FFA BEAM TRANSPORT DEMONSTRATION DEVELOPMENT FOR THE CEBAF 22 GeV UPGRADE[*]

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Abstract

Jefferson Lab is planning an upgrade of the Continuous Electron Beam Accelerator Facility (CEBAF) to deliver highly polarized electron beams up to 22 GeV using Fixed-Field Alternating-gradient (FFA) magnets. As the application of FFA technology in the 10–22 GeV energy range is unprecedented, experimental validation is required prior to full-scale implementation. To support this effort, a dedicated FFA test insert is proposed within the existing CEBAF infrastructure, with candidate locations in the Beam Switchyard (BSY) dump line or the Hall C beamline. The testbed will consist of a half or full FFA cell using combined-function permanent magnets and will enable systematic studies of beam transport, field quality, alignment, and magnet performance under realistic conditions. Operation with polarized beams in the 5–11 GeV range will closely replicate the energy scaling of the full upgrade. This paper presents the current design status and layout options for the proposed FFA beam transport test line.

INTRODUCTION

The 22 GeV CEBAF energy upgrade [1] proposes to install new high-energy FFA return arcs, after removal of the lowest-energy electromagnetic arcs and reassignment of the remaining CEBAF arc stack [2]. Each cell pairs a focusing and a defocusing combined-function magnet that simultaneously provides dipole bending and strong quadrupole gradients, while an open mid-plane geometry suppresses synchrotron radiation emission into the magnet bore. The resulting lattice must simultaneously transport six co-propagating electron beams spanning a 2.2:1 momentum ratio — a configuration with no direct experimental precedent at multi-GeV energies. The proposed design is a *non-scaling* FFA: particles at different momenta follow distinct closed orbits within the shared aperture, with orbit position and betatron tunes varying continuously across the energy range. The momentum-dependent beta functions and dispersion at the cell boundary require optical matching to be satisfied simultaneously for all six beams, while the momentum compaction factor α_c varies across the arc, influencing beam stability and the synchrotron radiation integral. Recent work has explored reducing α_c in single FFA beam arcs to control these effects [3]. Additionally, synchrotron radiation induces energy oscillations that perturb both betatron tunes and spin precession, with the orbit shift coupling radiation excitation directly into the transverse phase space [4]. To de-risk the upgrade program at an early stage, we plan to submit a lab-directed R&D project to deploy a single FFA magnet test insert within the current CEBAF complex in the 5–11 GeV range. The two candidate locations are indicated in Fig. 1. The testbed complements ongoing field-quality and radiation-resilience studies on prototype magnets [5] by providing the first beam-based measurements of multi-energy closed orbits and optical functions through an FFA element.

CANDIDATE TEST SITES

The primary site-selection criteria are: (i) compatibility with CEBAF's current operating energy range up to ~11 GeV, (ii) a momentum ratio close to the 2.2:1 of the upgrade, and (iii) sufficient upstream optics flexibility to match into the FFA periodic boundary conditions across all energies simultaneously.

BSY Dump Line

The BSY dump line is presently unused and could be refurbished as a dedicated high-energy FFA test facility [6], following the precedent of the CBETA fractional-arc test [7]. The line contains three dipoles; in the proposed configuration the first dipole (MBJ4C01) is replaced by the scaled FFA insert, as illustrated in Fig. 2. The remaining two dipoles and the downstream quadrupole triplet provide the necessary optical leverage for matching. Beam orbits through a single magnet or a full half-cell would be measured over the 5–11 GeV range, with the exact longitudinal position of the insert retained as an optimisation parameter. The BSY option offers a clean, unencumbered lattice and the possibility of long uninterrupted machine time without competing with the Hall physics program.

Hall C Beamline

Hall C offers an operational beamline equipped with a comprehensive diagnostic suite developed for nuclear-physics experiments, as shown in Fig. 3. Beyond orbit and optics measurements through a full FFA cell, the Hall C option uniquely enables polarisation transport studies: the existing Møller and Compton polarimeters provide absolute polarisation measurements at one-percent level [8], allowing direct experimental tests of spin-tune predictions [4] across the 5–11 GeV range. This is directly relevant to the high-polarisation goals of the 22 GeV upgrade [1] and cannot be

