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DESIGN PROGRESS FOR THE 22 GeV CEBAF ENERGY UPGRADE*

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Abstract

In this work we examine the progress made in the design of the proposed FFA upgrade to the Continuous Electron Beam Accelerator Facility (CEBAF). This proposed upgrade will double the number of passes through the two linacs by replacing the two highest energy arcs with new Fixed Field Alternating Gradient (FFA) arcs, roughly doubling the energy. These FFA arcs will use permanent magnets in a Halbach configuration to shape their fields. The design involves new optics for the linacs and remaining electromagnetic arcs, as well as new electromagnetic separators. These feed into the permanent magnet FFA arcs. We also report on ongoing studies of the dynamics of the beams, and an experiment to measure the effects of radiation on the permanent magnets.

THE CEBAF ACCELERATOR

Since 1994 Jefferson lab has operated the Continuous Electron Beam Accelerator Facility (CEBAF) [1]. CEBAF is a five-pass recirculating linac, which initially had a top energy of 6 GeV. These 6 GeV electron beams would then collide with fixed targets in three experimental halls, A, B, and C. Starting in 2015 the lab doubled its top energy to 12.1 GeV by adding 10 new cryomodules (five in each linac) which added an extra 1 GeV in acceleration per pass [2]. An experimental hall was also added with an extra half pass of acceleration. This upgrade was completed in 2017 and has been operating since. A diagram of CEBAF is shown in Fig. 1.

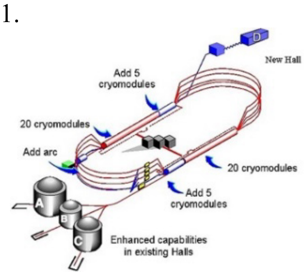

Figure 1: CEBAF after the 12 GeV upgrade.

Looking forward the lab is investigating future upgrades to CEBAF, the two we are focusing on are positrons and an energy upgrade [3,4,5].

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THE 22 GEV UPGRADE

The previous energy upgrade involved adding more acceleration capacity to the linacs of CEBAF, this was possible since there was empty space already planned in for future expansion. Increasing the amount of superconducting acceleration also required an increase in the cryogenic capacity of the lab as a whole. Due to the expense of adding more acceleration, the current plan for an energy upgrade will increase the number of passes through each linac, instead of increasing the acceleration of each linac.

In order to fit five additional passes into the existing tunnel we plan to replace the highest energy arcs on each side with Fixed Field Alternating Gradient (FFA) arcs each of which will be able to accommodate 6 passes of beam within a single beam pipe. FFAs date back to the 1950s [6], and there have been examples that are rings [7] and that are recirculating linacs [8].

In order to make sure the highest 6 passes through the FFA arcs have the proper beam parameters, we are adding horizontal splitters that will adjust the envelope functions, pathlength, and M_{56} to the proper values. We will also be adding an FFA based transition section to bring the beams back to being colinear as they enter the linacs. We also have initial designs for an extraction system to send the beam to the various halls, as well as a new injector that would make use of our existing Low Energy Recirculator Facility (LERF) [9]. A block diagram of the current upgrade baseline is shown in Fig. 2.

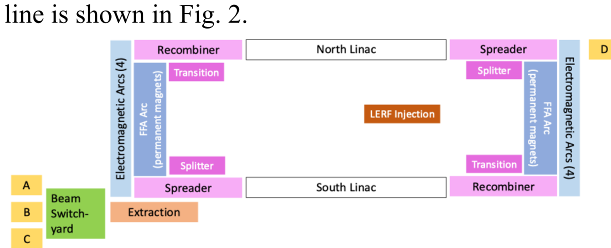

Figure 2: The plan for the proposed upgrade of CEBAF. Darker colors denote new additions to existing CEBAF infrastructure.

Linac Optics

While the current plan for the 22 GeV upgrade is to use the same accelerating cavities that are currently used in CEBAF, the optics will have to change. The lattice that keeps the beam focused and under control during acceleration tends to have diminishing effectiveness with each subsequent pass the electron beam takes, in the current 12 GeV machine the final pass almost acts like a drift from

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the electrons' perspective. We therefore need to alter the optics of the linacs so that we both don't overfocus the lower passes, while keeping the higher passes under control. An example of the updated optics is shown in Fig. 3.

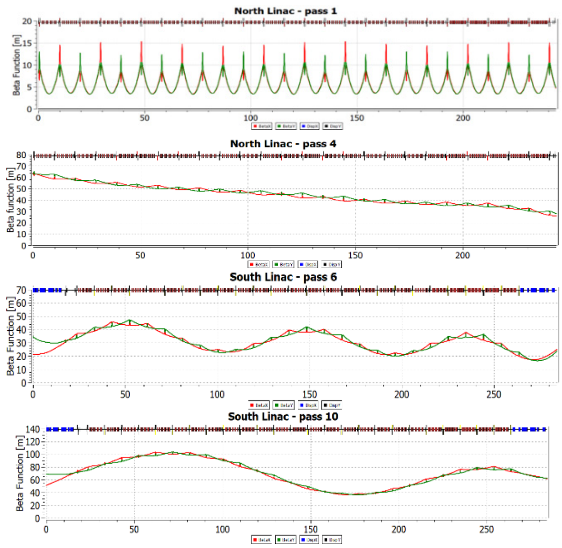

Figure 3: The beta functions of the beam as they pass through the 1st and 4th passes in the North Linac, and the 6th and 10th passes of the South Linac.

