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MULTI-GeV FFA BEAM TRANSPORT TEST AT CEBAF *

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Abstract

Jefferson National Lab (JLab) is planning an upgrade project to increase the beam energy in the Continuous Electron Beam Accelerator Facility (CEBAF) to 22 GeV with high polarization electron beams by using Fixed Field Alternating-gradient (FFA) magnets. The utilization of the FFA magnets for the 10-22 GeV beam energy range is unprecedented; therefore, their efficacy will need validation. For this reason, JLab is considering the design of an FFA magnet test bench, i.e., a half or full FFA cell, that would be deployed in the current CEBAF machine in the 5-11 GeV range. This test bench would evaluate the FFA magnet's field uniformity, permanent magnet resiliency, and beam optics. In this report, we present the preliminary design and status of this planned beamline for the FFA beam transport test at CEBAF.

INTRODUCTION

The 22 GeV CEBAF upgrade plans on replacing the highest-energy arcs with advanced beamline sections composed of periodic cells employing Fixed Field Alternating-gradient (FFA) magnets [1]. Each FFA cell comprises a pair of combined-function permanent magnets. The magnet design is inherently complex due to the high field strength, oval aperture, and open mid-plane configuration, which helps suppress synchrotron radiation. The resulting lattice is uniquely designed to meet the stringent beam dynamics requirements of six co-propagating electron beams. This configuration is critical for achieving precise beam focusing and orbit control. The proposed FFA cell layout features alternating focusing and defocusing combined function magnets that simultaneously provide strong field gradients and bending components.

FFA beamlines are typically categorized as scaling or non-scaling, depending on whether the magnetic field profile scales with particle momentum (i.e., the betatron tune varies with momentum). In this case, the proposed design is classified as a non-scaling FFA magnet. Moreover, particles across a broad momentum range remain confined within the magnet aperture, each following a distinct but stable orbit.

The racetrack FFA design requires precise configuration of beam optics to ensure stable beam transport warranted by well-understood beam dynamics across a wide range of energies. For this reason, JLab is planning to have an FFA test insert in the current CEBAF, either at Beam Switchyard (BSY) dump line or Hall C beam line; the overview of the CEBAF complex is presented in Fig. 1.

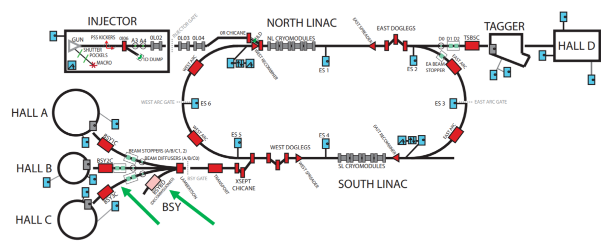

Figure 1: CEBAF complex, and proposed FFA testbed possible locations shown with green arrows.

An instrumented test site in the BSY dump line or Hall C line would enable systematic evaluation of magnet performance, including field uniformity and alignment, both essential for maintaining beam stability and minimizing losses in the 5-11 GeV energy range. Such a test site would need to provide flexibility to simulate different operational scenarios, allowing for optimization of beam optics and early identification of potential design issues. To facilitate that, we have proposed exploratory studies, as a lab-directed R&D project, to design a "testbed" capable of probing the beam transport through the FFA magnets. Its role extends beyond field quality validation currently being carried out at JLab [2]; it is also essential for refining design parameters and ensuring that the final accelerator beamline satisfies the requirements for reliable and stable operation. Investing in a comprehensive test bench will contribute significantly to the success of the CEBAF energy upgrade project and allow us to quantify the reliability and performance of FFA-based accelerator technology overall.

POSSIBLE TEST-SITES

The initial goal of this study is to identify and optimize potential test sites compatible with CEBAF's current operational energy range. We will first investigate the feasibility of implementing an experimental insert in the BSY dump line and Hall C, serving as a testbed for FFA beam transport within this energy range, approximately matching the energy ratio (~ 2.2) envisioned for the full 22 GeV CEBAF upgrade.

Although the BSY dump line is not currently in operation, it could be refurbished and repurposed as a high-energy test facility for proof-of-principle FFA validation [3]. Notably, Cornell BNL ERL Test Accelerator (CBETA) also conducted a fractional arc test prior to its full installation [4]. Specifically, we aim to measure beam orbits through a single or a full FFA magnet, i.e. "half-cell" or "full-cell" configuration, over the 5-11 GeV range at the BSY dump line. This

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setup is illustrated in Fig. 2, generated using the 3D floor coordinate plotting module of ELEGANT [5].

