DESIGNING THE SPREADERS AND SPLITTERS FOR THE FFA@CEBAF ENERGY UPGRADE*

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Abstract

The FFA@CEBAF energy upgrade study aims to approximately double the final energy of the electron beam at the Continuous Electron Beam Accelerator Facility (CEBAF). It will do this by replacing the highest-energy recirculating arcs with fixed-field alternating gradient (FFA) arcs, allowing for several more passes to circulate through the machine. This upgrade necessitates the re-design of the vertical spreader sections, which separates each pass into different recirculation arcs. Additionally, the FFA arcs will need horizontal splitter lines to correct for time of flight and R_{56} . This work will present the current state of the spreader re-design and splitter design.

INTRODUCTION

Jefferson Lab's Continuous Electron Beam Accelerator Facility (CEBAF) is a recirculating linear accelerator capable of accelerating electrons up to a nominal energy of 12 GeV. To do this, the beam accelerates through a pair of 1.1 GeV linacs up to 5.5 times. To accommodate the recirculation, each energy beam is separated into an independent electromagnetic (EM) recirculating arc. These arcs are distributed vertically, and the lowest energy beams are bent toward the arcs which are physically the highest in elevation. Each successive energy passes through an arc of lower elevation until the beam is extracted into one of four experimental halls.

Looking forward, the lab is considering an upgrade which will approximately double the nominal maximum energy to 22 GeV using Fixed-Field Accelerator (FFA) technology [1–4]. Part of this upgrade involves increasing the injection energy from the current 123 MeV to 650 GeV [3, 4]. This increase in injection energy changes the ratios of the energies passing through the spreaders (and the mirror-image recombiners located on the opposite end of each arc). This change necessitates a redesign of the spreaders/recombiners, both to accommodate the different ratios, but also to upgrade magnets which cannot handle the upgraded energies. This will be the focus of the first part of this paper.

The main key difference in the proposed upgrade is the use of FFA technology in our recirculation arcs. Specifically, the highest-energy recirculating arcs on each side of CEBAF will be replaced with multi-turn, permanent magnet FFA arcs [5, 6]. It is currently assumed that the pair of FFA arcs will each recirculate 6 passes of the beam. In the EM arcs, path length and time of flight (ToF) are corrected using dogleg chicanes, while R_{56} is corrected by adjusting the optics. For the FFA arcs, this is not possible. Therefore, horizontal splitters, similar in concept to those from the Cornell BNL ERL Test Accelerator (CBETA) [7], are required. The latter part of this paper will discuss the current state of the design for the splitters.

For the reader's understanding, our standard is to define the spreaders/recombiners as vertically bending, and the splitters as horizontally bending.

SPREADERS

The spreaders are located at the northeast (NE) and southwest (SW) corners of CEBAF, with the corresponding mirror-image recombiners taking up the northwest (NW) and southeast (SE) corners. For the purposes of brevity, this paper will focus on the spreader design, as the recombiners are designed to be mirror images of the accompanying spreaders in each arc. The numbering standard used at Jefferson Lab numbers after a pass through a single linac. This means that all passes in the North Linac (NL) and East Arc are oddly numbered, and all South Linac (SL) and West Arc passes are evenly numbered. Table 1 shows the nominal energies entering each pass in each arc. Please note, passes 9-20 (indicated in **bold** in the table) all pass through the same pair of FFA arcs.

Upon entering each spreader, all passes are in a common line. They are separated vertically by a common dipole magnet, with the lower energy beams being sent to a higher elevation. Some of the passes are then sent through a second common dipole, further separating them by elevation. The first four passes, often referred to as the EM passes, are sent into a two-step elevation change, leveling off after each step. This is done to help cancel vertical dispersion. Along the horizontal beamline after the first step, quadrupoles are placed to change the sign of the dispersion, as well as a single quadrupole (placed at the dispersion zero-crossing) to control the beta functions. Then, after the second step, the pass is matched into the EM arc proper.

The last 6 passes on each arc, often referred to as the FFA passes, are a new design. These passes are forced to follow the EM passes upward, but to a lesser degree, due to their increased beam rigidity. They share a common septum with the final EM pass. Then, after being separated from the final EM pass, the FFA passes go through a series

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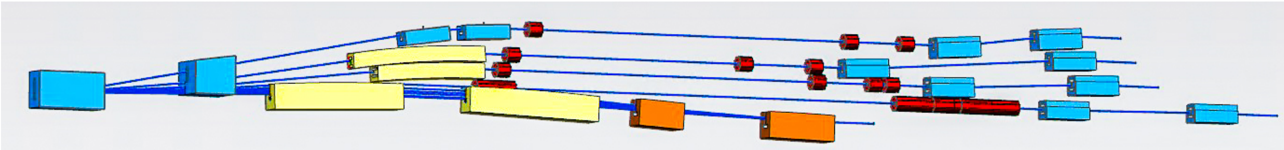

Figure 1: This is a model of one version of the new southwest spreader. Ten passes enter from the left and are separated vertically. The EM passes are fully separated into independent arcs, while the FFA passes are recombined into an FFA arc.

