ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPL182

CEBAF 22 GeV FFA ENERGY UPGRADE*

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Abstract

Extending the energy reach of CEBAF by increasing the number of recirculations, while using the existing linacs is explored. This energy upgrade is based on the multi-pass acceleration of electrons in a single non-scaling Fixed Field Alternating Gradient (FFA) beam line, using Halbach-style permanent magnets. Encouraged by the recent successful demonstration of CBETA, a proposal was formulated to nearly double the energy of CEBAF from 12 to 22 GeV by replacing the highest energy arcs with FFA transport. The new FFA arcs would support simultaneous transport of an additional 6 passes spanning roughly a factor of two in energy. One of the challenges of the multi-pass (11) linac optics is to assure uniform focusing over a wide range of energies. Here, we propose a triplet lattice that provides a stable periodic solution covering an energy ratio of 1:33. The current CEBAF injection at 123 MeV, makes optical matching in the first linac impossible due to the extremely high energy ratio (1:175). Replacement of the current injector with a 650 MeV recirculating injector will alleviate this issue. Orbital and optical matching from the FFA arcs to the linacs is implemented as a compact non-adiabatic insert. The design presented here is anticipated to deliver a 22 GeV beam with normalized emittance of 76 mm·mrad and a relative energy spread of 1×10^{-3}. Further recirculation beyond 22 GeV is limited by the large (974 MeV per electron) energy loss due to synchrotron radiation.

INTRODUCTION

The Continuous Electron Beam Accelerator Facility (CEBAF) at Thomas Jefferson National Accelerator Facility (TJNAF) in Virginia, shown in Fig. 1, is a recirculating linear accelerator (linac) that can deliver electrons with an energy up to 12 GeV. Electrons are accelerated up to five recirculating passes before being delivered to Experimental Halls A, B, or C, while electrons are accelerated five and a half passes before being delivered to Hall D; a recirculating pass includes accelerating through both the North and South Linacs, each of which nominally accelerates the beam by 1.1 GeV.

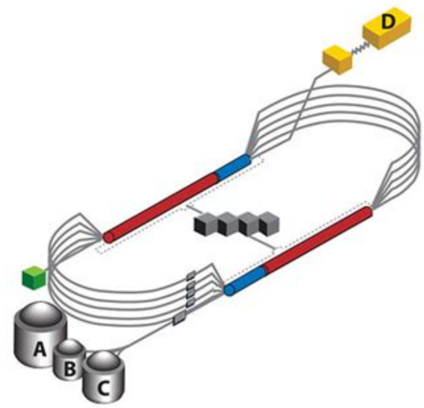

Figure 1: The current configuration of CEBAF. It consists of the current injector (green box on left), North Linac (top), South Linac (bottom), East and West Arcs consisiting of electromagnets (right and left, respectively), and four experimental halls (A – D), as labeled.

Following each linac is a vertical spreader, which separates the beams by energy into the appropriate arc – lowest energy beam at the top, highest energy at the bottom. Single energy transport in each arc allows for individual optics and path length control, before the multiple beams are merged in a vertical recombiner section and accelerated through the next linac. There is an extraction region after the spreader following the south linac, where the electron beam can either be delivered to the North Linac or experimental Halls A, B, and/or C. This extraction scheme uses normal conducting radiofrequency (rf) deflecting cavities and allows for flexibility in delivering multiple beam energies to different experimental halls simultaneously [1, 2].

CBETA, the Cornell-BNL ERL Test Accelerator, is the first successful demonstration of an SRF multi-turn energy recovery linac (ERL) [3–5]. Shown in Fig. 2, it features a non-scaling fixed-field alternating-gradient (FFA) return loop constructed using permanent magnets [6], which transport the four beam energies (42, 78, 114, and 150 MeV) simultaneously in a common beam pipe [3, 4]. The accelerator has a 6 MeV injector, the main linac cryomodule (MLC), SX and RX splitter sections, FFA return loop (FA, TA, ZX, TB, FB), and the beam stop line.

* Authored by Jefferson Science Associates, LLC under U.S. DOE Contract DE-AC05-06OR23177, Brookhaven Science Associates, LLC, Contract DE-SC0012704, and UT-Battelle, LLC, contract DE-AC05-00OR22725.
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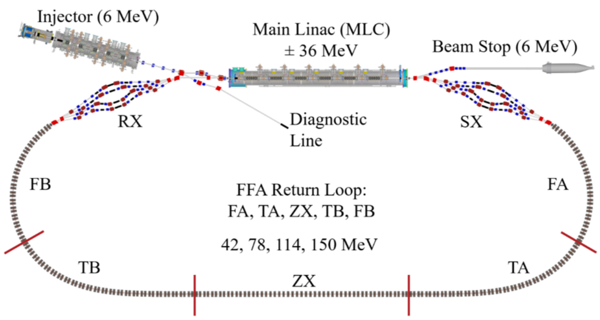

Figure 2: The four-turn configuration of CBETA. During energy recovery operation, seven beams of four different energies are simultaneously transported in the FFA arc.

