STATUS OF 22 GeV CEBAF UPGRADE USING FFA ARCS[*]

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Abstract

Jefferson Lab is exploring an upgrade to extend CEBAF's energy to ∼22 GeV within the existing tunnel by incorporating Fixed-Field Alternating-gradient (FFA) arcs. In this scheme, the two lowest-energy electromagnetic arcs—one on each side of the racetrack— are removed, the remaining arcs are reassigned accordingly, and a new pair of high-energy FFA arcs enables six additional recirculations using the existing SRF linacs. The non-scaling FFA lattice employs Halbach-derived permanent magnets with provisions for dipole, quadrupole, and higher-order components, offering large momentum acceptance and reduced operating cost. Implementing this concept requires updated linac optics, modifications to the remaining arcs, and a redesigned electromagnetic switchyard. Ongoing beam-dynamics studies address synchrotron-radiation–induced energy loss and emittance growth, along with strategies for their mitigation.

INTRODUCTION

CEBAF at Jefferson Lab has delivered world-leading nuclear physics results since the 12 GeV upgrade reached full operations in 2016 [1]. A rich approved programme will run for at least the next decade, while the community has identified a compelling scientific case for a further upgrade to ∼22 GeV [2]. The higher energy opens three categories of new physics: (i) *unique* measurements accessible only at 22 GeV—near-threshold J/ψ production to probe the proton's gluonic content and charm-containing multiquark spectroscopy; (ii) *enrichment* of existing 12 GeV topics including 3D nucleon tomography and hard-exclusive processes; and (iii) *complementarity* with the future EIC through precision mapping of the nucleon sea at intermediate to high x and identification of short-range correlations. Operating well above EIC luminosities in fixed-target mode, the facility would use existing halls and detectors, minimising cost and technical risk. The upgrade strategy exploits Fixed-Field Alternating-Gradient (FFA) technology demonstrated at the Cornell–BNL ERL Test Accelerator (CBETA), which achieved eight-pass energy-recovery recirculation with a single set of FFA return arcs [3]. A pair of Halbach-derived permanent-magnet FFA arcs, replacing the two highest electromagnetic arcs at CEBAF, can simultaneously transport six beam passes spanning a factor of two in energy, adding up to six new recirculation passes within the existing 80.6 m-radius tunnel. Figure 1 shows the overall upgrade concept.

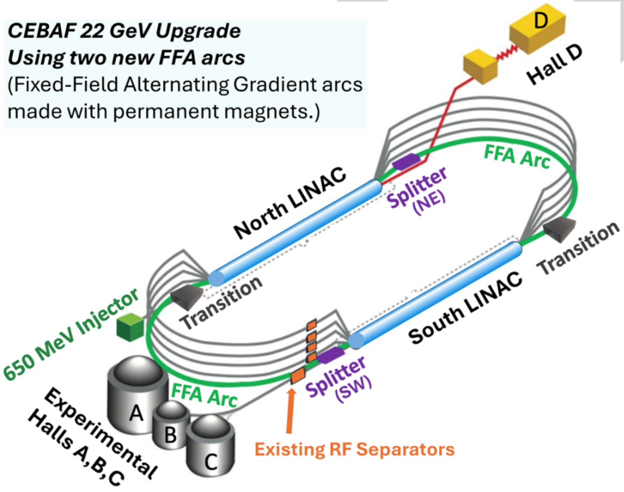

Figure 1: Overview of the FFA@CEBAF 22 GeV upgrade concept. Two new FFA arcs (green) become the highest-energy arcs after removal of the lowest-energy electromagnetic arcs. NE and SW splitter beamlines separate the six FFA passes. The 650 MeV injector is housed in the existing LERF building.

MACHINE LAYOUT AND LINAC OPTICS

The upgrade is staged: an initial configuration reaches ≈20 GeV with five new FFA passes; subsequent cryomodule upgrades (replacing lower-gradient cryomodules with C100 units) raise the linac energy from 1.1 to 1.21 GeV per pass and the top energy to 22 GeV. The existing five-and-a-half-pass racetrack is retained for the first four and half passes.