Horizontal Splitters

In order to bring the beam into the arcs with the proper separation and beam envelope properties we need to add a set of horizontal splitters. For the currently operating version of CEBAF we use a set of vertical spreaders to separate the different energies of beams for recirculation. Since there is not sufficient space to double the number of vertical spreaders, and since we need to funnel 6 different energy beams into the same beam pipe, we have opted to use horizontal splitters for the 6 highest passes.

These splitters must fit within a rectangular area of 2.939 m by 92 m. The length is determined by the distance between the last cryomodule and the beginning of the arc, and the width is constrained by the need to keep enough of the tunnel clear to allow personnel to move freely past this portion of the machine. While we have researched other designs for the splitters [10], the current baseline design for the horizontal splitters is shown in Fig. 4.

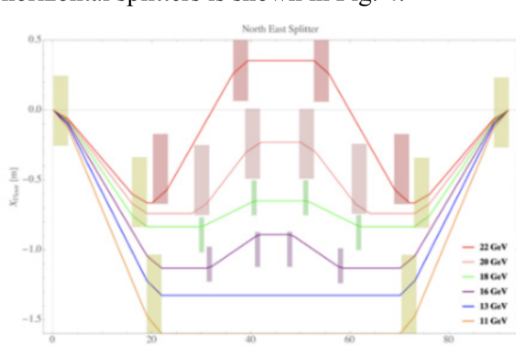

Figure 4: The current design for the horizontal splitters. The quadrupoles not shown, boxes denote dipoles.

FFA Arcs

Fixed Field Alternating Gradient lattices use a pattern of oppositely bending dipoles to not only bend the beams, but also to provide focusing without the need for quadrupoles. They have the advantage of a momentum acceptance that is so large that it can hold multiple passes of beam. Our design makes use of the lessons learned during the CBETA project at Cornell University which built and operated an FFA based recirculating linac using permanent magnets.

In order to more finely control the optics of each beam as it moves through the FFA arcs the permanent magnets are arranged in a Hallbach array [11,12]. Examples of the Hallbach array and the orbits of the beams moving through the arcs are shown in Figs. 5 and 6.

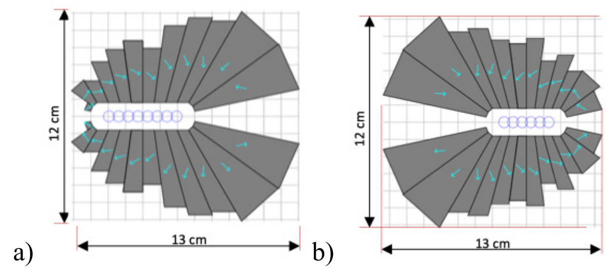

Figure 5: A cross section of the Hallbach array magnets. With a) being the focusing magnet and b) being the defocusing magnet.

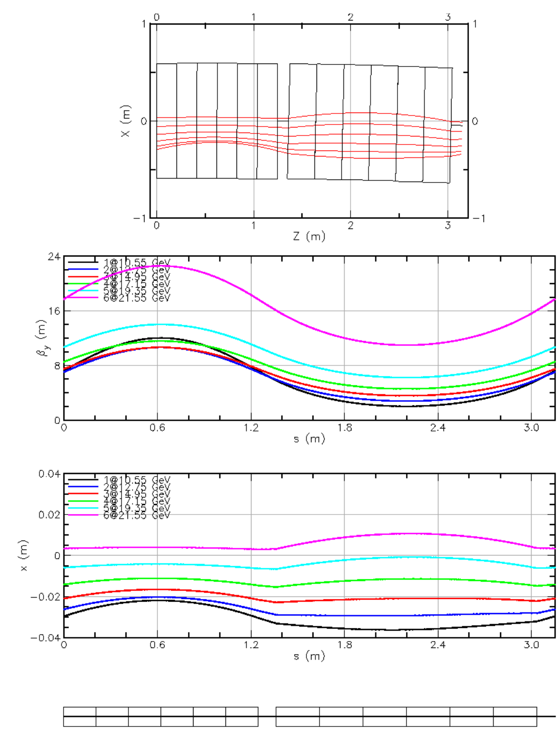

Figure 6: The orbits of the electron beams through the FFA arc as well as the vertical beta. In this figure the horizontal dimensions are magnified by a factor of 10.

