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DESIGN UPDATE ON THE TRANSITION BEAMLINE FOR THE CEBAF ENERGY UPGRADE*

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Abstract

For Jefferson Lab's 22 GeV upgrade, two new fixed field alternating gradient (FFA) permanent magnet arcs will be integrated to serve the accelerator's six highest-energy recirculation passes. Connecting these FFA arcs to the existing linear accelerator (linac) requires a carefully engineered transition section. The current design has two parts where the first part adiabatically matches the beam dispersion and orbit trajectories, while the second part aligns the Twiss parameters (alpha and beta functions) with those at the linac entrance. Given the tight spatial constraints and multiple matching requirements, a genetic algorithm is being explored to optimize beam optic matching. This paper presents current progress in developing and optimizing this transition.

INTRODUCTION

Jefferson Lab is evaluating an upgrade to the Continuous Electron Beam Accelerator Facility (CEBAF) that would approximately double the number of beam acceleration passes through its superconducting linacs [1]. Due to spatial constraints within the existing tunnel, a conventional expansion of recirculating arcs is not feasible. Instead, the proposed design introduces two new Fixed-Field Alternating Gradient (FFA) arcs, using permanent magnet technology [2], to accommodate the additional passes (see Fig. 1).

In the current CEBAF layout, each beam pass is directed through a unique electromagnetic (EM) arc. A recombination system then merges beams of differing energies into a common trajectory before returning to the linac. In the proposed upgrade, the FFA arcs transport all new passes within a single plane, which allows their recombination with existing EM arcs via a fixed magnetic chicane. However, this chicane does not provide independent control of optics for each energy pass. To achieve proper optical matching between the FFA arcs and the linac, a dedicated transition section is required. Although separating the FFA passes into multiple beamlines for individual matching would offer greater flexibility, it was not practical due to space constraints of the existing CEBAF facilities. Therefore, a combined matching

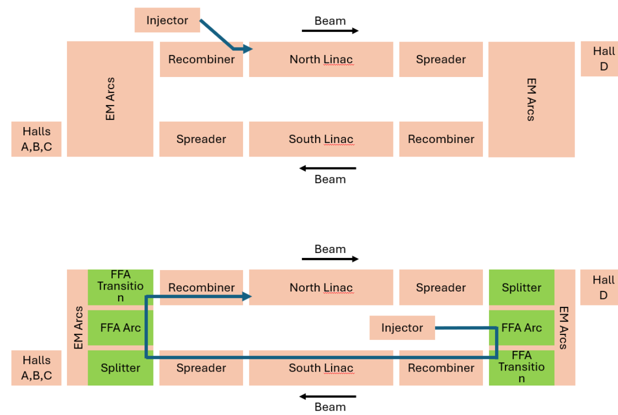

Figure 1: A block diagram illustrating the existing CEBAF layout (top) and the proposed configuration for the energy upgrade (bottom) is shown. In the upgraded design, the new FFA arc replaces the current lowest-energy electromagnetic arc and is positioned beneath the remaining arcs. To integrate this FFA arc into the CEBAF, a dedicated transition and splitter [3] sections for the high energy passes will be added, as shown. Extraction [4] is integrated into the splitter section.

strategy where all high-energies passes are simultaneously matched within a single FFA transport line is being worked on.

It is worth noting that the CEBAF linac provides virtually no focusing for high-energy passes and that favors large betas with small alphas, which is challenging to reach for all passes simultaneously in the limited space available while maintaining the beam size reasonably small.

TRANSITION BEAMLINE LAYOUT

In the previous design [5], a single beamline section was used to simultaneously suppress dispersion and orbit offsets while matching the Twiss parameters for all energy passes. However, this combined approach has shown to be suboptimal due to emerging issues (to be detailed later), which complicate achieving both objectives effectively within the same section. To address this, we are now exploring a two-stage transition scheme. In the first stage, the focus is solely on eliminating orbit deviations and dispersion across all energies. Once these are adequately corrected, the second stage performs the Twiss function matching required for

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linac injection. This separation provides greater control and flexibility in the optical design and is expected to improve matching performance for the upgraded beamline configuration.

In this layout, the transition section is limited to a straight segment of approximately 15 meters without any dipole magnets. This available length is insufficient to simultaneously match the orbits, dispersions, and Twiss parameters for all six high-energy passes. Given the complexity of handling multiple energy beams through a shared transport channel, a longer and more flexible matching section is required.