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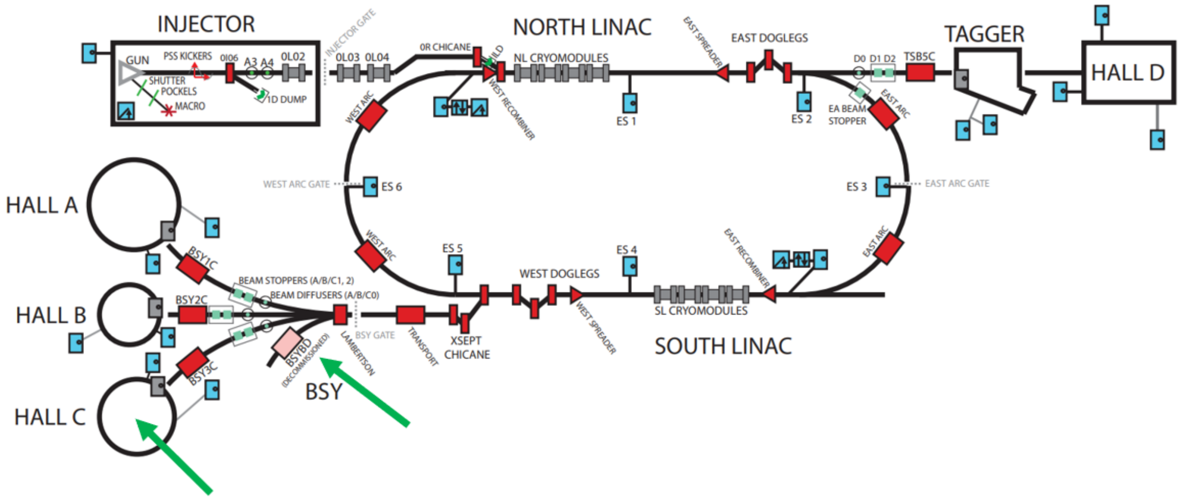

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Figure 1: The CEBAF complex. Green arrows indicate the two candidate locations for the FFA testbed: the BSY dump line and the Hall C beamline.

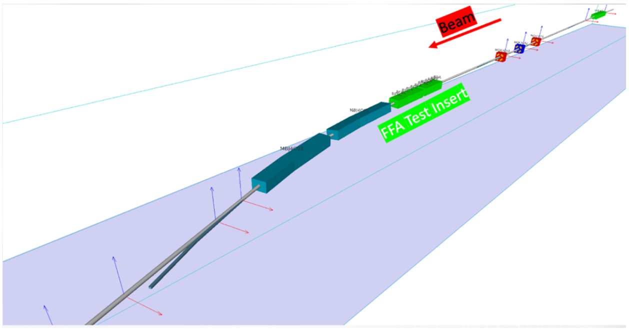

Figure 2: BSY dump-line layout generated with the Elegant 3D floor-coordinate module [9]. The first dipole (MBJ4C01) is replaced by the scaled FFA insert.

replicated in the BSY. The trade-off is reduced scheduling flexibility and the need to integrate the FFA insert within an active experimental line.

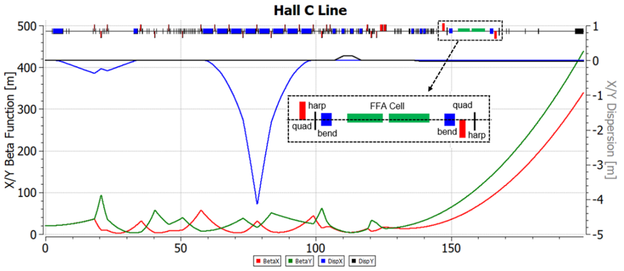

Figure 3: Hall C optics layout with the candidate FFA testbed location, produced with OptimX [10].

FFA TEST MAGNET DESIGN

Lattice Scaling

The 22 GeV upgrade arc lattice is being developed along two parallel tracks [3, 11–13]: a linear-field FFA supplemented by higher-order multipole components up to the dodecapole, and a Halbach permanent-magnet design incorporating dipole and quadrupole fields optimised for maximum momentum acceptance and dynamic aperture. For the testbed, the baseline 10–22 GeV cell [13] has been scaled to the 5–11 GeV range by reducing magnet lengths and bending angles proportionally, which preserves the phase advance per cell and the ratio of dispersion to beam size to first order. Because the periodic solution of a non-scaling FFA cell is momentum-dependent, a global optimisation over 5–11 GeV is aimed to minimise optical mismatch of the full Twiss and dispersion conditions ($\beta_{x,y}$, $\alpha_{x,y}$, D_x, D'_x) using the available bends, steerers, and quadrupole triplets, keeping residual beta-beating within acceptable limits.

Simulated Performance

Figure 4 shows the beta functions and dispersion at 11 GeV alongside the closed orbits for four momenta spanning 5.5 to 11 GeV, computed with Bmad [14]. The horizontal orbit shifts by several millimetres across this range, reflecting the non-scaling character of the lattice, while the vertical orbit remains essentially fixed due to the absence of vertical dispersion in the cell design. The dispersion function reaches a peak of $D_x \sim$ -0.06 m at the centre of the focusing magnet (see Fig. 4) which together with the momentum spread of the CEBAF beam drives the dominant contribution to the horizontal beam size at the insert entrance.