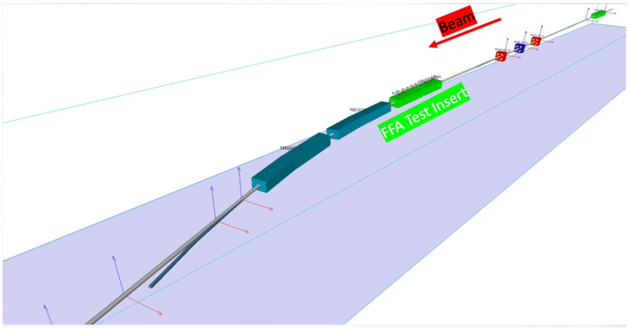

Figure 2: The BSY dump line consists of three dipoles. In this study, the first dipole (MBJ4C01) is replaced with a scaled FFA test insert, whose position and exact placement within the beamline remain parameters to be optimized.

Hall C could also host a dedicated demonstration site for "full cell" orbit and optics measurements, as shown in Fig. 3. Additionally, because of Hall C's existing diagnostics tools for the nuclear physics experiments, this option would have the added feature of polarization studies to the FFA testbed.

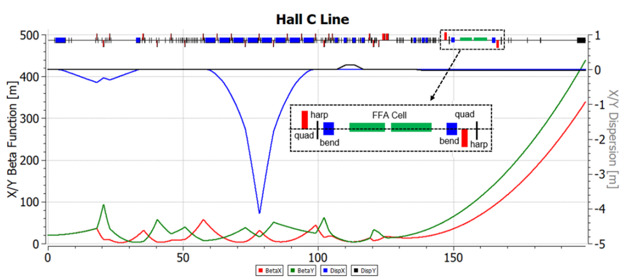

Figure 3: Hall C optics is shown with possible location of the FFA testbed via OPTIMX [6].

FFA TEST MAGNET INSERT

The 22 GeV CEBAF upgrade lattice design is currently underway [7, 8]. On one side, we are developing a lattice based on FFA magnets with linear fields supplemented by higher-order magnetic field components, extending up to the dodecapole term. In parallel, we are also working on a Halbach permanent magnet FFA lattice, incorporating dipole, quadrupole, and sextupole field components (or combinations thereof). This design is being optimized for maximum momentum acceptance and dynamic aperture over the 10-22 GeV energy range using MUON1 code [9].

We are benchmarking the FFA magnet lattice designs using optics codes such as ELEGANT, MUON1, and BMAD [10] to analyze closed orbits and Twiss parameters for beam energies in the 5–11 GeV range. The objective is to determine the optical matching requirements—including beam centroid position and angle, Twiss parameters, and dispersion—using a combination of bends and steerers to integrate the FFA magnet(s) into either the BSY line or Hall C.

To guide this effort, we have scaled the 10–22 GeV FFA magnet design we have developed [11] by the square root of its length and bending angle to approximate a lattice configuration suitable for the targeted energy range. Figure 4 shows simulated closed orbits for four beam momenta spanning 5.5 to 11 GeV. The CEBAF FFA upgrade targets a 10–22 GeV energy range through the arcs, making a 5–11 GeV FFA test insert sufficient for initial testing. However, to account for possible CEBAF linac failures, such as cryomodule issues that could lower injection energy to ~9 GeV, FFA lattice designs with extended momentum acceptance are also being explored. These low-energy scenarios are now being incorporated into the design of the testbed magnet.

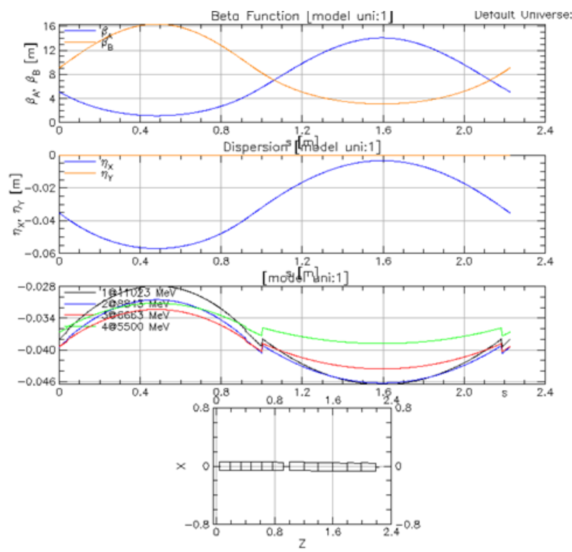

Figure 4: A preliminary design of a scaled FFA lattice, pending further optimizations aimed at enhancing the lowest energy down to 4.4 GeV or so. The resulting beta functions and dispersion for 11 GeV, orbits for 5.5-11 GeV, along with a physical layout of magnets are illustrated.

