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HORIZONTAL SPLITTER DESIGN FOR FFA@CEBAF ENERGY UPGRADE: CURRENT STATUS*

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Abstract

Thomas Jefferson National Accelerator Facility (Jefferson Lab) is currently studying the feasibility of an energy upgrade based upon Fixed-Field Alternating Gradient (FFA) permanent magnet technology. The current plan is to replace the highest-energy recirculation arcs with FFA arcs, increasing the total number of beam recirculations, thus the energy. In order to accommodate multiple passes in the FFA arcs, horizontal splitters are being designed to control the beam parameters entering the FFA arcs, as well as time-of-flight and R_{56}. In the current design, six passes will recirculate through the FFA arcs, necessitating the design of six independent beamlines to control the optics and beam dynamics matching into the arcs. These beamlines must fit into the current CEBAF tunnel while allowing for personnel and equipment access. They must also be flexible enough to accommodate the beam under realistic operational conditions and fluctuations. The constraints on the system are highly restrictive, complicating the design. This document will describe the current state of the design and indicate the work remaining for a complete conceptual design.

INTRODUCTION

For the FFA@CEBAF energy upgrade, fixed-field (permanent) magnets will be used to recirculate up to six passes in the same beam pipe in the East and West Arcs. The current design baseline assumes there is a single FFA arc on each of the East and West Arcs, each containing six passes. There will be four electromagnetic (EM) passes, and six FFA passes. The FFA arcs replace the current ARC9 (after the beam traverses nine LINACs) and ARCA (after ten LINACs) in CEBAF.

The Halbach magnets to be used in the FFA arcs [1, 2] will have Panofsky-style correctors [3–6], but otherwise will not be adjustable or tunable. In order to transport multiple passes, strict matching into the FFA arcs is required. Furthermore, since there will not be doglegs for the FFA passes, time-of-flight (ToF) will need to be adjusted externally.

Based upon the experiences at CBETA [7], horizontal splitters are envisioned for use [8, 9]. The splitters must independently control the optics for each pass in the FFA arc. This means that for six passes, six separate lines are required. The FFA passes exit co-linearly from the LINAC, pass through the vertical spreader where they are separated vertically (since the EM passes must be separated into their respective recirculating arcs), and then recombined co-linearly. The beams then enter the splitter, where they are separated horizontally. Once fully separated and no longer sharing magnets, each line must match the Twiss parameters (α, β), dispersion and dispersion prime (η, η'), horizontal position and angle (x, x'), time of flight, and R_{56}. At a minimum, this requires seven quadrupoles, though it is highly recommended that eight or more be used.

Design Rationale

The guiding design rationale for this work can be most succinctly summed up as, "measure twice, cut once." Insofar as reasonable, a pessimistic view was maintained. As many realistic constraints and design restrictions as possible were used as boundary conditions, as it is easier to remove them to ease the design limitations than it is to impose them later. Furthermore, a focus on simplicity,flexibility, and operational robustness was prioritized over novel or newer methods and technological leaps.

All of the magnets used in this design work are either currently used in CEBAF or based on designs made specifically for this use [10–19]. All are electromagnets. The quadrupoles are currently used in the operating CEBAF, and the dipoles are all 3 m long and 0.5 m across (full-width), with the exception of four smaller, 1.5 m dipoles of the same transverse size and six extraction septa/dipoles (to send the beam from any pass to the experimental halls), which have a smaller transverse dimension of 0.3 m across in the horizontal plane.

Occasionally, assumptions have been made about how the beam will propagate through some of these magnets. Some of these assumptions may prove incorrect: for example, the beam may not be going through a good-field region of the magnet. Most of these assumptions are minor and likely fixable, but it is important to be up-front about them so that they are not ignored or forgotten later.

CONSTRAINTS

As an upgrade, the design must remain within the preexisting bounds of our tunnel, and accommodate health and safety requirements. Furthermore, equipment access must be maintained as much as possible, especially access for large equipment.

The latter point provides our first major limitation: limiting the Splitters to the upstream side of each FFA arc. Given

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the equipment access points located only in the Northwest (NW) and Southeast (SE) corners and the transverse space requirements of the Splitters, we cannot place two Splitters on each FFA arc. The use of ramps over the Splitter lines will have a large impact operationally and logistically. Since the Splitters are at LINAC height and the magnets are currently envisioned as approximately 0.25 m in half-width, the clearance height of the ramp would necessitate long ramps to reduce the incoming angle and may also put the heads of personnel into the Oxygen Deficiency Hazard (ODH) zone near the ceiling of the tunnel. Given these concerns, ramps should be considered as a last resort, if reasonable solutions cannot be found otherwise.

