# CEBAF 22 GeV FFA ENERGY UPGRADE\*

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#### Abstract

Extending CEBAF energy reach by increasing the number of recirculations, while using the existing SRF system is being explored. Proposed energy upgrade is based on a new approach to multi-pass acceleration of electrons in a single Fixed Field Alternating Gradient (FFA) beam line, configured with Halbach-style permanent magnets. Encouraged by recent success of CBETA, a proposal was formulated to nearly 'double' CEBAF energy by replacing the highest energy arcs with a pair of FFA arcs. The new non-scaling FFA arcs would support simultaneous transport of additional 6 passes with energies spanning a factor of two. One of the challenges of the multi-pass (11) linac optics is to assure uniform focusing in a vast range of energies, in a fixed field lattice. Here, we propose a triplet lattice that would provide a stable periodic solution covering energy ratio of 1:33. The current CEBAF injection at 123 MeV, makes optical matching in the first linac virtually impossible due to extremely high energy span ratio (1:175). Replacement of the current injector with a 650 MeV recirculating injector will alleviate that problem. Orbital and optical matching from the FFA arcs to the linacs is implemented as a compact non-adiabatic insert. Presented scheme would promise to deliver a 22 GeV beam with normalized emittance of 76 mm mrad and with a relative energy spread of 1×10-3. Further recirculation beyond 22 GeV is limited by large, 974 MeV per electron, energy loss due to synchrotron radiation.

## **INTRODUCTION**

The Continuous Electron Beam Accelerator Facility (CE-BAF) 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 consisting 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.

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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 2*Y* passes through the MLC and 2*Y* – 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.

In the current concept, the beam is injected at 650 MeV into the North Linac, and the optics through both linacs are altered from their current design, in order to accommodate for the energy ratio of 1:33, with a higher top energy.



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.

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 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.

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