650 MeV Universal Injector

The existing 123 MeV injector is replaced by a three-pass racetrack in the Low Energy Recirculation Facility (LERF) vault [4]. Three C-75 cryomodules (eight 5-cell, 1497 MHz cavities each, 71.3 MeV energy gain per pass) take an 8 MeV photo-injector beam to 650 MeV in three recirculations. All five 180° arcs use Flexible Momentum Compaction (FMC)

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optics for independent R_{56} control [4] with bipolar transfer-line dipoles to serve both the positron and FFA CEBAF upgrade plans in their respective eras.

Multi-Pass Linac Optics

With up to ten (or eleven) simultaneous passes, the momentum ratio at the linac entrance reaches 1:175—far beyond the range of conventional FODO matching. The solution adopts a *twin-cell* building block: pairs of strongly-focusing alternating triplets (110° phase advance per cell at the lowest energy) with alternating polarity. At low energy the triplets provide strong confinement; at high energy they morph smoothly into singlets (FODO-like), covering a 1:33 momentum ratio within a single linac structure. For FFA passes 5–10, a controlled β-beat is induced across the linac to create nodes (small β, near-zero α) at the linac ends, greatly relaxing matching requirements into the FFA arcs.

Electromagnetic Arcs (Passes 1–4)

The existing arc dipoles cannot sustain the increased rigidity at the new injection energy (field ratios exceed $B_{\max}$ for arcs 1 and 2). The adopted solution discards arcs 1 and 2 and shifts each remaining arc "up by one" in the tunnel stack [5]. New spreader and recombiner beamlines are designed for each arc. Each arc proper uses a four-cell achromatic lattice; quadrupoles inside the bends tune R_{56} via the horizontal dispersion while maintaining isochronicity.

FFA ARCS: LATTICE, MAGNETS, AND TRANSITION

Non-Scaling FFA Lattice

The two FFA arcs each simultaneously transport six passes over ≈9–22 GeV. The minimal cell structure is **BD o BF o**: two combined-function magnets (defocusing BD, focusing BF) separated by short drifts. Five lattice options (A–E) have been optimised [6] using the `Muon1` genetic-algorithm tracker, progressively allowing sextupole content and extending the low-energy reach. Table 1 summarizes the performance statistics. Option C achieves a 48% reduction in average magnet cross-sectional area relative to the baseline while Option D extends the low-energy reach to ~9 GeV for linac energy flexibility—important when cryomodules are derated or bypassed. Alternative approaches to momentum-compaction management in single FFA arcs are explored in [7]. Figure 2 shows closed orbits and Twiss functions for the sextupole-allowed lattice demonstrating viable transport across the full energy range, with an orbit excursion below 45 mm.

Table 1: Figures of Merit for FFA Lattice Options [6]

Option	$\lvert\mathbf{B}\rvert_{\max}$ (T)	Orbit exc. (mm)	Avg. area (cm^2)
A – baseline	1.535	44.97	84.69
B – re-opt.	1.614	28.61	75.75
C – sextupole	1.492	23.60	44.29
D – ext. range	1.469	41.74	54.38
E – narrow tune	1.544	42.97	64.24

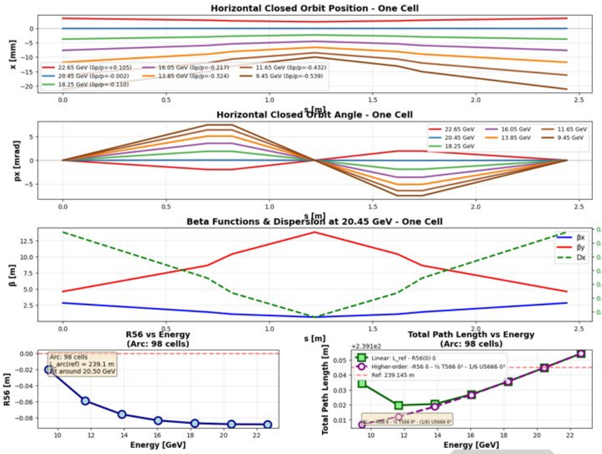

Figure 2: FFA cell closed orbits (top), horizontal closed orbit angle (middle top), beta functions and dispersion at 20.45 GeV (middle bottom), and R_{56} and total path length vs. energy for a 98-cell arc (bottom). The arc is isochronous near 20.5 GeV; R_{56} varies smoothly with energy [7].

