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SUMMARY OF JEFFERSON LAB LDRD ON FFA@CEBAF BEAM DYNAMICS SIMULATIONS*

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Abstract

As Thomas Jefferson National Accelerator Facility (Jefferson Lab) looks toward the future, we are considering expanding our energy reach by using Fixed-Field Alternating Gradient (FFA) technology. Significant efforts have been made to design a hybrid accelerator which combines conventional recirculating electron LINAC design with permanent magnet-based FFA technology to increase the number of beam recirculations, and thus the energy. In an effort to further this progress, Jefferson Lab awarded a Laboratory Directed Research and Development (LDRD) grant to focus not on the design, but on detailed simulations of the designs created by the larger collaboration. This document will summarize the work performed during this LDRD, and direct the reader to other proceedings which describe elements of the work in greater detail.

INTRODUCTION

As the design of the FFA@CEBAF energy upgrade develops, a full validation of the optics and beam dynamics must occur to be sure that the design is feasible. The collaboration is responsible for conceptual designs [1–8], but the task of ensuring the viability of the design must be completed. This includes error analysis, beam loss and power deposition studies, and the development of diagnostics requirements. This work also needs to identify and address any problems that are found with the design, feeding back into the design process when necessary.

To address this need, Jefferson Lab awarded an LDRD grant to focus on the start-to-end simulations and error analysis needed to insure viability of the conceptual designs. This grant was funded from Fiscal Year (FY) 2022 through FY23 (October 1, 2021 through September 30, 2023).

This report will summarize the results of our work, pointing to the relevant proceedings for further details. It will also discuss implications for the overall design of CEBAF's FFA-based energy upgrade, and further work which must be performed or repeated in order to complete a full Start-to-End (S2E) simulation. More detailed discussions can be found in a technical note [9].

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WORK PLAN

Initially, this project was planned and approved to take three years. However, the LDRD program at Jefferson Lab was updated, and limited all projects to two years in total. This necessitated a change of scope after the first year.

The plan for the project involved funding a PhD student to perform studies on the FFA arcs to be installed for the energy upgrade. These studies included error analysis, development of a diagnostic and correction scheme for the FFA arc, and providing initial requirements for the placement of diagnostics and correctors. Details of this work can be found in [10] and these proceedings [11].

The plan also called for hiring a postdoctoral researcher to "upgrade" the rest of the CEBAF facility. This work included identifying sections of CEBAF, updating the optics for higher energies, performing error analysis, and connecting the adjacent segments together for realistic S2E simulations. Details of this work can be found in these proceedings [12].

RESULTS

The majority of the work for this project can be divided into two main categories: work on the FFA arc, and work on the Start-to-End simulations (using Bmad and elegant [13, 14]). Each of these sections will be described separately below.

FFA Arcs

The first step in this work was to identify the significance of various beam and lattice errors. For the former, one of the best ways to do that is to perform an "acceptance" study, whereby input beam parameters are varied as inputs into the lattice, and only those that survive to the end of the lattice are plotted.

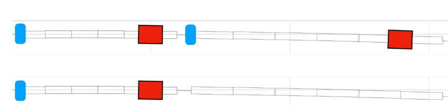

Figure 1: Two placement options for the BPMs and Correctors, shown in blue and red, respectively.

Lattice studies were performed, including lattice components misalignment. To correct these errors (as well as beam errors), a multipass correction scheme was developed. Placement of the diagnostics, as well as the corrector magnets, was determined using statistical analysis [11, 15]. The BPMs are assumed to be button-style BPMs, due to space constraints between FFA magnet cells. The correctors are assumed to be Panofsky-style quadrupole correctors with additional dipole windings, which will be placed over the

