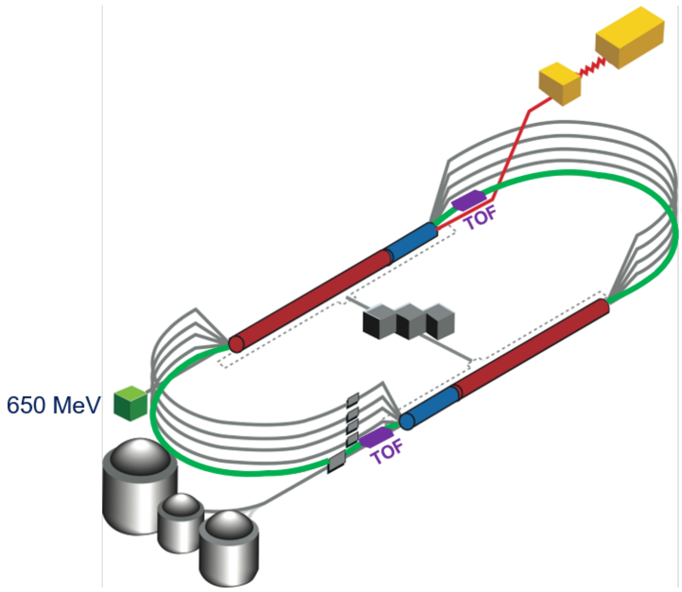

Figure 1: Sketch of the CEBAF accelerator with the two highest energy arcs, Arc 9 and Arc A, replaced with a pair of FFA arcs (green).

2. Accelerator Complex

The design is based on an exciting new approach to accelerate electrons efficiently with multiple LINAC passes and transporting them through a single FFA beamline, as was successfully demonstrated by CBETA project. The Non-Scaling FFA approach allows beam acceleration within a small beam pipe as in synchrotrons, but without varying the magnetic field. These recirculating 180° FFA arcs are made up of 75 repeating cells. The arc's building block is a compact, 3.15-m-long, FODO cell composed with two magnets and two drifts. Each of the magnets is a multi-function Halbach magnet [3], [4] with dominant dipole and quadrupole fields. One magnet per cell bends and focuses the electron beam, and the other bends and de-focuses in the same plane. As illustrated in Fig. 2, different energy beams may be transported through a narrow beam pipe, since the transverse orbit offsets are confined to small aperture of about 4 cm. Closely spaced orbits and low betas (a few meters) result from very strong focusing, reducing the horizontal dispersion function from meters in conventional separate functions arcs down to a few cm in the FFA arc.

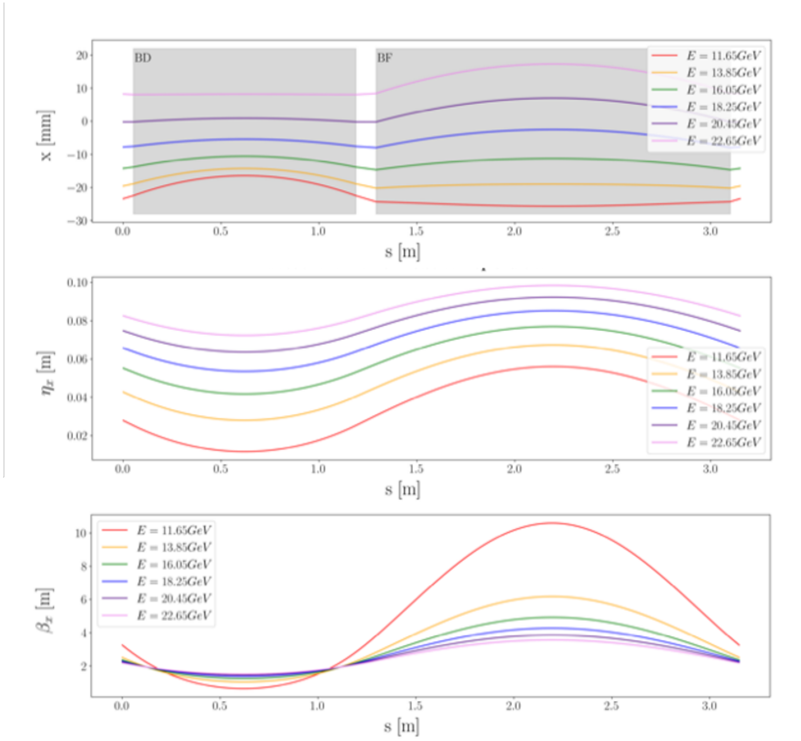

Figure 2: Compact FODO cell configured with two combined function magnets featuring closely spaced orbits and small Twiss functions for six different energy beams.

