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CURRENT STATUS OF THE FFA@CEBAF ENERGY UPGRADE [*]

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Abstract

An upgrade to the Continuous Electron Beam Accelerator Facility (CEBAF) at the Thomas Jefferson National Accelerator Facility (JLAB) to extend its energy reach from 12 GeV to 22 GeV is being explored. The upgrade pushes the boundaries of the current CEBAF facilities and will require several state-of-the-art beamline components. The first of which is nonscaling Fixed Field Alternating (FFA) Gradient recirculation arcs, using novel Halbach-style permanent magnets. These new arcs would replace the current highest-energy recirculating arcs and allow up to six new beam passes spanning approximately a factor of two in energy. Matching into these arcs will require the design of splitter bend systems proceeding the north and south linac sections; Twiss parameters, R_{56}, time-of-flight, bend-plane offset, and dispersion are required to be tuned for each pass. Matching from these arcs into the proceeding linac section will be achieved using a novel transition section. Additionally, several major changes to the existing CEBAF accelerator will be implemented including a 650 MeV recirculating injector which serves to alleviate the high energy ratio in the linacs, a new multi-pass linac optics design based on a triplet focusing lattice, and a newly designed spreader/recombiner bend systems to accommodate the higher energy requirement. In this paper, we will give an overview of the current status of the FFA@CEBAF design.

INTRODUCTION

The CEBAF at JLAB is a recirculating linear accelerator capable of delivering electrons with energies up to 12 GeV [1]. A single pass through the machine includes acceleration through both the North and South Linacs, each nominally adding 1.1 GeV, and recirculation via the electromagnetic (EM) East and West Arcs. Vertical Spreaders before the arcs separate the electron beams by energy and transport them to their respective arc. Vertical Recombiners after the arcs merge the beam back to the linacs. Electrons undergo up to five recirculating passes before being directed to Experimental Halls A, B, or C, while five and a half passes are required for Hall D. An extraction region after the South West Spreaders allows for flexibility in delivering multiple beam energies to different experimental halls using normal conducting radiofrequency deflecting cavities.

The Cornell-Brookhaven National Laboratory (BNL) Energy Recovery Linac Test Accelerator (CBETA) is the first successful demonstration of a superconducting radiofrequency (SRF) multi-turn energy recovery linac (ERL) [2]. It features a non-scaling fixed-field alternating gradient (FFA) recirculation loop constructed using permanent magnets to transport four beam energies simultaneously. Configurable for one to four turns, CBETA can achieve energies of 42, 78, 114, and 150 MeV. Independent control of parameters like dispersion and orbit is facilitated by dual splitter lines in the SX and RX sections.

CBETA demonstrated multi-pass beam recirculation with energy recovery. The non-scaling FFA principle, implemented with Halbach-style permanent magnets, allowed for simultaneous transport of multiple beams with energies spanning roughly a factor of 4. CEBAF plans to build upon the success of CBETA's use of FFA technology via the FFA@CEBAF design effort. Initial proposals for this upgrade have been presented since IPAC21 [3–5].

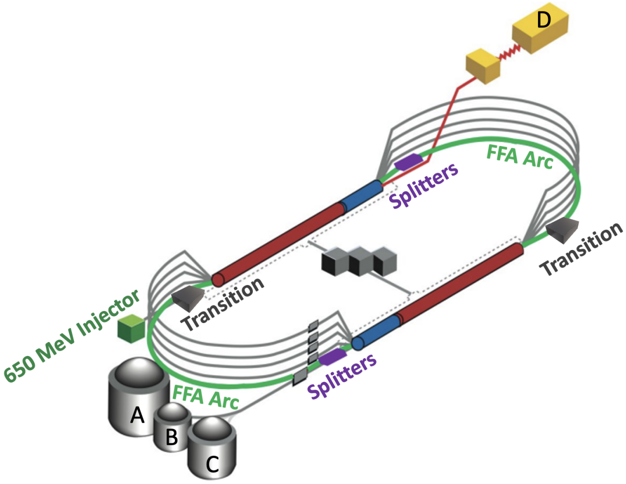

Figure 1: The current 22 GeV CEBAF baseline design. It consists of the upgraded 650 MeV injector (green box, actual location is in the center of the racetrack in the Low Energy Recirculating Facility (LERF)), linacs (red and blue), EM arcs (grey curves), FFA arcs (green curves), Splitters (purple), Transition (dark grey), and four experimental halls (A – D).

