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STATUS OF CONCEPTUAL HORIZONTAL SPLITTER DESIGN FOR FFA@CEBAF ENERGY UPGRADE*

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Abstract

Jefferson Lab's Continuous Electron Beam Accelerator Facility (CEBAF) is currently investigating the feasibility of upgrading its maximum operating energy using Fixed-Field Alternating-gradient (FFA) recirculating arcs to increase the total number of recirculations the beam through the pair of LINACs. These FFA arcs will be composed of permanent magnets, with small Panofsky-style multipole correctors. Horizontal splitters are needed to control the beam parameters through these FFA arcs. The geometrical and physical constraints, as well as the beam matching requirements are very restrictive, complicating the design. This work will show the current status of the most mature design, which includes matching solutions, as well as options for extraction of the beam.

INTRODUCTION

As part of the FFA@CEBAF energy upgrade [1], CEBAF's current ARC9 (after nine LINAC traversals) and ARCA (after ten LINAC traversals) will be replaced by new FFA arcs. These arcs will use permanent magnets to guide up to six beam passes through a single shared vacuum chamber. The baseline design incorporates one six-pass FFA arc in each main arc, resulting in four electromagnetic (EM) passes and six FFA passes during operation.

The FFA arcs will employ Halbach arrays [2, 3] with Panofsky-style correctors [4–8], but will otherwise be non-adjustable. Strict matching is required to transport multiple passes through the FFA arcs. Additionally, because the FFA design omits doglegs, time-of-flight (ToF) adjustments must be performed separately.

Drawing on experience from CBETA [9], horizontal Splitters are being developed for this upgrade [10–14]. These Splitters must independently control the optics of each pass, horizontally separating up to six beams after vertical separation by a spreader (which also routes the EM passes into their respective arcs). The combined FFA beam ensemble enters the Splitter, where it is separated onto independent lines, each with dedicated magnets. Each line must precisely match Twiss parameters (α, β), dispersion and dispersion prime (η, η'), horizontal coordinates (x, x'), ToF, and R_{56}. Inside the FFA arcs, the passes are no longer co-linear, each following a trajectory that corresponds to its energy.

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Design Rationale

The design approach is deliberately conservative, prioritizing **flexibility** and **operational robustness**. Wherever possible, pessimistic boundary conditions were chosen based on realistic constraints. Novel technologies such as multi-function or permanent magnets are avoided in this stage but may be added later if beneficial.

All electromagnets are either currently in use at CEBAF or derived from existing designs [15–24]. The quadrupoles are in present operation, while the dipoles have been conservatively designed with transverse dimensions intentionally larger than necessary to preserve future flexibility. All dipoles are 3 m long and 0.5 m wide (full width), except for four shorter 1.5 m dipoles of the same width and six extraction septa/dipoles, which are 0.3 m wide in the horizontal plane.

As noted in previous reports, some assumptions have been made regarding beam transport through these magnets. For example, certain beam trajectories may fall outside the magnets' good-field regions. While these issues are expected to be minor and correctable, they are noted here for transparency and future review.

CONSTRAINTS

Since they have been detailed in previous reports [10–13], only a brief summary of the relevant constraints is provided here. The design must fit within the existing CEBAF tunnel while meeting health, safety, and equipment access requirements, particularly for large components. The longitudinal and transverse space constraints are summarized in Table 1 and illustrated in Figure 1.

Table 1: Splitter Physical Geometrical Constraints

Name	Value
Wall to Beamline Center	1.3716 m
Beamline Center to Clearance Limit	1.5665 m
Total Available Transverse Space	2.939 m
Beamline Center Height	LINAC Height
Total Length in Z	92 m

The Splitters must match the beam into the FFA arc, including the required horizontal offsets (x, x') for each pass. Additionally, they should provide a mechanism to extract higher-energy passes, as no other system currently exists for this function.

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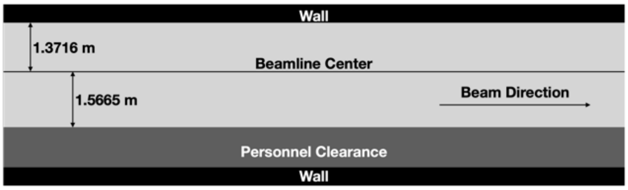

Figure 1: Transverse constraints in the tunnel.

GEOMETRIC LAYOUT

Transport Dipoles

Due to severe physical constraints in this region, the first design priority was to "fit the pieces in the box," developing a layout of the dipoles that accommodates six beamlines. Bmad [25] was used for this task, as it can simultaneously model multiple beamlines, including real magnet sizes.

Each Splitter line uses common dipoles to separate the initially collinear beams until six independent lines are formed. Each line includes chicanes to adjust the time of flight (ToF) independently for each pass.