CBETA can be configured for one to four turns, with the top energies of each configuration corresponding to 42, 78, 114, and 150 MeV, respectively. For a configuration of Y turns, the beam completes $2Y$ passes through the MLC and $2Y-1$ passes through the FFA return loop. In the SX and RX sections, each beam energy has a corresponding splitter line; this allows for independent control for $\alpha_{x,y}, \beta_{x,y}$, horizontal dispersion and its derivative, R_{56}, and orbit; the path length is controlled by moving stages installed in the center of the splitter lines. In the SX section, the splitter lines are labeled S1, S2, S3, and S4, with the lowest line energy being transported in S1 which is located closest to the interior of the loop. Consequently, S4, the highest energy line, is located furthest from the interior. A similar numbering scheme and orientation is applied for the RX section [3, 4].

Select successes of the commissioning period include single-turn high-transmission energy recovery [5], four-turn energy recovery, orbit correction of multiple beams at different energies using a common set of corrector magnets, and measuring seven different beams simultaneously through the FFA arc [3]. This capability of transporting multiple beam energies in a common transport is the basis for this energy upgrade concept.

FFA@CEBAF

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 delivered to Halls A, B, and C unchanged. In this proposed upgrade, the energy gain per pass remains unchanged, while the number of recirculation passes is increased to a top energy of approximately 22 GeV. This is achieved with ten recirculation passes, replacing the highest energy arc in both the east and west with an FFA arc – four passes using electromagnetic arcs and six passes using a pair of FFA arcs [7, 8]; the current design layout is seen in Fig. 3.

The current injector is 123 MeV; with a top energy of 22 GeV, this requires the North Linac optics to accommodate an extremely high energy ratio of 1:175. The upgrade concept is to replace the injector with a recirculating linac

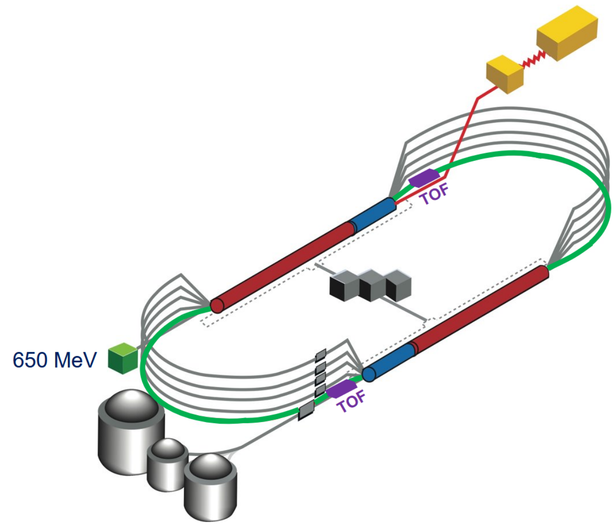

Figure 3: The FFA@CEBAF energy upgrade layout. The green arcs represent the FFA transport, while the purple TOF boxes are splitter sections, meant to handle time of flight correction for each beam energy.

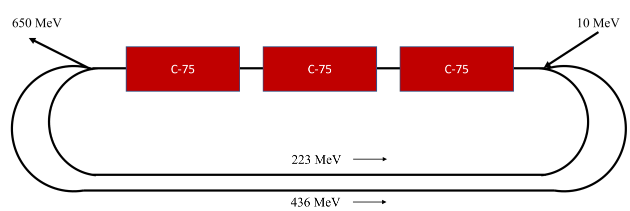

Figure 4: A conceptual layout of the upgraded 650 MeV injector, a recirculating linac with three accelerating passes.

that produces 650 MeV electrons, seen in Fig. 4. This allows for the energy ratio of the optics in the North Linac to be reduced to 1:33. The electromagnetic arcs, spreaders, and recombiners [9] are being redesigned to accommodate for the increased top energy.

The Halbach-style permanent magnets being designed for this effort [10, 11] have an open mid-plane, in order for the synchrotron radiation to pass through the magnets while minimizing radiation damage to the permanent magnet material. The two FFA arcs are slightly different, as they transport slightly different energy ranges.

Each FFA arc requires a splitter to provide optics, orbit, and path length control of each energy – the purple "TOF" boxes in Fig. 3. While previous baseline designs had two splitters per arc, we currently hope to only require one splitter per arc. As in CBETA, these splitters bend horizontally and have very strict space requirements, since they need to fit into the existing CEBAF tunnel. Design work of this particularly challenging aspect is ongoing and will iterate as the designs are refined [9].

In CBETA, the splitters on either side of the MLC would match the orbit and optics into and out of the FFA arc, while all beams are transported through the MLC. The

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FFA@CEBAF baseline design has only one splitter per arc, which serves the role of setting up the different energies for their appropriate orbits and optics into the FFA; however, that leaves an alternate solution for matching the orbits and optics out of the FFA back into the recombiner and linac. A non-adiabatic transition is under development, which should address that design requirement [12, 13].

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. The individual hall lines – transport from the beam extraction to each experimental hall – are also being redesigned for higher energy transport. While the full design is not yet complete, simulation work, including an error correction study and start to end tracking, is in progress [14].

CONCLUSION

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 the full design is not yet completed, we are working toward that goal as we begin to consider other aspects of this upgrade concept.

ACKNOWLEDGEMENTS

Some research described in this work was conducted under the Laboratory Directed Research and Development Programs at Thomas Jefferson National Accelerator Facility and Brookhaven National Laboratory for the U.S. Department of Energy.

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