Integration into the BSY Line

The scaled lattice has been incorporated into the full BSY dump-line model, with periodic boundary conditions matched using the existing quadrupole triplet upstream of the MBJ4C01 location. The resulting optics are shown in Fig. 5. At the FFA insert entrance the rms beam sizes are approximately 4 mm horizontal and 0.1 mm vertical. The geometric tilt of the BSY line relative to the FFA mid-plane and resid-

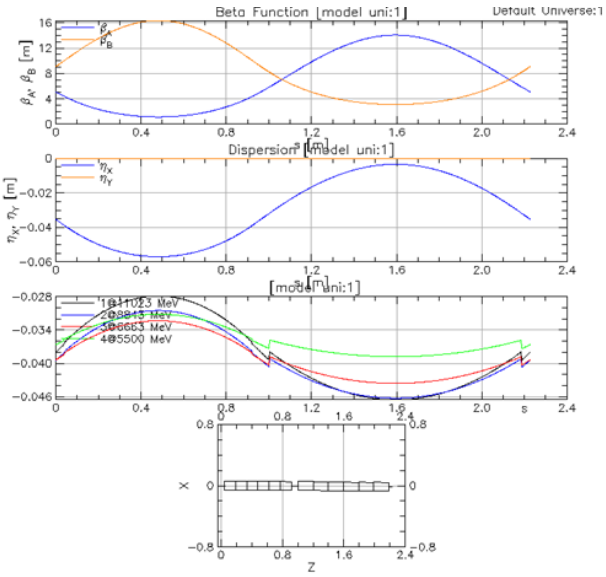

Figure 4: Preliminary scaled FFA lattice computed with Bmad. Beta functions and dispersion at 11 GeV; closed orbits for 5.5–11 GeV. Optimisation to extend acceptance to ~4.4 GeV is ongoing.

ual x–y coupling will be corrected with skew quadrupoles placed downstream of the insert.

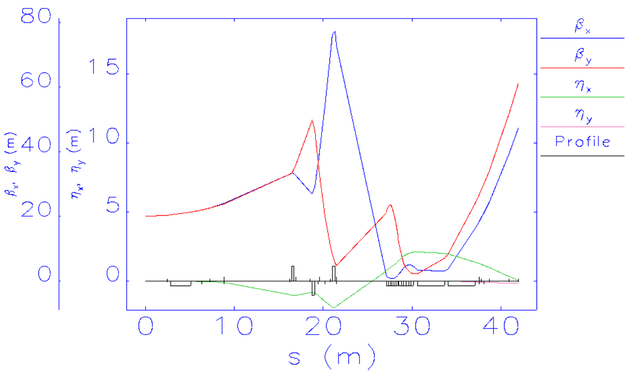

Figure 5: BSY dump-line optics matched to the periodic boundary conditions of the scaled FFA lattice at 11 GeV.

SCOPE OF STUDIES

Spin polarisation and synchrotron radiation effects. The non-scaling FFA lattice presents a qualitatively different environment for spin transport: the momentum-dependent closed orbit produces an energy-dependent spin-precession angle per cell, so the spin tune $\nu_s \approx a\gamma$ acquires corrections that vary non-monotonically across the 5–11 GeV range, potentially driving low-order depolarising resonances [15]. Synchrotron radiation further induces stochastic energy oscillations that modulate the orbit position and spin-precession rate, exciting spin–orbit coupling at fractional resonances absent in a fixed-tune lattice [4]. Full spin-tracking simulations with Bmad will characterise equilibrium polarisation; where Hall C is the host site, Møller polarimetry will provide direct experimental benchmarks.

Momentum compaction and longitudinal dynamics. The momentum compaction factor α_c of the FFA arc has a direct bearing on the sensitivity of the orbit length — and hence the RF phase — to momentum deviations. In a non-scaling FFA the orbit shift with momentum is finite by design, which in principle allows α_c to be tuned by adjusting the cell geometry. Recent studies [3] have explored configurations in which α_c is significantly reduced relative to the nominal design, with implications for the longitudinal acceptance and the tolerance to energy jitter from the linac. The testbed will allow α_c to be measured directly from the momentum-dependent orbit shift through the insert, providing an experimental cross-check of the lattice model and informing the choice of α_c for the full upgrade arc. **Momentum acceptance and large-emittance transport.** The testbed will characterise the dynamic aperture and momentum acceptance of the scaled FFA cell through multi-turn tracking benchmarked against beam-loss measurements by sweeping the beam position at different energies. Of particular interest is the performance for large-emittance beams, relevant to a potential future positron programme at CEBAF. Intentionally degraded electron beams — produced by controlled upstream optics manipulation — can emulate key positron phase-space characteristics [16], providing a cost-effective transport benchmark without a dedicated positron source.

CONCLUSION

We have presented the conceptual design and current status of a multi-GeV FFA beam-transport testbed for CEBAF. The proposed insert — to be deployed in either the BSY dump line or the Hall C beamline — will deliver the first beam-based measurements of multi-energy closed orbits and Twiss functions through a permanent-magnet non-scaling FFA element in the 5–11 GeV range. The programme extends beyond optics validation to encompass direct measurement of the momentum compaction factor [3], spin-polarisation transport benchmarks [4], and large-emittance acceptance studies. Together, these measurements will provide proof-of-principle validation of the core beam-physics assumptions underlying the 22 GeV CEBAF energy upgrade [1], and enable early identification and mitigation of technical risks before commitment to full arc construction.

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