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BASELINE DESIGN

The FFA@CEBAF upgrade aims to increase the final beam energy up to 22 GeV by implementing six additional passes. Under its current baseline design (Fig. 1), this is done cost-effectively through several modifications to the existing 12 GeV CEBAF beam transport.

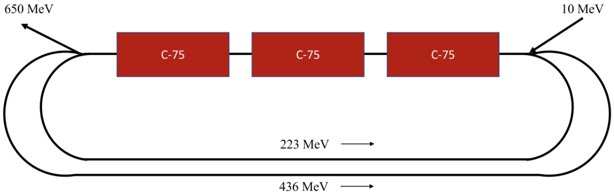

Figure 2: A conceptual layout of the new 650 MeV injector.

First, the current injector's energy of 123 MeV will be upgraded to 650 MeV, significantly reducing the energy ratio requirement for the linac optics (from 1:175 to 1:33). The new injector (Fig. 2) utilizes linacs and FFA return loops similar to CBETA, allowing energy flexibility from roughly 50% to 100%. Second, the linac's FODO-based lattice optics will be augmented with a new triplet-based (doublet was explored in earlier iterations) focusing lattice that provides stable beam optics even in the latter high-energy passes. Then, modifications to all current CEBAF bend systems are required to handle the increased beam energies. This includes all Spreader/Recombiner systems and the EM arcs [6]. Next, the highest energy arcs (ARC 9 and ARC A) will be replaced with FFA arcs. The Halbach-style permanent magnets designed for the proposed FFA arcs feature an open mid-plane to minimize radiation damage. Each FFA arc will require a splitter bend system for optics and orbit matching into the FFA arcs and a non-adiabatic transition to address orbit and optics matching out of the FFA arcs. Lastly, the extraction lines to the experimental halls will need to be revamped. In particular, improvements to the magnetic septa, dipole magnetic field strength, and optics to accommodate the overall increase of beam energy will be required [7].

The challenges facing the FFA@CEBAF design include achieving uniform focusing over a wide energy range and transitioning between arc and straight cell configurations. Simulation work is ongoing to refine designs and address technical complexities as they emerge. Overall, the proposed upgrades aim to significantly enhance CEBAF's capabilities for future research endeavors [8].

CURRENT STATUS AND FUTURE WORK

Lattice optics tracking of the EM portion of the machine have been completed (Fig. 3). The next milestone for the FFA@CEBAF project is to have a completed machine (up to extraction) to conduct start-to-end (S2E) studies of the beam quality and accelerator performance. Pursuant to this goal, lattice designs of the splitter and transition sections are in process of being finalized.

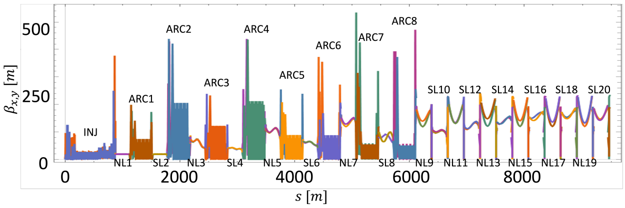

Figure 3: Beta function tracked though the completed portions of FFA@CEBAF. Incomplete sections (FFA Arcs, Splitter, Transition etc.) were modeled via a transfer matrix.

Unlike that of CBETA, the FFA@CEBAF splitter and transition sections will be taking on higher energies (GeV rather than MeV), more dedicated beamlines (six compared to four), and a large amount of matching conditions which include Twiss parameters, R_{56}, time-of-flight, bend-plane spatial and angular offset, and dispersion and its derivative. Additionally, the splitter design faces challenges due to necessitating large magnets within limited space availability; strategic magnet placement is essential. Initial work on the North East Splitter demonstrates feasibility within physical constraints and has inspired a variety of designs [9–11]. The transition section matching the exit of the FFA arc to the proceeding linac is being designed with both adiabatic and parametric resonance techniques [12, 13]. As the work progresses, these conceptual designs may change.