Table 1: Energies Entering Each Spreader

Location	Pass Number	Energy (GeV)
Northeast	1	1.750
	3	3.950
	5	6.150
	7	8.350
	9	**10.550**
	11	**12.750**
	13	**14.950**
	15	**17.150**
	17	**19.350**
	19	**21.550**
Southwest	2	2.850
	4	5.050
	6	7.250
	8	9.450
	10	**11.650**
	12	**13.850**
	14	**16.050**
	16	**18.250**
	18	**20.450**
	20	**22.650**

of reverse bends, which are mirror symmetric to those that raised their elevation. This mirror-symmetric chicane brings the FFA passes back to LINAC height and cancels dispersion. Figure 1 shows a version of the newly designed SW Spreader [8]. In Figure 1, the blue, yellow, and orange magnets are dipoles or septa. The red magnets are quadrupoles. The outer quadrupoles on each line are used for dispersion compensation. The central quadrupole is placed at the dispersion zero crossing and is used to adjust the optics.

Alternative versions exist, and further iterations will be made as the overall FFA@CEBAF design evolves. Furthermore, as start-to-end simulations are ongoing [9], fine-tuning of these designs is required, as the matching parameters and beam requirements are in flux.

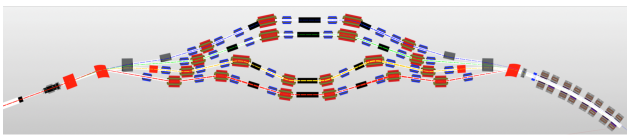

Figure 2: The CBETA splitters [7].

SPLITTERS

Since all of the FFA passes are contained within a single beamline, the dogleg chicanes present in the EM arcs are not capable of adjusting the path length. Instead, horizontal splitters, similar to those from CBETA [7], shown in Figure 2, are being designed. The splitter design at CEBAF is complicated by the significantly higher energies (requiring much larger magnets), the need for six lines as opposed to four, and the incredibly tight transverse space available.

Physical Constraints

Originally, it was envisioned to use four splitters in a symmetric manner, similar to the spreaders. However, CEBAF only has two access points for large equipment: one in the SE corner, and one in the NW corner. In order to allow access to the full site, it was decided to attempt using only two splitters to correct time of flight, R_{56}, and match the optics into the FFA arcs. If this proves to be infeasible or inadequate, alternative solutions may be required that will allow for both access for large equipment and four splitters to coexist. However, the current baseline dictates two splitters, each at the beginning of the respective FFA arcs, and two merge/match sections at the end of each FFA arc [10, 11].

Transversely, there is not a lot of available space for the splitters. The beamline center to the near wall is 1.37 m, and from beamline center to the far wall is 2.68 m. However, minimum personnel clearance is 44 inches $\approx$ 1.12 m. This leaves only ~2.94 m of space for all six passes.

Longitudinally, there are less constraints. The section of the machine defined as the Spreader region is approximately 45 m long. However, nearly 20 m of this space is used by the new Spreader design. The following section, Extraction, is available for some of the splitter line, as extraction will necessarily be different for the FFA passes (and is still under investigation). This gives another ~66 m of space, if needed. It is hoped that the splitter design will not encroach too far into the extraction region, as this will impede the number of FFA arc cells used for the arc. The general idea is to keep the length as short as reasonably achievable. However, given the tight transverse constraints, magnet interleaving will be necessary, which results in longer beamlines.

Design Methodology

The splitters must be designed to manage time of flight correction, R_{56} adjustment, and optics matching. Each pass must be separated, and contain chicanes to correct for time of flight. Furthermore, each pass needs eight quadrupoles to