The longitudinal and transverse space constraints, discussed more fully in a tech note [20], are summarized in Table 1. This is also summarized graphically 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

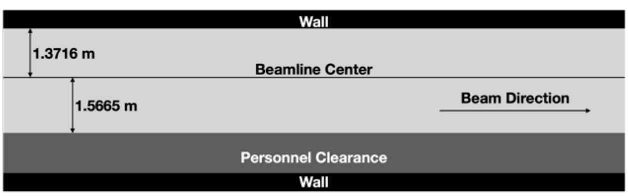

Figure 1: Transverse constraints in the tunnel.

GEOMETRIC LAYOUT

Given the tight spatial constraints, the initial priority was to "fit the pieces in the box." Bmad [21] was used to do this, as it is capable of performing design and simulation work on multiple beamlines simultaneously, including real magnet sizes.

The beams enter the Splitters co-linearly, so they must first be separated by common dipoles. Since there is slightly more room toward the personnel clearance, the first dipole bends all passes to the right, and the beams are further separated by successive dipoles. In order to avoid dipole collisions, the two highest-energy passes are bent in the opposite direction of the first bend, and the orbits cross over each other. In order to re-combine the orbits at the other end in the proper order, the trajectories must be re-crossed so that the lowest-energy passes are furthest to the right (inside path around the arc), and the highest energy passes are on the left (outside path around the arc).

Once separated, each beam must pass through at least one chicane which is capable of adjusting path length and ToF. At least one of these chicanes should also have a set of movers so that the path length can be more easily compensated as the CEBAF machine expands and contracts due to environmental factors. These movers may not be necessary, but it is easier to remove them than add them later. Figure 2 shows the function of these movers.

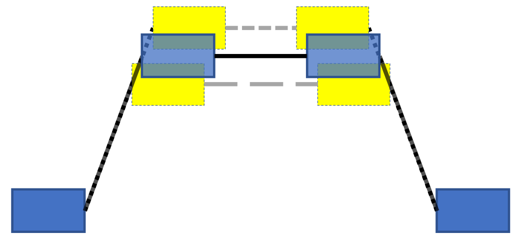

Figure 2: Mover system for the Splitters. Blue rectangles are dipoles, and yellow ones indicate possible positions of the dipoles after moving. The grey lines show the orbit for the different paths.

While it would be a simpler design to recombine each line in a manner symmetric to that in which they were separated, this is not simpler operationally, and it would limit the number of quadrupoles, diagnostics, and other equipment that can be installed on the lines. Furthermore, recombining through common dipoles may result in difficulties matching each pass into the FFA arcs, as they are not entering these arcs co-linearly. Instead, each pass is recombined and matched into the FFA arc independently. This allows for most of the lines to have a final matching section just before the FFA Arcs, giving operators more fine control over each pass.

Fitting all of the beamline components into the available space is extremely challenging. Many components are interleaved with those from other beamlines, and concerns of magnet cross-talk are legitimate. This often forces compromises over the ideal placement of beamline elements. Much of this pressure would be relieved if we reduce the number of passes to five rather than six. This idea is under consideration.

After the geometric layouts were complete for all passes, ToFs were corrected. To accomplish this, the path lengths in each chicane were adjusted by changing drift lengths and dipole positions to be sure that each pass would arrive at the correct part ($n \times 2\pi$) of the RF phase in the SRF LINAC. This was only done for the currently completed sections of the beamline and did not account for missing sections which are currently being designed [22]. It will need to be repeated once the rest of the design is complete.

OPTICS DESIGN

After the geometric design work and corrections for ToF and path length, the priority switched to designing the optics. Each of the six lines has unique input parameters as well as unique match requirements into the FFA arc.

Figure 3 shows the current floor plan layout. No components are touching any other component (though they are