Independent recombination and matching of the six lines into the FFA arcs provide significant operational advantages. This allows installation of additional quadrupoles, diagnostics, correctors, and other necessary components along each beamline. It also avoids the complications of using common dipoles, where non-collinear entry into the FFA arcs would make matching more difficult and error-prone. Final matching sections placed just before the FFA arcs offer finer control over each individual pass.

Time of Flight Management

To correct ToF for each pass, the chicanes' path lengths were adjusted by modifying drift spaces and dipole positions, ensuring proper arrival at the RF phase ($n \times 2\pi$) of the SRF LINAC. These ToF values do not yet include the Transition from the FFA arc into the Recombiner and next LINAC [26, 27], so further adjustment will be needed once that section is finalized. The Transition section brings the separated beams back to co-linearity into the Recombiner and LINAC, while also adjusting the optics parameters. The length and overall behavior of this section is still under investigation, and the ToF and R_{56} values are still to be determined. Operational adjustments will also be required to compensate for path length changes during runtime. This may be accomplished either through adjusting the dipole strengths, or physically moving them. Given the large variations experienced at CEBAF, the chicanes may require mechanical movers. A conceptual diagram of this system is shown in Fig. 2.

Extraction

This Splitter design is currently the only design that is capable of allowing beam extraction to the experimental halls. Each pass requires dipoles for extraction. These dipoles can be activated for magnetic extraction, sending beams to Halls A, B, and C at the same energy, while Hall D operates separately. Alternatively, timed vertical kicks provided by

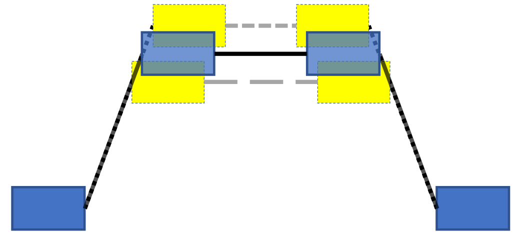
Figure 2: Mover system for the Splitters. Blue are dipoles, and yellow are possible dipole positions after moving. Grey lines show the orbits for different passes.

upstream radio frequency (RF) kickers, combined with septa, may enable extraction of individual passes. This concept is under investigation [28].

Regardless of method, the current design reserves space for dipoles and/or septa to ensure extraction capability is maintained.

OPTICS DESIGN

Each of the six Splitter lines has unique input parameters and distinct matching requirements into the FFA arc. The transport dipoles control the time-of-flight (ToF), horizontal position, and angles at FFA entry, while quadrupoles control the optics and R_{56} compensation.

Figure 3 shows the overhead layout. No components physically contact each other, though clearances are often tight. Some downstream dipoles will require chamfering to minimize overlap with adjacent beamlines. Fringe and stray-field mitigation, such as carbon steel beam pipes and additional shielding, will also be necessary. Furthermore, correctors will be necessary not only for orbit corrections, but also to counteract any remaining uncorrected fringe and stray fields to ensure the beams enter the FFA arc at the correct position and angle.

Matching

Matching the optics parameters ($\alpha_{x,y}$, $\beta_{x,y}$, $\eta_{x,y}$, $\eta'_{x,y}$) into the FFA arcs is achievable for each line individually. However, including R_{56} compensation complicates these solutions. Because R_{56} also depends on the incomplete Transition section [26, 27], it is treated as a "soft target."

Multiple matching solutions were created by varying both the entry point into the FFA cell (e.g., cutting the FFA cell at different locations) and the LINAC input conditions. This approach demonstrates the Splitter's flexibility and helps define the range of R_{56} values that are realistically achievable. Once the Transition section is complete, future updates to the FFA arc may further reduce the R_{56} burden on the Splitters.

For each match, the "natural" R_{56} is identified for each optics matching solution. These solutions are then adjusted toward the soft target by incrementally modifying the optics parameters, maintaining as many optics matches as feasible.

Currently, six separate matching solutions exist. Four use smaller incoming β functions from strong focusing triplet (SFT) LINAC optics, and two use larger β functions from a weakly focusing triplet (WFT) LINAC design. This was