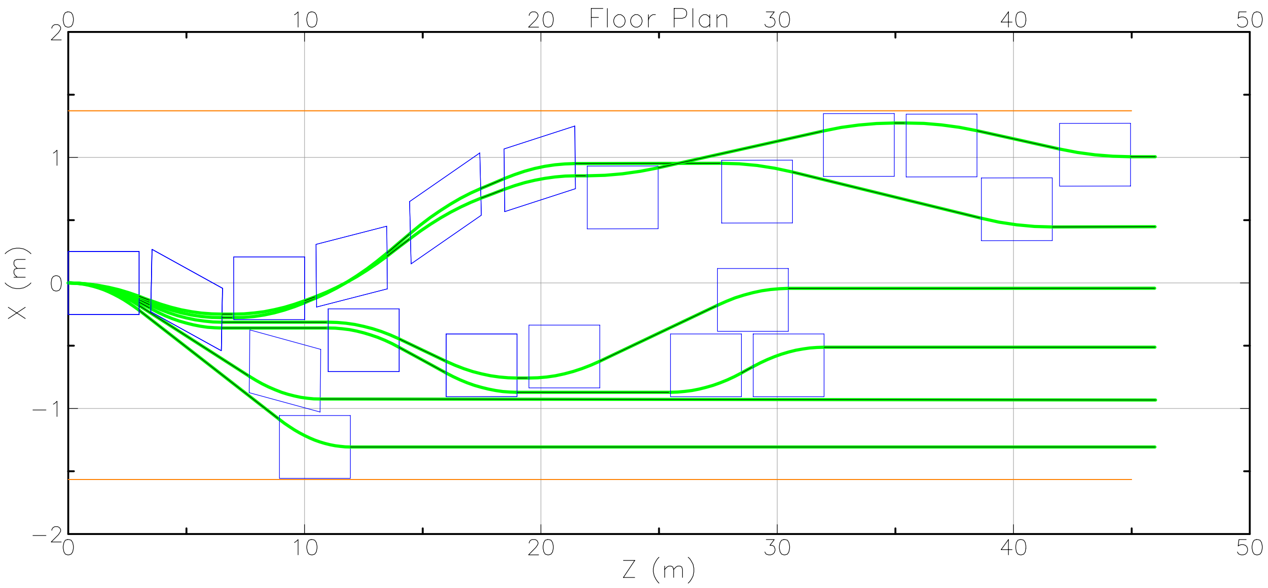

Figure 3: The NE Splitter is currently in the early stages of design. This plot shows the separation of each of the six passes horizontally. Please note, all magnets are 3 m rectangular magnets. The orange lines indicate the tunnel wall (top) and the walkway limitation (bottom). Oddly-numbered passes 9 through 19 are separated, with the lowest energy pass, 9, on the bottom of this image, and the highest energy pass, 19, at the top. Extra long drifts are included so that it is easier to visualize the transverse displacement of the different passes.

allow adjustment of these variables plus the standard optics matching.

Given the physical constraints, "fitting the pieces in the box" is the first step. To accomplish this, first the six passes need to be separated. Next, chicanes will need to be added, and then the passes recombined into a common line at the FFA arc. Quadrupoles will need to be added to each of the six lines, as well as space for diagnostics, vacuum pumps, and other auxiliaries.

Once the pieces are placed, path length will be adjusted for each line. All passes must be an integer number of wavelengths apart: CEBAF operates at 1497 MHz, giving a wavelength of just over 20 cm.

After the path lengths are adjusted, matching for the R_{56} and optics can take place. This matching will likely also impact the path length, so the process will be iterative until a robust solution is found.

Design work has started on the NE Splitter. Figure 3 shows the current state of the design. As of the time of this writing, six-pass separation has been demonstrated feasible within the limitations of the physical constraints. For this initial design, the same rectangular dipoles are used: all are 3 m long and 0.5 m wide (full width) [12], and all of these magnets are set to either 1.7 T or 1.0 T, depending on the need and location.

Some of the orbits may pass through regions of the magnets with poor field quality, or regions where the coils do not adequately reach. Additionally, some of the dipoles are placed extremely close to other magnets and beamlines. However, this initial step aimed to use a uniform magnet shape to identify spatial limitations and check for overall feasibility. Future iterations will include the use of permanent magnet dipoles in conjunction with these electromagnetic dipoles. The permanent magnet dipoles have lower fringe fields and smaller transverse size. Replacing sections of the EM dipoles with permanent magnet dipoles should help ease some of these concerns. Further iterations will also attempt to shorten the overall length of the separation, as the downstream chicanes and recombination section of the splitter will also require adequate space.

Iterative design work on both splitters will continue as described above, with the goal of proving the feasibility not only of fitting the splitters within the physical constraints, but also achieving the required goals in two, rather than four splitters. If this proves futile, investigation of four splitters will need reconsideration.

CONCLUSION

The current state of the design for the FFA@CEBAF Spreaders and Splitters has been presented in this work. Future work will iterate and improve upon these designs. Please see the accompanying conference poster for further complimentary details.

ACKNOWLEDGEMENTS

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