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FFA@CEBAF BEAM TRANSPORT ERROR AND TOLERANCE SIMULATION STUDIES *

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Abstract

The Continuous Electron Beam Accelerator Facility (CEBAF) is a 12 GeV recirculating electron accelerator at the Thomas Jefferson National Accelerator Facility (JLAB). Major upgrades to the accelerator are being investigated which include a new 650 MeV injection beamline and state-of-the-art fixed-field alternating (FFA) gradient recirculation arcs. The upgrade will extend the energy of the electron beam to over 20 GeV. In this paper, we provide an error and tolerance simulation study of the amended beam optics transport of the existing accelerator tuned for 22 GeV operation. The study is conducted with the particle tracking codes elegant and Bmad in two parts. In the first part, we treat each section of the accelerator (electromagnetic arcs and linacs) modularly with ideal conditions at the beginning. The second part is a pseudo start-to-end (S2E) simulation with accumulated errors propagating from one beamline to the next.

INTRODUCTION

Major upgrades to the CEBAF accelerator that will extend the energy of the electron beam to over 20 GeV are being investigated by the FFA@CEBAF collaboration (Fig. 1). These upgrades will effectively divide the accelerator into electromagnetic (EM) and FFA parts. The EM portion of the accelerator will consist of a new injector and four passes through the linacs and EM recirculation arcs. The FFA portion will consist of six passes through the linacs, the splitters, FFA recirculation arcs and transition sections. Only the EM portion of the upgrade will be discussed in this paper.

The EM beam transport consists of two anti-parallel linacs (North and South) each containing 200 superconducting radio-frequency (SRF) accelerating cavities interspersed with a new triplet set of quadrupoles (D-F-D). Before each triplet, is a corrector magnet (successively alternating from horizontal to vertical planes) and beam position monitor (bpm) used for steering. Each linac provides ~ 1.1 GeV of energy gain and a total of ~ 2.2 GeV per pass. To recirculate the beam, two 180° horizontal arc sections (East and West) are used. Each arc is composed of a new Spreader/Recombiner bend system and a re-tuned arc proper section [1]. The spreader is an achromatic vertical bend system that displaces the beam to its respective arc proper section (depending on energy). The recombiner is the mirror image of the spreader. The arc proper section contains four flexible momentum compaction (FMC) cells and are tuned to make the entire arc isochronous. Due to the beam rigidity, four pairs (for East and West sides of CEBAF) of unique electromagnetic arc sections are designed for each pass.

Accelerator elements cannot be positioned or operated with perfect precision. It is therefore important to take these errors into account when designing beamlines for the FFA@CEBAF. This document describes the general method of error analysis done for the EM portion of the 22 GeV CEBAF with the weakly focusing optics in the linacs (latest findings have opted for strongly focusing optics which are still under development). The analysis is conducted in two parts. In the first part, we treat each section of the EM portion of the accelerator separately with ideal conditions at the beginning. The second part is a pseudo start-to-end (S2E) simulation of each error propagating from one beamline to the next. All simulation work presented in this paper was conducted using elegant and corroborated with Bmad [2, 3].

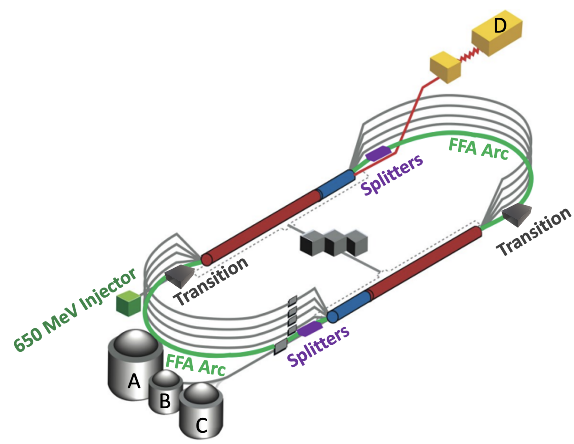

Figure 1: The current 22 GeV CEBAF baseline design. It consists of the upgraded 650 MeV injector (green box, actual location is in the center of the racetrack in the Low Energy Recirculating Facility (LERF)), linacs (red and blue), EM arcs (grey curves), FFA arcs (green curves), Splitters (purple), Transition (dark grey), and four experimental halls (A – D).

ERROR SOURCES

We tested for two types of errors present in the accelerator: positional and operational. Positional errors (see Fig. 2) are deviations of the spatial (δx, δy, δz) and angular (roll, pitch, yaw) position of elements with respect to the accelerator axis. All accelerators have limitations of precision in the alignment of their beamline elements. This can affect the fields that the electron beam experiences and perturb the

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design optics. A robust accelerator design can accommodate such alignment errors.

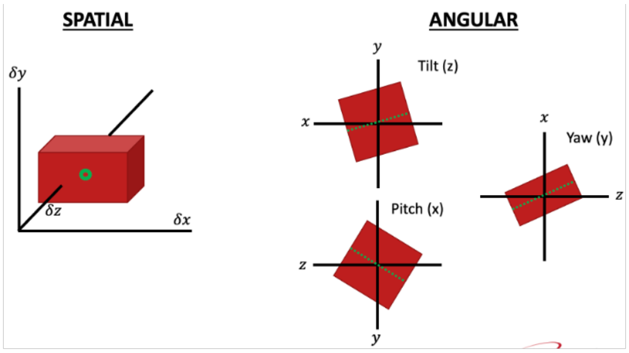

Figure 2: Description of positional errors tested in these studies.