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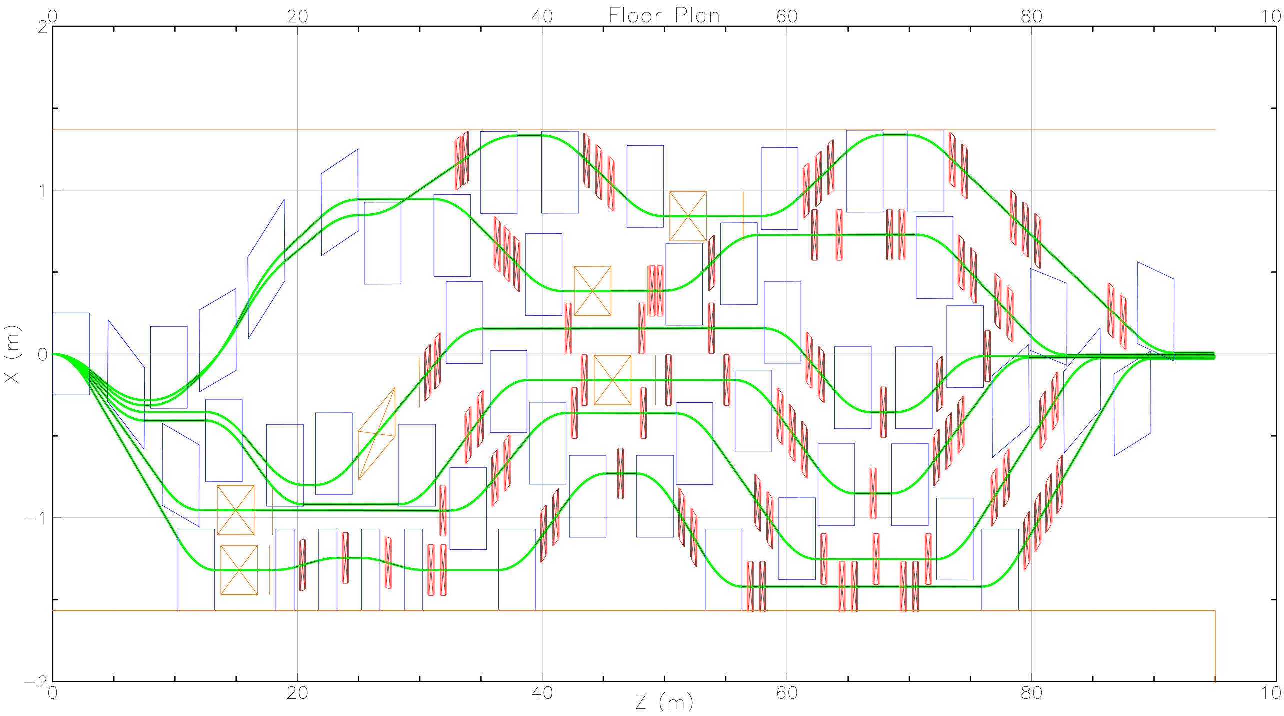

Figure 3: Overhead view of Splitter floor plan. Note unequal scales. Dipoles (blue), extraction dipoles (orange), and quadrupoles (red) shown with real dimensions. Horizontal orange lines indicate transverse spatial limits, with the wall at the top and the walkway at the bottom. Beam travels left to right.

done for two reasons: to demonstrate the flexibility of this Splitter design in accommodating a large range of incoming beam parameters, and because the design of the SFT is based upon quadrupoles that are far beyond state of the art. All of the solutions are generated in pairs (for a total of three pairs): one set in each pair matches the full optics terms without R_{56} correction, while the second set includes R_{56} considerations by adjusting selected optics parameters, and maintaining as many of the optics parameters as possible.

Two of the SFT matches target the beginning of the FFA cell, while the other two match roughly midway into the first magnet. The WFT solutions also use the midway point.

Due to space constraints, the reader is encouraged to view the poster which accompanies these proceedings. The poster graphically shows the location of the Splitters in CEBAF, how the FFA Cell is divided into separate match points, as well as examples of some of the match solutions.

SUMMARY AND FUTURE WORK

The six matching solutions for this Splitter design demonstrate substantial flexibility and robustness. They also show an ability to accommodate many possible future changes to the FFA arc design and CEBAF upgrade elements. Additional matching solutions can be performed to ensure the most resilient options are used. It remains the only current solution that provides both multiple matching options and beam extraction capability. Furthermore, it is adjustable for ToF, and matches each pass into the FFA cell with the appropriate horizontal offsets.

Once the Transition section design is complete, and the full ToF and R_{56} values are known, re-matching of the Splitters will be necessary. A combination of re-matching the Splitters and refining the FFA arc design will likely be required to take place in an iterative manner so that the burden upon the Splitter matching is reduced.

Future efforts will focus on ensuring the solutions remain realistic with respect to engineering constraints and real magnet limitations. While first-order considerations have been addressed, further investigation is needed regarding magnet good-field regions, cross-talk, and proximity to beamline infrastructure such as pumps, valves, cabling, and cooling. Reducing the Splitter's contribution to emittance growth is also a priority. If necessary, multi-function magnets can be introduced into the design, though they may introduce undesirable nonlinearities.

Many of these concerns mentioned above would be mitigated by removing the sixth pass, which would create additional space for the remaining five. The overall design would be simpler, and more flexible.

For further details and optics plots, see the technical note on constraints and geometric layout [13] and the accompanying poster.

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