Transition Sections

The transition section serves two main purposes, it has to bring the beams back to being co-linear, with the proper envelope functions, while simultaneously leaving enough

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lateral space in the tunnel to move cryomodules in and out. This is accomplished with another FFA type of lattice that will gradually change its magnet properties as the beams get closer to the linacs. An example of the envelope functions and horizontal separation is shown in Fig. 7.

Extraction Sections

Once the electrons have been accelerated, they need to be extracted and sent to the halls. In the current iteration of CEBAF we use horizontal and vertical RF separators which allow us to send beam at any pass to each of the three main halls, while simultaneously sending beam to Hall D.

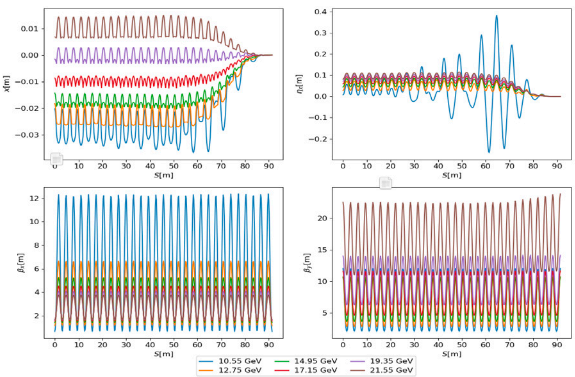

Figure 7: The orbits and envelope parameters of the transition section.

For the proposed upgrade the only place we could put extraction for the higher passes would be in the horizontal spreaders. The current idea is to place RF cavities on either end of the horizontal spreaders that would add, then subtract a vertical kick. The optics of the spreaders would nominally keep the kicked beam within their aperture, while the pass to be extracted would change its phase advance so that the kicks were amplified and the beam extracted. A diagram of this scheme is shown in Fig. 8.

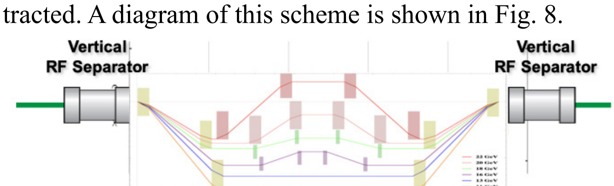

Figure 8: A diagram of our extraction setup.

While passes 1-4 would be extracted as they were before, if halls A, B, or C want beam at the higher passes, they all have to receive the same energy beam.

Injection Section

Both the spreaders and splitters require the different passes to have energies with strict ratios so that shared magnets will bend them at the correct angles. In order to make these angles work with the higher number of turns we need to increase the overall energy of the beam being injected into the first linac. Since the portion of the tunnel currently housing CEBAF's injector is not large enough to give the energy we need, we are looking at making use of the LERF complex already at Jefferson Lab.

The LERF is situated within the perimeter of CEBAF. We plan to build a smaller recirculating injector in the LERF complex, create a small tunnel that will connect the LERF vault to the CEBAF tunnel, and then build a transfer line that will transport the beam around CEBAF until it comes to the north linac where it will be injected. The current plan is for the LERF based injector to use existing cryomodules with added lines to bring the energy up to 650 MeV. The transfer line will likely be suspended from the ceiling of the tunnel as it wraps around, so the overall footprint will be small. A diagram of the transfer line of the proposed LERF injector is shown in Fig. 9.

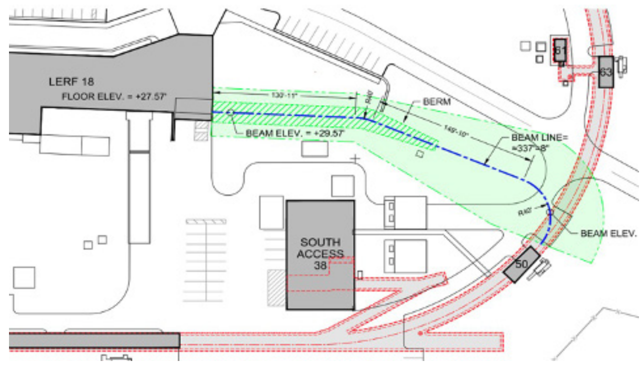

Figure 9: The transfer line from the LERF building to the CEBAF Tunnel.

CONCLUSIONS AND FUTURE WORK

A great deal of work has been done to design an energy upgrade for CEBAF. We are also actively performing other research in support of this goal. We are working on a test of permanent magnet resiliency in a radiation environment, which involves exposing permanent magnet materials to high radiation environments in the machine and periodically measuring them [13]. We also are investigating a short test line of our FFA magnets either in the beam switchyard portion of CEBAF, or in experimental hall C [14].

We currently have preliminary designs for all of the sections required of the upgrade. The next major step will be to integrate them together and do an end-to-end simulation. We also need to design the transfer lines that will take the beam from the extraction section to the experimental halls.

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