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COMPUTATIONAL SIMULATIONS AND BEAMLINE OPTIMIZATIONS FOR AN ELECTRON BEAM DEGRADER AT CEBAF*

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Abstract

An electron beam degrader is under development with the objective of measuring the transverse and longitudinal acceptance of the Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab. This project is in support of the Ce^{+}BAF positron beam capability currently under development. Computational simulations of beam-target interactions and particle tracking were performed using the GEANT4 and Elegant toolkits. A solenoid was added to the setup to control the beam's divergence. Parameter optimizations of a new solenoid and existing beamline quadrupoles were performed to further reduce particle loss through the rest of the injector beamline.

INTRODUCTION

The Jefferson Lab 12 GeV Continuous Electron Beam Accelerator Facility (CEBAF) delivers a beam of highly polarized electrons to provide experiments at four experimental halls. The proposed Ce^{+}BAF upgrade [1] intends to inject a positron beam through the accelerator. Due to the larger transverse and longitudinal emittance of the proposed positron beams, an accurate measurement of the CEBAF injector acceptance is required. In an effort to test the transport of larger emittance electron beams in a controlled way, an electron beam degrader was designed and is being installed in the CEBAF injector [2, 3].

The degrader is composed of a target ladder assembly with three carbon foils (thicknesses: 1 µm, 5 µm and 10 µm) and a view screen, two apertures used to define the degraded beam transverse emittance (aperture size combinations: 1 mm/4 mm, 3 mm/4 mm and 3 mm/8 mm) and a solenoid for divergence control. This degrader will be located approximately 9 meters downstream of the injector booster quarter cryomodule. A schematic of the injector beamline with the degrader is shown in Fig. 1. A model of the degrader is also shown in Fig. 2.

This contribution describes studies done for the design of the degrader consisting of beam dynamics and beam-matter interaction simulations and beam loss minimization by adjusting the solenoid field and gradient of the closest focusing quadrupoles.

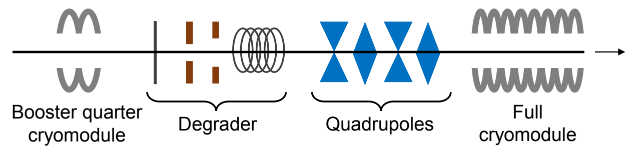

Figure 1: Schematic of a section of the CEBAF injector beamline with the position of the degrader. The arrow denotes continuation to the rest of the injector beamline.

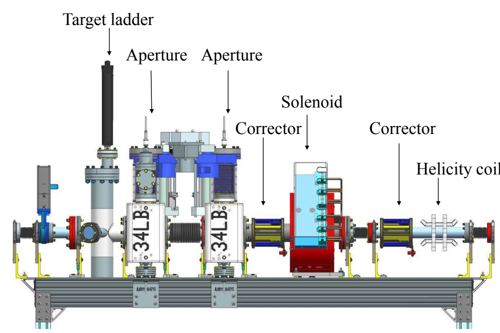

Figure 2: Model of the electron beam degrader. The electron beam flows from left to right.

Table 1: Simulated Beam Parameters at the Target

Parameters	Values
E, [MeV]	6.24
ΔE [keV]	6.72
ε_x, ε_y [mm mrad]	0.0813, 0.0813
σ_x, σ_y [mm]	0.81, 0.52
α_x, α_y [-]	2.62, -0.27

DEGRADER SIMULATIONS

Beamline simulations were conducted using GEANT4 [4] for beam-matter interactions, and Elegant [5] for beam tracking. First, a beam distribution is generated at the target position based on previously simulated beam parameters. These parameters are summarized in Table 1. The generated beam distribution is then imported into GEANT4 where the interaction of the beam with the target and the two apertures is simulated. Finally, the beam distribution at the exit of the apertures is exported to Elegant for further beam tracking through the rest of the CEBAF injector beamline. This pro-

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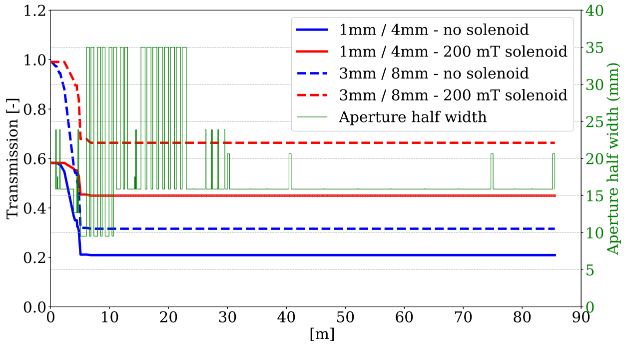

Figure 3: Simulated transmission comparison between runs without and with a 200 mT solenoid downstream of the second aperture. Target thickness for this run is 1 µm and aperture combinations are (1 mm/4 mm and 3 mm/8 mm). The approximation of the half aperture width for the rest of the beamline is shown in green.