The new pair of arcs configured with an FFA lattice would support simultaneous transport of 6 passes with energies spanning a factor of two. This wide energy bandwidth could be achieved using the non-scaling FFA principle implemented with Halbach-style permanent magnets. As illustrated in Fig. 3, the magnet design features an open mid-plane geometry, in order for the synchrotron radiation to pass through the magnets, while minimizing radiation damage to the permanent magnet material. This novel magnet technology saves energy and lowers operating costs.

In addition to the spreaders, one must design the time-of-flight horizontal ‘Splitters’ for each of the energies that pass through the FFA arcs. These will be located along the new FFA arcs, downstream of the spreaders (shown as purple boxes in in Fig. 1) Conceptually, they will be similar to those at CBETA. They will need to fit in the space currently occupied by the highest-energy passes in the CEBAF recirculating arcs. This would necessitate a pair of time-of-flight splitters, which are capable of adjusting the momentum compaction, M_{56}, at both East and West FFA arc.

One of the challenges of the multi-pass LINAC optics is to provide uniform focusing in a vast range of energies, using fixed field lattice. The current CEBAF is configured with a 123 MeV injector feeding into a racetrack Recirculating Linear Accelerator (RLA) with a 1.1 GeV LINAC on each side. Increasing number of LINAC passes to 10+ makes optical matching virtually impossible due to extremely high energy span ratio (1:175).

The proposed new building block of LINAC optics is configured as a sequence of triplet cells

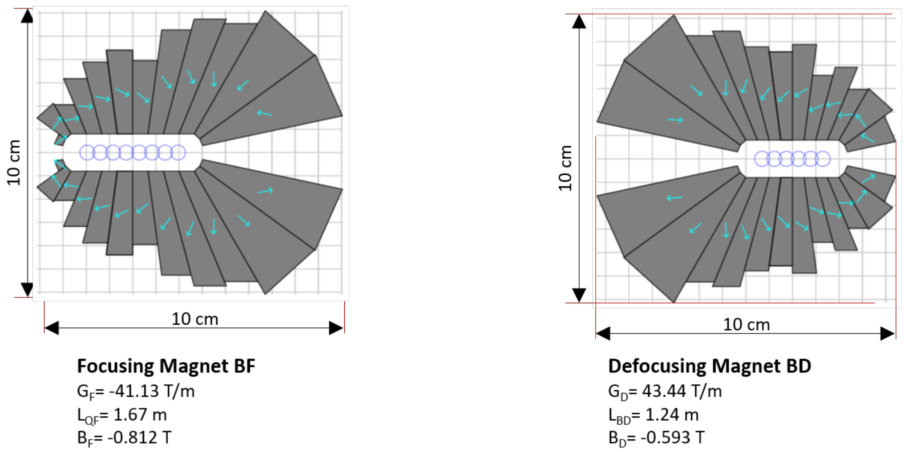

Figure 3: The cross section and field specs of the open mid-plane magnets consisting of 24 wedge-shaped pieces of NdFeB. The outer wedges are symmetrical, while the top and bottom wedges have two edges parallel to the horizontal axis.

flanking two cryomodules. Initial triplets, based on 45 Tesla/m quads, are scaled with increasing momentum along the LINAC. This style LINAC focusing provides a stable multi-pass optics compatible with much smaller beta functions in the FFA arcs and it is capable of covering energy ratio of 1:33. This sets the minimum injection energy at 650 MeV. In the current concept, it is proposed to replace old 123 MeV injector with a 650 MeV 3-pass recirculating injector based on the existing LERF facility augmented by three C-70 cryomodules. The upgraded 650 MeV injector is schematically illustrated in Fig. 4. The beam is then transferred from the LERF vault through a dedicated fixed energy 650 MeV transport line and injected into the North LINAC

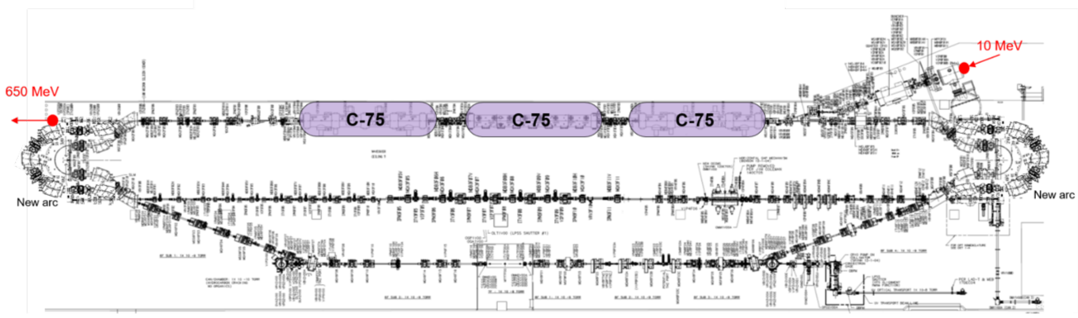

Figure 4: Schematic view of 650 MeV recirculating injector (3-pass) based on LERF.