Permanent Magnet Design and Prototyping

The FFA magnets are Halbach-derived combined-function NdFeB permanent magnets with an open mid-plane for synchrotron-radiation extraction [8]. The baseline design uses 24 wedges (12 per side), a ±12° midplane gap, ±8 mm vertical aperture, and N42EH grade NdFeB (B_r = 1.28–1.33 T, $\mu_0 H_{cJ}$ = 2.9 T). A 45 mm prototype fabricated at BNL was tuned to relative field errors below 10^{-3} in B_y and B_x across the ±10.5 mm good-field region, meeting the CBETA acceptance criterion [9]. Radiation resilience of NdFeB under the JLab environment is under active study [10], as is a half- or full-cell FFA insert testbed within CEBAF [11].

Transition Section

A transition beamline between the conventional electromagnetic arcs and the FFA arcs is required to match the Twiss parameters and dispersion from the linac end into the FFA cell acceptance. The transition section must transport and match the optics of six distinct beam energies from the FFA arc into the recombiner and linac. Figure 3 shows the closed orbit positions and dispersion functions for all six passes through the transition section, demonstrating that the optics converge to the FFA cell boundary conditions within the available physical length.

SPLITTERS AND BEAM EXTRACTION

Splitter Beamlines

Six-pass simultaneous transport in a single FFA arc requires spatial separation of passes before and after each arc in dedicated splitter beamlines. Each splitter must fit within a 2.94 m transverse clearance and 92 m longitudinal extent inside the existing tunnel. Independent four-dipole chicanes in each pass line provide R_{56} and time-of-flight correction to within a fraction of the 1497 MHz RF wavelength (≈20 cm). Figure 4 shows the layout of all six splitter

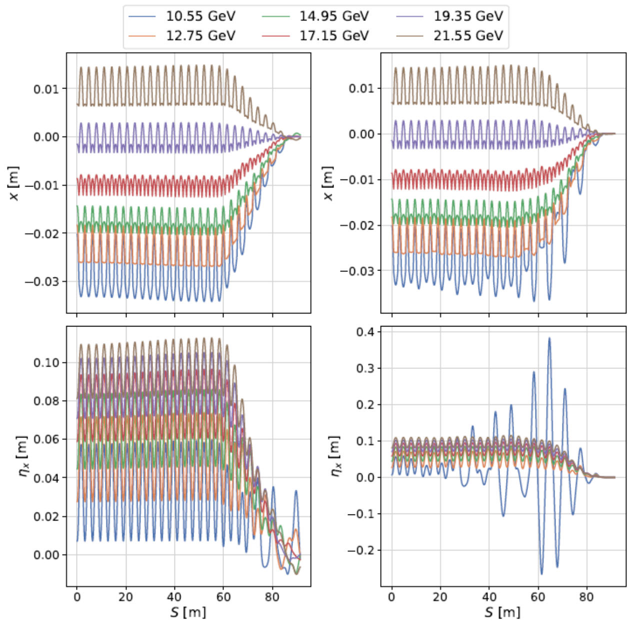

Figure 3: Transition section optics for all six FFA passes (10.55–21.55 GeV). Top row: horizontal closed orbit position x without (left) and with (right) transition matching. Bottom row: horizontal dispersion η_x for the same cases. Matching substantially reduces the dispersion mismatch at the FFA arc entrance.

lines. Horizontal separation of the passes is achieved via a series of electromagnetic dipoles and septa. CEBAF-style compact quadrupoles (≈53.6 T/m at 1 cm radius) provide the required 3π phase advance over the ≈60 m active length of each line. The beamlines are recombined at offsets of a few centimeters to respect the FFA arc entry positions.