Operational errors are deviations of magnet field strength from nominal. When a magnet has a magnetic field error, δB, it can cause a deviation in the design optics. For example, in a dipole magnet, a field error perturbs the bend radius, ρ, and deflection angle, θ_B. In a quadrupole magnet, a field error perturbs the field gradient, $\partial B/\partial x = g$, and focusing parameter, K_1. These perturbations can affect optical parameters such as betatron-mismatch, dispersion, and momentum compaction. Table 1 shows the range of various errors sampled for this study. These errors have been taken from past studies and are representative of a worst-case estimate of CEBAF's precision [4, 5].

Table 1: RMS Values For Various Errors Sampled From A Gaussian Distribution

Error Type	Units	RMS
Spatial Shift	µm	200
Angular Shift	mrad	2
Field Strength	%	0.01

ORBIT CORRECTION & ERROR TOLERANCE

Errors intrinsic to the accelerator environment can affect the machine's performance. So, it is essential that accelerators have an orbit correction scheme to ensure proper function. In CEBAF, orbit correction is achieved with an ensemble of horizontal and vertical corrector magnets (i.e. weak dipole magnets) and interspersed beam position monitors (BPM). The corrector magnets provide an angular kick to the beam and the BPMs give feedback on the beam response to the corrector kicks. Due to the finite number of correctors the orbit correction cannot be perfect. In practice, a successful orbit correction system is one that can keep various beam parameters within spec (e.g. emittance or energy spread). For these preliminary studies, we define the error tolerance only by the beam orbit not exceeding the accelerator's admittance (<1 cm).

Now, we provide simulation results of the orbit correction scheme with the upgraded 22 GeV optics in two parts. In the first part, we simultaneously impose all errors sampled from Table 1 on each beamline separately and implement the orbit correction procedure for a total of 10k simulation runs to develop statistics. In all simulations, the orbit correction system was successful in correcting the orbit within the accelerator's admittance (1 cm). An example of the orbit correction results for the first pass of the North Linac (NL1) is shown in Fig. 3.

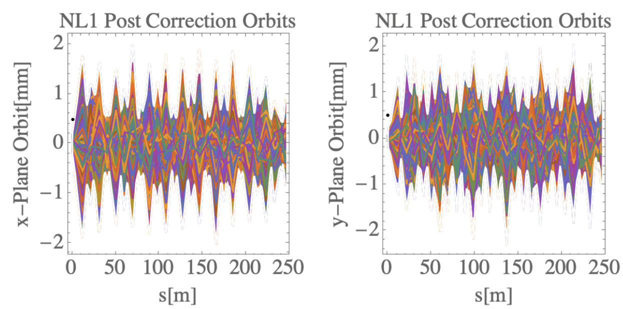

Figure 3: Horizontal (left column) and vertical (right column) orbit correction for the first pass of the North Linac (NL1) of the FFA@CEBAF accelerator. All errors are sampled from distributions detailed in Table 1. Only 100 runs of the total 10k runs are displayed.

For the second part, we impose the same errors as before but now on the entire EM portion of the CEBAF beamline and allow the errors to propagate downstream. The orbit correction system is then used to control the beam's orbit. The current 12 GeV correction scheme performs well and keeps the majority simulation's rms orbit within tolerance (Fig. 4). Of 10k simulation runs, there are < 4% of runs that result in orbits that exceed the chamber walls. In these instances, the violation occurred ~ 4 times more often in the vertical plane than in the horizontal. Spreader 4, 6 and 7 and Recombiner 8 are primary locations of beam loss.

CONCLUSIONS

In conclusion, this paper has presented preliminary results of error and tolerance simulation study for the FFA@CEBAF upgrade. The study focused specifically on the electromagnetic (EM) portion of the accelerator, addressing both positional and operational errors and if the current 12 GeV CEBAF orbit correction system is robust enough to handle the energy upgrade. The results demonstrated the efficacy of the orbit correction scheme ensuring that the beam orbit can be corrected within the accelerator's admittance. Looking ahead, as upgrades to the CEBAF accelerator progress, continued refinement of error analysis and orbit correction system will be crucial to evaluate the beam transport.

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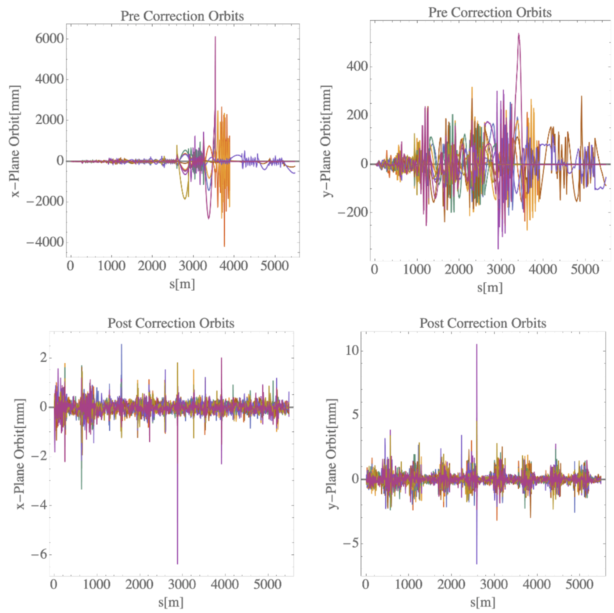

Figure 4: Horizontal (left column) and vertical (right column) orbit correction for the entire EM portion of the FFA@CEBAF accelerator. All errors are sampled from distributions detailed in Table 1. Only ten runs of the total 10k runs are displayed.

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