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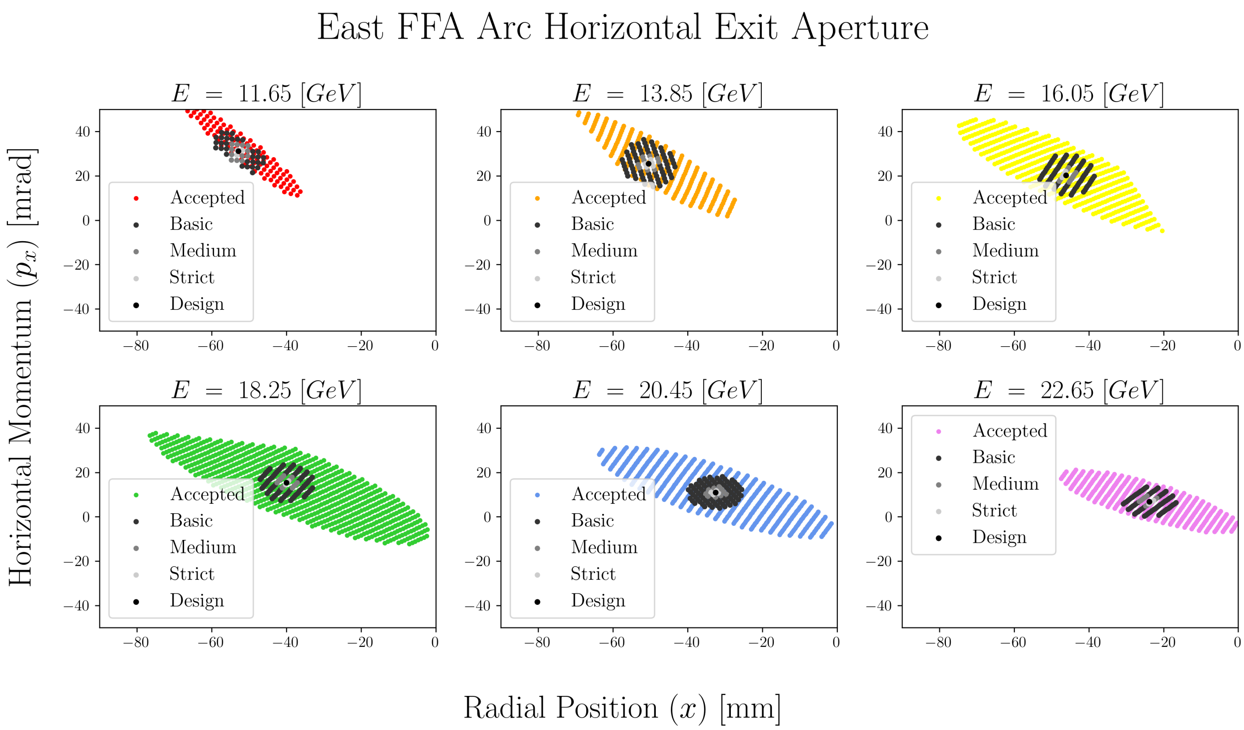

Figure 2: Survival plots of beams in the East FFA Arc for each energy. Points plotted survive to the end of the Arc with linear corrections applied. The different colors on each subplot indicate the restrictions on emittance exiting the FFA Arc.

Halbach magnet arrays [16]. Figure 1 shows the placement of the diagnostics and BPMs.

Figure 2 shows the results of the aperture study for the East FFA Arc. These plots show the phase space ellipses that are capable of being transported through their respective FFA arcs after linear (steering) corrections are applied. The different colors of each subplot are indicative of placing limitations on the emittance exiting the FFA arc. “Strict” means the most restrictive acceptable emittance, and “Basic” is the most flexible allowable emittance. Please note that these plots do not specify the beam quality on the output end.

The initial correction scheme was developed using the standard Singular Value Decomposition (SVD) method, which creates orthogonal tuning knobs to control each of the six passes and correct their orbits toward the nominal trajectories. In order to correct multipass beams, one must weigh how this will be done in an operating machine: the lowest energy pass must successfully transverse the machine, then the next higher, continuing until the highest-energy pass. Corrections occur in the same order, where the lowest-energy beam is corrected first, ensuring proper optics at the output and that the beam survives to the next pass. Once the knobs are selected for that pass using the SVD method, those correctors are effectively frozen and not used for future tuning.

After developing the correction scheme, the data from this work was used to train a Neural Network (NN) to see if it was capable of correcting the optics to a similar or better level than the standard method. In the end, the NN is capable of correcting at the same level as the SVD method, but much more quickly. These results are detailed in other proceedings from this conference [11].

Start-to-End Simulations

Figure 3: Image showing the “promotion” of the magnets and optics from the higher energy passes to the lower energy passes.