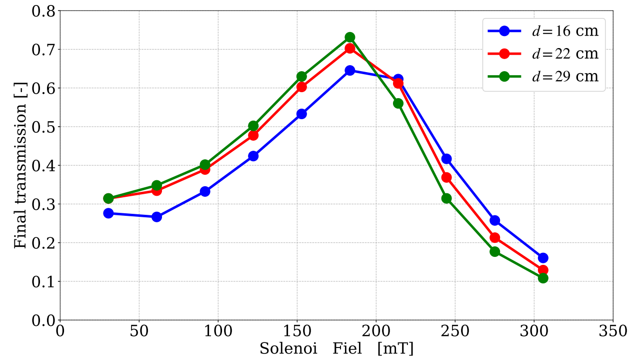

Figure 4: Simulated transmission at the end of the CEBAF injector chicane for different solenoid field values and distance to the second aperture (d). These simulations were performed with a 1 µm thick target, and 3 mm and 8 mm aperture sizes.

cedure was repeated for the different target thicknesses and aperture size combinations.

For these simulations, the beampipe and beamline elements aperture sizes are crucial since the degraded beam exhibits significantly larger emittance and size compared to the nominal electron beam. Therefore, an approximation of the whole CEBAF injector aperture size as a function of the longitudinal position was implemented to better estimate its impact on beam loss. This approximation has a rectangular shape, but will be refined to a circular shape in the future. The half aperture width is shown in Fig. 3. Preliminary results show that, even for the thinnest carbon target (1 µm), most of the beam was lost in the first 6 meters of the beamline due to the degradation. Consequently, a solenoid was added for beam divergence control. The position of the solenoid has some flexibility, but initially was as close as possible downstream of the second aperture, with a 200 mT maximum magnetic field on axis. As shown in Fig. 3, transmission was significantly improved by the addition of the solenoid, however substantial beam loss was still present in the same region.

SOLENOID POSITION OPTIMIZATION

The next analysis was a 2-parameter scan varying the solenoid magnetic field and its distance from the second aperture. This parameter scan was performed to optimize the transmission at the end of the injector beamline. The selected magnetic field range was from 30 to 300 mT, while the distance range was from 16 cm to 29 cm. The rest of the elements present in the injector beamline were left in their nominal settings. The simulated transmission for the different values of the solenoid magnetic field and longitudinal displacements is shown in Fig. 4. It should be noted that moving the solenoid further away from the second aperture helps achieve better transmission because the focusing length has a better match to the downstream beamline quadrupoles. Also, there is an optimum magnetic field value (around 180 mT) after which there is an overfocusing effect that reduces the maximum transmission. From these results, it was decided to position the solenoid as far downstream as possible.

MAGNETIC ELEMENTS OPTIMIZATION

With the position of the solenoid fixed, the next step was to modify the other magnetic elements to minimize beam loss through the rest of the injector beamline. Due to the position of the beam loss, the region of interest is the section between the exit of the degrader and the next accelerating cryomodule. In this region, the only focusing elements are three normal and one skew quadrupole. Thus, including the magnetic field of the solenoid, there are five free parameters.

The measured solenoid field map was implemented into GEANT4 in the form of fitted functions. In this manner, the implementation is faster and easier with almost no loss in accuracy. Simultaneously, the built-in optimizer in Elegant was used to identify the optimum setup with the highest possible transmission. The optimizer was run first with a solenoid element in Elegant and then refined with the solenoid field map in GEANT4. In the following sub-sections, the two solenoid models and their equivalence will be detailed.

Elegant Implemented Solenoid

The built-in solenoid element in Elegant is implemented as a 2nd order transfer matrix with fringe edge fields. The field inside the body of the solenoid is longitudinal and of constant magnitude B_0. From this, if L is the length of solenoid, the focusing length is inversely proportional to $B_0^2 L$ while Larmor rotation angle is proportional to $B_0 L$.

GEANT4 Implemented Solenoid

The implemented solenoid model in GEANT4 is more complicated. First, the measured magnetic field map is fitted to the linear optics approximation of the magnetic field of a solenoid with length L and transverse radius R.

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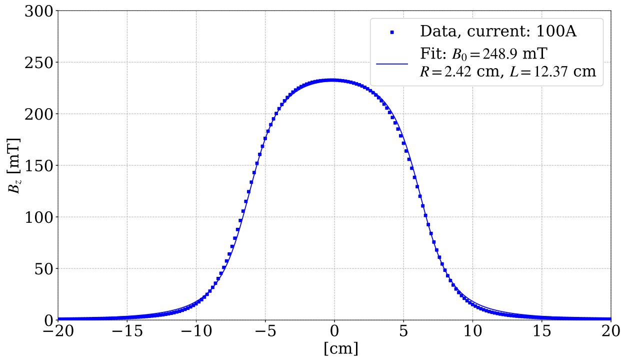

Figure 5: Fitted function to the longitudinal component of the measured solenoid magnetic field map. Fit was done to Eq. (1) via the B_0, L and R parameters.