Preliminarily, we implemented the scaled FFA lattice shown in Fig. 4 into the BSY dump line and matched the periodic conditions of the lattice using an existing triplet magnet available in the beamline. The resulting optics are shown in Fig. 5.

Figure 6 shows the beam size evolution through the FFA insert, simulated using operational CEBAF beam parameters. At the entrance of the FFA insert, the rms beam sizes are approximately 4 mm (horizontal) and 0.1 mm (vertical). Given the small beta functions and non-zero horizontal dispersion in the FFA lattice along with the geometric tilt of the BSY dump line, the deployment of skew quadrupoles downstream of the FFA magnet or lattice may be required. These elements would facilitate beam waist scans and provide the necessary transverse beam size matching to confine the beam and ensure proper delivery to the beam dump at the end of the line.

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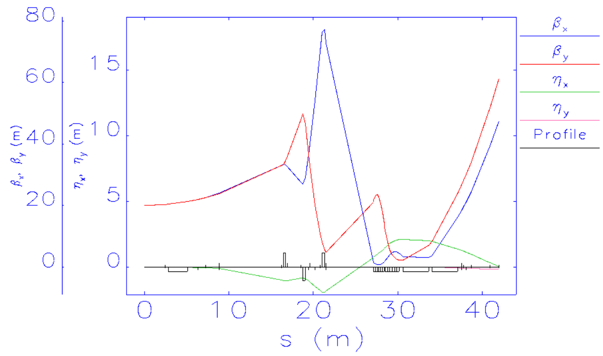

Figure 5: Present optics of the BSY dump-line matched to the scaled FFA lattice.

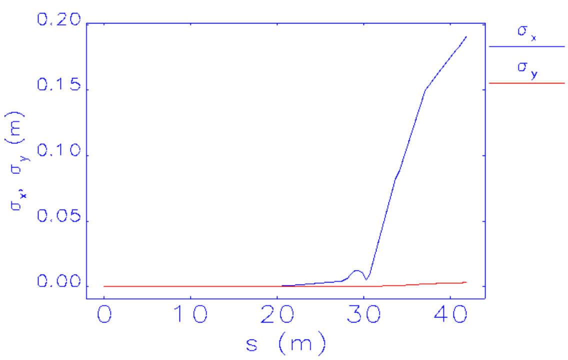

Figure 6: Beam size evolution throughout the BSY dump line with the FFA magnet insert.

SCOPE OF THE PROJECT

Spin tracking simulations will be performed utilizing the BMAD framework. The transport of spin polarization through the FFA structure presents nontrivial challenges, primarily due to the non-scaling character of the FFA lattice, wherein the closed orbit varies with energy, introducing nonlinear spin dynamics [12]. These variations result in energy-dependent spin precession rates and may induce non-monotonic behavior in the spin tune, leading to a potential degradation in overall polarization. To characterize these effects, the evolution of the spin tune and polarization vector will be investigated under the influence of synchrotron radiation, and the degree of polarization preservation over the 5–11 GeV range will be quantitatively assessed.

The momentum acceptance and dynamic aperture of the FFA lattice will be systematically evaluated to determine the feasibility of transporting positron-like large emittance beams. Therefore, the degraded electron beams at CEBAF emulating key aspects of positron beam can be used to benchmark the FFA transport performance [13].

CONCLUSION

The multi-GeV FFA beam transportation project aims to develop both a conceptual and engineering design for an experimental insert to be deployed in either the BSY dump line or the Hall C beamline of CEBAF. The proposed insert will facilitate beam-based measurements of orbits and optical functions through a permanent-magnet FFA element across multiple beam energies. This will serve as the foundation for a proof-of-principle demonstration of multi-energy beam transport through an FFA magnet. Overall, we seek to proactively identify and resolve potential challenges that may hinder the successful implementation of the 22 GeV FFA CEBAF upgrade program at an early stage.

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