The impact of the proposed upgrade on the extraction system and beam delivery to the experimental halls is also under investigation. This analysis hinges on the experimental program's requirements and the chosen beam extraction method, which is still in its initial stages. For beam delivery, enhancements to the magnetic septa and strengthening of the dipoles leading to the hall lines are anticipated.

Work on examining the multi-pass steering in the FFA arcs is also being conducted [14–16]. Algorithms based on singular value decomposition (SVD) and a machine learning (ML) scheme are being employed to steer all six beams through the arc and their relative performance is evaluated. Preliminary investigations indicate that the ML scheme possesses the capability to achieve error correction comparable to that of the SVD method, albeit with significantly reduced computational time.

Another FFA@CEBAF project is part of a larger program aimed at studying the effects of radiation on the proposed permanent magnets [17]. Investigating the radiation impact on permanent magnet materials (e.g. samarian cobalt and neodymium iron boron) intended for the upgraded FFA arcs plays a central role in the feasibility of the FFA@CEBAF effort. Since these magnets have not undergone testing in high energy, radiative environments, a comprehensive study is crucial for material assessment. This work not only contributes to the FFA@CEBAF effort but also to global studies on permanent magnet degradation due to radiation exposure. Placing selected magnet samples in different radiation regions of the operational 12 GeV CEBAF will provide data, combined with simulations and external studies, to evaluate radiation hardness and material lifetime.

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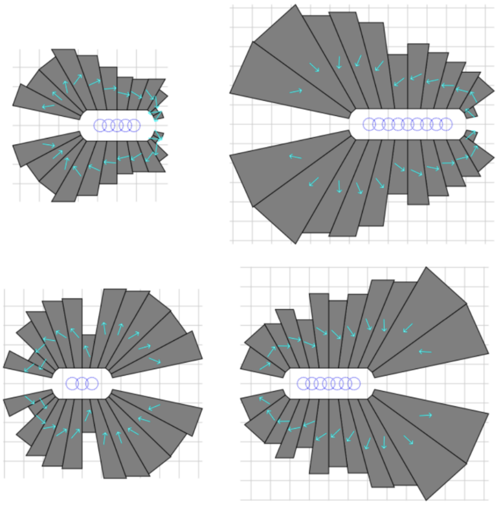

Figure 4: Focusing (top) and defocusing (bottom) 2-dimensional permanent magnet designs for the FFA arcs. The left column is a design including sextupole components while minimizing magnet volume. The right column is the baseline design.

Lastly, methods to optimize the energy acceptance of the FFA arcs are planned to be investigated. The first of which is an alternative FFA lattice optics. As presently designed, the FFA permanent magnets are at the limit of their aperture and strength, which would have limited flexibility to reduce energy, if, e.g. several cavities were de-rated, or one of the cryomodules bypassed. Furthermore, linac energy flexibility is now used to optimize polarization to multiple halls in combination with the Wien filter; with fixed linac energy, only one hall can get a polarized beam. To expand the energy flexibility exploration from the existing Focusing-Defocusing (FODO) structure in the FFA arc to a Flexible Momentum Compaction (FMC) lattice is being planned [18]. This new lattice could potentially ease several stringent operational constraints on the splitters and transition beamlines. Additionally, the potential of incorporating higher-order field components into the FFA permanent magnets will be explored (Fig. 4). This modification has shown promise in preliminary studies (where only a sextupole field component was added) towards extending the energy acceptance window of the FFA arcs by several percent [19].

CONCLUSION

We have presented the current status of the FFA@CEBAF upgrade. Initial studies indicate a promising path forward for CEBAF beyond the 12 GeV era.

The FFA@CEBAF collaboration has made significant towards formulating an overall design. Currently, the focus has shifted towards delving into finer details of the design and incorporating necessary iterations. While the collaboration has not yet achieved a full conceptual design status, the support from respective institutions and ongoing work signify substantial progress toward reaching this milestone. Although there is still much ground to cover, the collaborative effort is well underway.

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