To address this issue, an alternative lattice configuration is being considered that would increase the tunnel space available for the transition optics. The CEBAF linac is composed of various types of cryomodules (C25, C75, and C100) where the number indicates the approximate energy gain per cryomodule in MeV. By replacing four C25 with a single C100, it is possible to gain nearly 30 meters of additional space that can be put towards the transition section. This substitution, while extending the available space, also preserves the required total energy gain per linac [6].

However, this modification also introduces new integration challenges. In particular, the recombiner section—which merges the multiple beamlines before injection into the linac—must be relocated further downstream to accommodate the shifted cryomodule arrangement. The implications of this downstream displacement on beamline alignment, timing, and infrastructure are being evaluated as part of the overall upgrade study. The section that deals with orbits and dispersion already uses some of the ARC space by slightly increasing and then reducing the bend angle of the FFA arc magnets adiabatically [7] as we previously discussed.

MATCHING BEAM PARAMETERS

Orbits and Dispersion

As mentioned previously, Orbit and dispersion matching are now treated independently from Twiss parameter matching, using a combined section consisting of part of the ARC and an adjacent straight segment. The method begins with adiabatic matching, in which the bending angles of the FFA magnets are gradually reduced following a third-order polynomial profile. This suppresses the bulk of the energy-dependent orbit and dispersion offsets without disturbing the overall optics. To correct the remaining residuals, a resonant excitation scheme is applied using a sequence of corrector magnets tuned to the betatron frequencies of the individual passes. The combination of adiabatic tapering and resonant correction allows all energy passes to be brought to near-zero orbit and dispersion as shown in Fig. 2.

Twiss Functions

The previous approach, which attempted to simultaneously match orbits, dispersion, and Twiss parameters within a single beamline section, showed limited effectiveness.

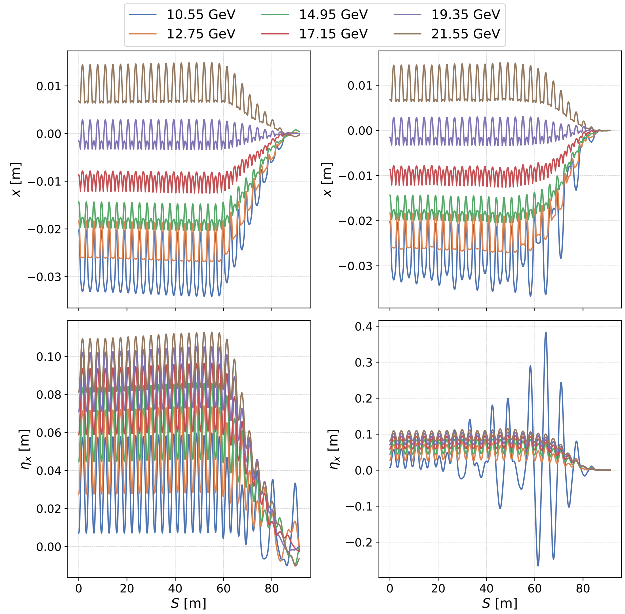

Figure 2: Comparison of beam dynamics in the north-west transition section with (left) and without (right) resonance correction in addition to the adiabatic correction which is applied to both. The top plots shows the horizontal beam orbits, while the bottom plots shows the corresponding horizontal dispersion functions.

While acceptable solutions could be found for a small number of passes, the addition of more energy passes introduced growing orbit excursions that became increasingly difficult to contain within the magnet apertures.

In addition to affecting orbits and dispersion, the application of harmonic resonance kicks for Twiss parameter correction also introduces significant cross-talk between passes. Ideally, a harmonic excitation applied to a single energy pass should only modify the targeted Twiss parameter in that pass. However, because of the lack of a fully orthogonal set of tunes between passes, the excitation couples across both planes and multiple energies. This results in unwanted distortions in non-targeted parameters.

Figure 3 shows an attempt to match the β_x functions of two high-energy passes and the resulting impact on other parameters. With β_x reaching a minimum when β_y is near its maximum, raising both simultaneously to acceptable levels becomes difficult without significantly increasing the overall beta functions. Since harmonic resonance kicks are most effective when the betatron oscillation remains stable, it is strongly preferred that the matching point satisfies $\alpha_{x,y} \rightarrow 0$.