While much of the focus of the FFA@CEBAF energy upgrade focuses on the new FFA arcs, start-to-end simula-

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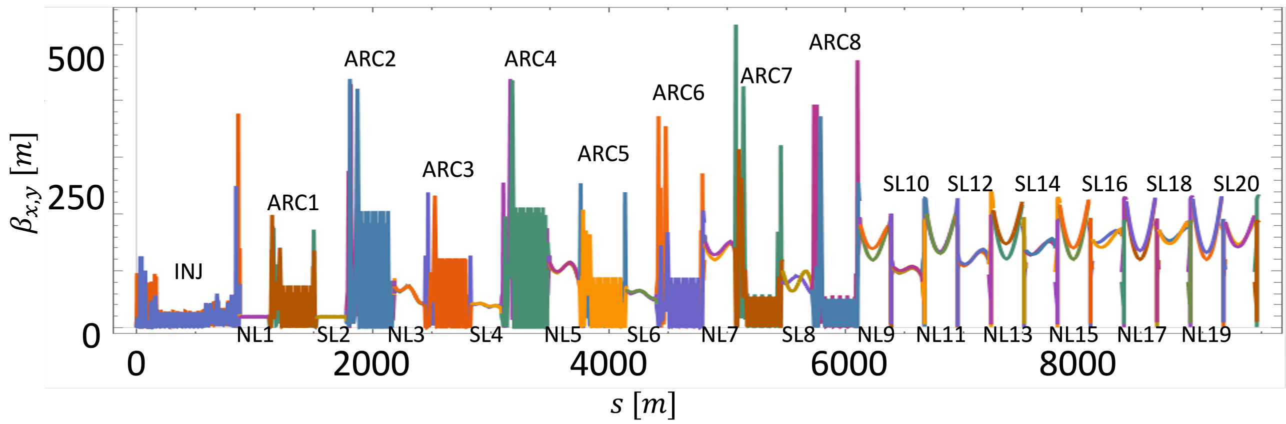

Figure 4: β_x and β_y throughout the upgraded CEBAF, with the exception of the FFA Arcs and yet-to-be designed sections.

tions must include the whole CEBAF facility, including the sections that currently exist, but which will see different energies. This work involved converting all of CEBAF's current lattices to handle higher energies, as well as updating the LINAC optics and rematching the whole electromagnetic (EM) machine.

The optics of each EM recirculating arc needed to be "promoted" in a manner where the optics from a higher-energy arc in the 12 GeV machine were re-used and rematched at a physically higher, but lower-energy position. This is needed because the current dipole magnets are near their operational limits in the current 12 GeV machine, and the new 650 MeV injection energy would increase the energies in each arc beyond their capabilities. Figure 3 shows this graphically.

Once the arcs were promoted, the re-designed spreaders and recombiners [17] were matched to the arcs. With the LINACS matched to the spreaders and recombiners, and those matched to the arcs, efforts were then focused on the remaining sections of the electromagnetic (EM) CEBAF. The remainder of the passes are FFA passes and depend upon the completion of the sections between the LINACs and the FFA arcs, which are still in the design phase at the time of this writing.

Since the sections connecting the Spreaders to the FFA Arcs (this section is the horizontal Splitters [18]), and the section connecting the FFA arcs to the Recombiners (called the Transition section [19]) are not finished, a "match" matrix was used to match the optics from one section to another. Once those sections are completed, they can replace these "match" matrices.

These efforts are summarized in Fig. 4, which plots the $\beta_{x,y}$ functions starting at the exit of the new injector [20], propagating through the entire EM CEBAF, and showing the LINACs in the FFA passes. In this figure, the optics within the new injector, Splitters, Transition, and Extraction are not represented, and the FFA arcs are not shown, as at this scale they would appear to be lines. Instead, the "match" matrices were used to propagate the beam. The experimental Hall lines can also be included once the Extraction system has a solution.

IMPLICATIONS OF RESULTS

Given the assumption that the machine baseline changes minimally, this work could have been readily completed upon the completion of the collaboration's design efforts. However, during the process of designing the Transition section, it was determined that the Weakly Focusing LINAC optics used β functions that are far too large.

It was then decided to revert to an earlier LINAC design, which uses Strongly Focusing Triplets. This was the design from 2021, and it uses smaller β functions in both planes. The benefit of returning to this earlier design is that designing the Splitters and Transition is easier. However, this change also requires rematching the entire EM CEBAF again. At the time of this writing, only the North LINAC optics have been completed.

The work from this LDRD project provides the framework for future start-to-end simulations. The code infrastructure and organization exists, and most of the EM CEBAF will not change, but the entire machine must be rematched with the new optics.

CONCLUSIONS AND FUTURE WORK

Given the scope of this LDRD project within the greater collaboration, as well as the rules and changes of scope required by the LDRD program, this work was able to meet all of the milestones, though some were on the contingency track. This project was successful in creating and building the organization, code, and overall infrastructure to redo the work for the updated designs provided by the FFA@CEBAF collaboration. As the collaboration continues its work, the work performed by this LDRD should enable a more rapid turnaround of the required simulations to attain a full start-to-end simulation.

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