3. Synchrotron Radiation Impact on Beam Quality

Staying within the CEBAF footprint, while transporting high energy beams (10-22 GeV) calls for special mitigation of synchrotron radiation effects. One of them is to increase the bend radius at the arc dipoles (packing factor of the FFA arcs increased to about 92%). Arc optics was designed to ease individual adjustment of momentum compaction and the horizontal emittance dispersion,

H, in each arc to suppress adverse effects of the synchrotron radiation on beam quality: dilution of the transverse and longitudinal emittance due to quantum excitations Table 1 lists arc-by-arc cumulative dilution of the transverse, $\Delta\epsilon_N$, and longitudinal, $\Delta\sigma_{\frac{\Delta E}{E}}$, emittances due to quantum excitations calculated using the following analytic formulas:

$$\Delta\epsilon_N = \frac{2\pi}{3} C_q r_0 < H > \frac{\gamma^6}{\rho^2}, \quad (1)$$

$$\frac{\Delta\epsilon_E^2}{E^2} = \frac{2\pi}{3} C_q r_0 \frac{\gamma^5}{\rho^2}, \quad (2)$$

Here, $\Delta\epsilon_E^2$ is an increment of energy square variance, r_0 is the classical electron radius, γ is the Lorentz boost and $C_q = \frac{55}{32\sqrt{3}} \frac{\hbar}{mc} \approx 3.832 \cdot 10^{-13}$ m for electrons (or positrons). The horizontal emittance dispersion in Eq. 1, is given by the following formula: $H = (1+\alpha^2)/\beta \cdot D^2 + 2\alpha\, DD' + \beta \cdot D'^2$ where D, D' are the bending plane dispersion and its derivative, with averaging over bends defined as: $< ... > \;=\; \frac{1}{\pi} \int_{bends} ... \, d\theta$.

Pass number	Beam Energy [GeV]	ϵ_N^x [mm mrad]	$\sigma_{\frac{\Delta E}{E}}$ [%]
1	2.8	1.0	0.01
2	5.0	2	0.02
3	7.2	4	0.02
4	9.4	12	0.03
5	11.5	20	0.03
6	13.7	21	0.04
7	15.8	23	0.05
8	17.9	26	0.06
9	19.9	34	0.08
10	21.9	49	0.11
10.5	22.9	61	0.12

Table 1: The horizontal and longitudinal emittances diluted by synchrotron radiation (arcs contribution) after respective passes is summarized. Additional net contribution from the horizontal 'splitters' is estimated as: an emittance dilution of 20 mm·mrad with a relative energy spread of $0.3 \cdot 10^{-3}$. Here, $\sigma_{\frac{\Delta E}{E}} = \sqrt{\frac{\Delta\epsilon_E^2}{E^2}}$.

4. Summary

The proposed 22 GeV, 10-pass, design would promise to deliver a normalized emittance of 81 mm·mrad with a relative energy spread of $1.5 \cdot 10^{-3}$. Further recirculation beyond 22 GeV is limited by large, 0.9 GeV per electron, energy loss due to synchrotron radiation, which depends on energy to the fourth power. The net energy loss is comparable to the energy gain per LINAC, which clearly sets the limit of reasonable number of recirculations.

Finally, given the greater total energies expected with this upgrade, we are also investigating the impact this will have on our extraction system and beam delivery to the experimental halls. For the extraction system, this will depend partly on the needs of the experimental program, and partly on how we choose to extract the beam. For the beam delivery to the halls, the hall beamlines are currently under investigation. Improvements to the magnetic septa are expected to be required, and the dipoles to the hall lines will need to be strengthened and improved as well. The overall optics will require some adjustments, but should be manageable.

5. Outlook

Significant progress has been made in the design of the energy upgrade for CEBAF using FFA transport. Over the last year, we have settled on a design concept, developed more detailed designs of various machine sections, and iterated some sections as simulations were performed. While the full design is not yet completed, we are working toward that goal as we begin to consider other aspects of this upgrade concept. One of the more challenging aspects of this design is the method of beam extraction. Multiple methods are under consideration, each with associated limitations on the flexibility of beam delivery – the resulting scheme has to balance the needs of the users, technical feasibility, and cost.

Funding Information

Work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contracts DE-AC05-06OR23177 and DE-SC0012704.

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