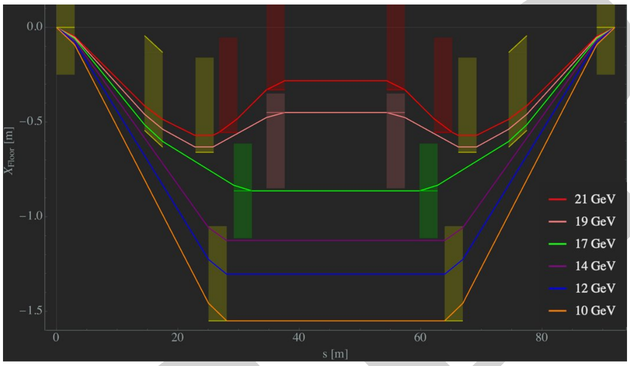

Figure 4: Layout of the six splitter beamlines (horizontal view). color lines: six energy passes; blue: dipole bends; orange: extraction magnets; red: quadrupoles. Note the Y-axis spans to 2 m and the X-axis extends to 100 m.

RF-Based Beam Extraction

The splitter sections are the natural extraction points, as they are the only regions where FFA passes are spatially separated. Two RF kickers—one upstream and one downstream of each splitter—kick all passes simultaneously: for non-extracted passes, the splitter optics provide an even-π phase advance between the kickers so the kicks cancel; for the selected pass, they add coherently, and downstream septum magnets complete the extraction. This preserves compatibility with the existing approximately 749 MHz (Hall D) and 499 MHz (Halls A–C) RF separator scheme without requiring dedicated cavities in each splitter line [12].

BEAM DYNAMICS STUDIES

Synchrotron Radiation Effects

At 22 GeV, synchrotron radiation (SR) in the FFA arcs becomes significant. The critical photon energy rises steeply with beam energy, and the resulting energy loss and quantum excitation drive both emittance growth and energy spread. Multi-particle tracking including SR emission is being performed with Bmad for all FFA passes, with particular attention to the highest-energy passes where quantum effects dominate [13]. Mitigation strategies under study include adjusting the optics to reduce the dispersion in the high-field regions of the FFA magnets, thereby limiting the SR-driven horizontal emittance growth.

Orbit Correction

The orbit correction scheme for the FFA arcs exploits the linear independence of the six simultaneous beam orbits, which is guaranteed by their differing cell tunes across the energy range [14]. A single set of corrector magnets can simultaneously correct all six passes by solving a combined response matrix. Tolerance studies covering magnet misalignments, field errors, and BPM noise are in progress.

Field-Map-Based Tracking

Three-dimensional magnetostatic field maps of the Halbach FFA elements will be imported into Bmad for high-fidelity particle tracking using adaptive Runge-Kutta integration. This will validate the linear optics model and quantify the impact of intrinsic FFA nonlinearities, edge-field effects, and off-momentum orbit excursions on emittance preservation and phase-space matching.

SUMMARY

FFA@CEBAF offers a cost-effective path to 22 GeV by inserting a pair of permanent-magnet FFA arcs into the existing CEBAF tunnel while retaining the proven SRF infrastructure. Key results to date include: a non-scaling FFA cell with 48% magnet volume reduction relative to the baseline via sextupole optimisation (Option C); a 45 mm NdFeB prototype tuned to < 10^{-3} relative field quality; twin-cell multi-pass linac optics covering a 1:33 energy ratio; a six-pass splitter beamline concept with RF-kicker-based extraction compatible with existing Hall delivery; and a transition matching solution for all six FFA passes. Ongoing work focuses on SR-driven emittance and depolarization, full start-to-end tracking with errors, and positron program integration [4, 15].

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