GENETIC ALGORITHM

Due to the high dimensionality of the variable space and the complexity of the constraints, a genetic algorithm (GA) approach was considered. The matching problem involves a large number of coupled parameters, including magnet strengths, optics constraints, and targets for multiple energy passes. Traditional optimization techniques often struggle in

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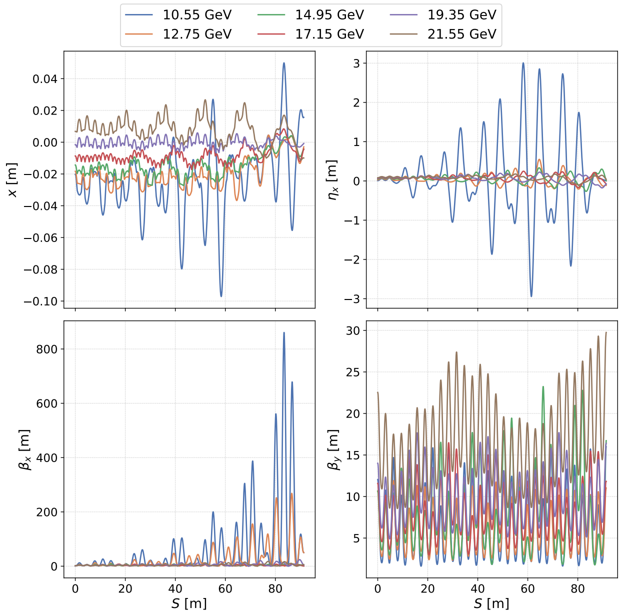

Figure 3: Twiss parameters of the north-west transition section with β_x corrected for the first two high energy passes. The top left plot shows the orbit and the top right plot shows the dispersion. The bottom left and right plots show the horizontal and vertical β functions, respectively.

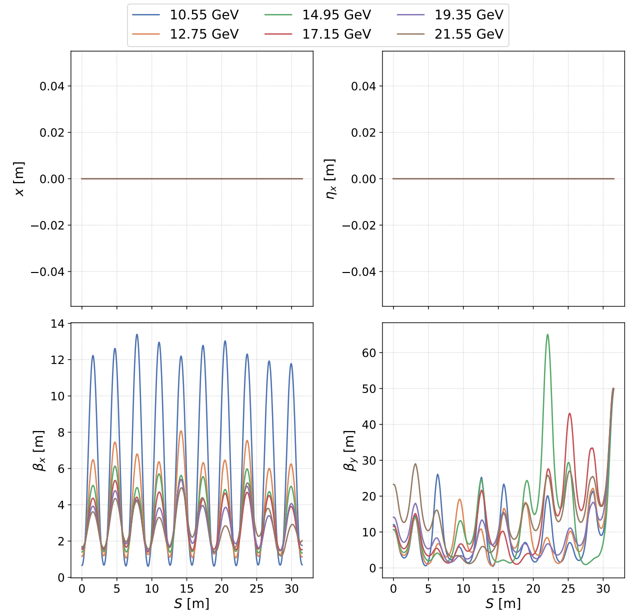

Figure 4: Twiss parameters of the north-west transition section with β_y corrected for the all five high energy passes. The top left plot shows the orbit and the top right plot shows the dispersion. The bottom left and right plots show the horizontal and vertical β functions, respectively.

such high-dimensional nonconvex landscapes, particularly when the solution space includes multiple local minima. A GA is a suitable choice given the large number of variables and constraints involved. Its ability to effectively search large parameter spaces without relying on gradient information makes it well suited to this optimization problem. The algorithm naturally handles multiple objectives and can be adapted to respect physical constraints through its fitness evaluation.

By using the `geneticalgorithm` library in Python, we were able to identify a viable solution to raise the vertical beta functions while keeping the horizontal betatron oscillations within acceptable limits. Figure 4 shows the results of this genetic algorithm optimization using a population size of 10,000 per generation over the course of 100 generations. It is important to note that the results shown are achevied using the new available space after the adiabatic matching section previously used in Fig.3.

ONGOING WORK

Although reasonable results were obtained in the vertical plane, the horizontal plane proved more difficult to match. This difficulty arises because the match point corresponds to a minimum of the horizontal β-function, while the vertical plane is matched near a maximum. Since both β_x and β_y ideally need to be of similar magnitude at the match point, achieving simultaneous optimization without significantly increasing the overall beta functions is challenging. To address this, we are exploring approaches that use coupling between the planes to our advantage, as well as alternative magnet configurations such as triplet focusing lattices, while maintaining the same phase advance per cell.

SUMMARY

Achieving fully ideal solutions remains challenging due to the presence of six high-energy passes sharing a common beam pipe. This makes it near impossible to find a completely orthogonal set of tunes, which would be required for the resonance harmonics to act independently on each plane and pass without cross-talk. However, separating the Twiss parameter matching from the orbit and dispersion correction has led to improved results, as demonstrated in this study. Furthermore, applying a genetic algorithm for optimization has significantly enhanced the quality of the Twiss matching.

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