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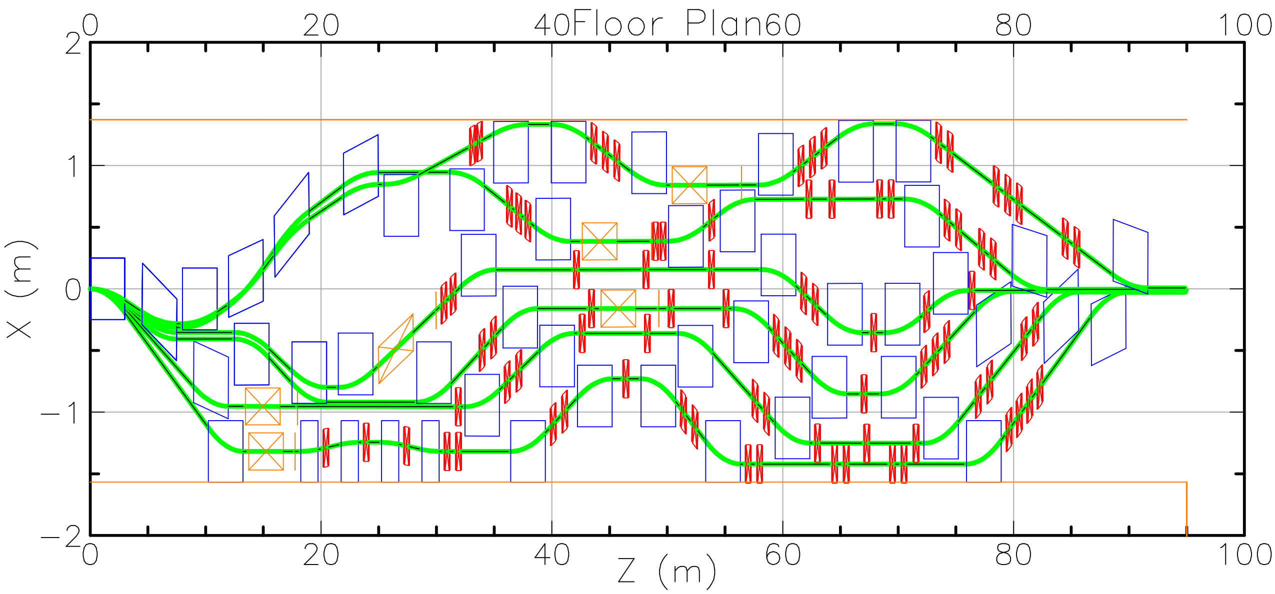

Figure 3: Overhead view of Splitter floor plan. Note unequal scales. Dipoles (blue), extraction dipoles (orange), and quadrupoles (red) shown with real dimensions. Horizontal orange lines show transverse spatial limitations with the wall at the top and the walkway at the bottom. Beam travels left to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

often close). Some of the downstream-end dipoles will need to be chamfered to reduce overlap with the common beamlines. Furthermore, fringe and stray-field protections will be needed, such as carbon steel beam pipes and other mitigation strategies.

Due to the geometric design, all trajectories are entering the FFA arcs at the correct positions (not co-linearly), and the ToF is correct for the current design state of the machine. Matching the optics ($\alpha_{x,y}$, $\beta_{x,y}$, η_x, η'_x) alone into the FFA arcs can be accomplished for each line, albeit with large β values. However, once R_{56} compensation is added, these solutions are no longer valid. The dispersion inherent to the geometric layout is of the wrong sign and must be changed using strong quadrupoles. These quadrupoles do not fit in the lattice until after tens of meters, thus necessitating heavy-handed dispersion kicks which also impact the optics parameters.

Currently, all of the optics parameters can be matched into the FFA in the absence of R_{56} compensation. Several of them can be matched if R_{56} compensation is included. However, to ease the burden of matching, a different match point along the FFA cell will be used going forward. Currently, matches have been assuming an entry into the FFA arc at the beginning of an FFA cell, but if one assumes entry at the halfway point of an FFA cell, the optics matching parameters may prove easier to achieve, as the α terms are zero and the β terms are at a maximum or minimum.

Figure 4 shows some of the current optics. In this case, matching was possible with horizontal β and R_{56}, was close with η_x, β_y and $\alpha_{x,y}$ for most beamlines, and not close with η'_x except a few beamlines. For more details and plots, please see the poster that accompanies these proceedings.

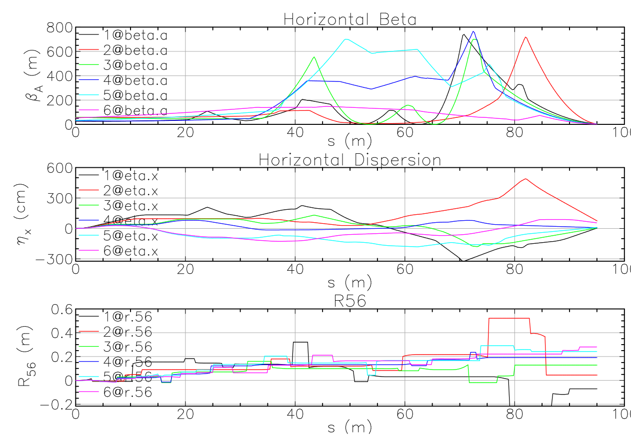

Figure 4: β_x, η_x, and R_{56} matching.

SUMMARY

Work will continue to find robust matching solutions for all of these Splitter beamlines. The match parameters will be updated to match into the midpoint of an FFA cell in the hopes that this will open more solutions. The process will be iterated as more elements of the overall FFA@CEBAF design are completed and the input parameters into the Splitters change. For further details and plots, please see the tech note describing constraints and geometric layout [20] and the poster which accompanies this document.

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