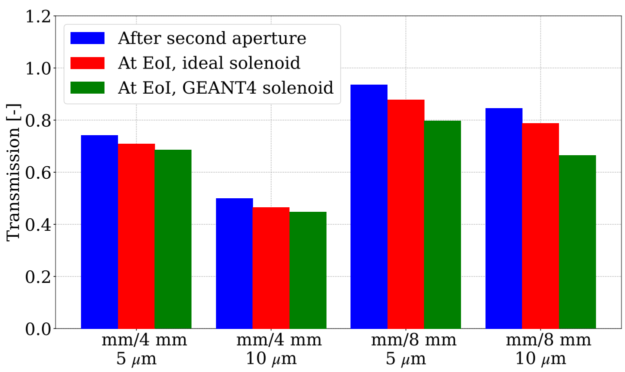

Figure 6: Optimized transmissions at the end of the injector (EoI) for both solenoid implementations. Transmission after the second aperture is plotted as a reference. Results are shown for two different target thicknesses (5 µm and 10 µm) and two aperture size combinations (3 mm/4 mm and 3 mm/8 mm).

The longitudinal and radial components are given by:

$$B_z(r,z) = \frac{B_0}{2}\left(\frac{z+\frac{L}{2}}{\sqrt{(z+\frac{L}{2})^2+R^2}} - \frac{z-\frac{L}{2}}{\sqrt{(z-\frac{L}{2})^2+R^2}}\right) \quad (1)$$

$$B_r(r,z) = -\frac{1}{2}\frac{\partial B_z}{\partial z}r.$$

The fit parameters in this case are B_0, L and R. A comparison between the longitudinal component of the field map and the fitted function is shown in Fig. 5.

The equivalence between the fitted function and the ideal solenoid from Elegant is then given by the value of B_0 that translates to the same focusing length and Larmor rotation. This was done by comparing the following integrals of the longitudinal component of (1), $\int_{-\infty}^{+\infty} B_z^2(z)dz$, $\int_{-\infty}^{+\infty} B_z(z)dz$, to the corresponding focusing length and Larmor rotation angle for an ideal solenoid.

Optimization Results

For the ideal solenoid implementation the optimization procedure was as follows. The degrader part was simulated

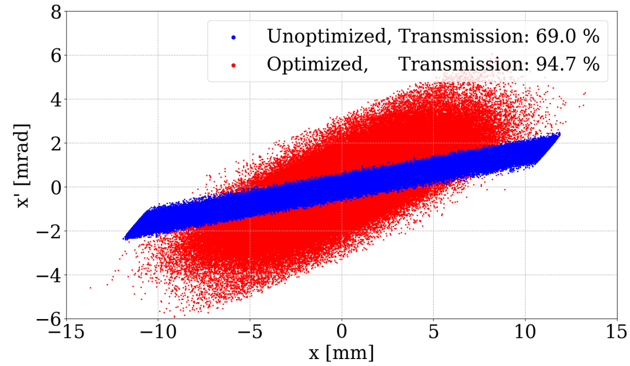

Figure 7: Comparison of the horizontal phase space at the entrance of the closest accelerating cryomodule between optimized and unoptimized runs. Target thickness for this run is 1 µm and aperture sizes are 3 mm and 8 mm.

using GEANT4. The distribution after the second aperture was imported to Elegant for beam tracking in optimization mode. The optimizer was run to maximize the transmission through the rest of injector beamline by adjusting the solenoid field and four quadrupole gradients. From the optimum solenoid field, the corresponding fitted field was calculated and implemented into GEANT4. The same procedure was repeated for the GEANT4 solenoid optimization but with the optimizer only adjusting the four quadrupole gradients for maximum transmission.

This optimization procedure resulted in an average increase of 40% of the transmission for all cases. A comparison of the maximum transmission at the end of the injector beamline is shown in Fig. 6 for both solenoid implementations at different target thicknesses and aperture combinations. Depending on the target and aperture combination, the preservation of 78% to 92% of the beam that makes it past the second aperture is possible by setting the magnets optimally. Smaller transmission values of the GEANT4 solenoid optimization are attributed to the use of the more realistic magnetic field. For a better illustration of the optimization, a comparison of the horizontal phase space right at the entrance of the closest downstream cryomodule before and after optimization is shown in Fig. 7 for one target thickness and aperture combination. It should be noted that the collimation of the unoptimized case was heavily mitigated and that transmission was greatly improved. Similar results were found for the other target and aperture combinations.

OUTLOOK

The use of an external optimizer program will be explored to adjust the scaling of the solenoid field map directly. The construction and assembly of the degrader is currently in progress. Installation and first experimental measurements of the CEBAF injector acceptance are planned for later this year.

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