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 capability currently under development [1]. Computational simulations of beam-target interactions and particle tracking were performed integrating the GEANT4 [2] and Elegant [3] toolkits. A solenoid was added to the setup to control the beam's divergence. Parameter optimization of the solenoid field and magnetic quadrupoles gradient was also performed to further reduce particle loss through the rest of the injector beamline.

INTRODUCTION

The Continuous Electron Beam Accelerator Facility (CEBAF) is the largest accelerator at Jefferson Lab. With the 12 GeV update, a high energy beam of highly polarized electrons is delivered into the four experimental halls. A proposed upgrade to CEBAF is the Ce^{+}BAF project [1] which intends to circulate a bremsstrahlung-based positron beam through the accelerator. Because of the larger transverse and longitudinal emittance of this kind of positron beams, an accurate measurement of the CEBAF injector acceptance is required. In an effort to have this measurement in a controlled way, an electron beam degrader ("degrader" from now on) is being installed in the injector section of CEBAF.

This degrader device will be placed approximately 9 meters downstream from the injector booster cryomodule. It's is composed of a target ladder assembly with three thin carbon foils and a viewer, and two aperture collimators for emittance definition with an added solenoid for divergence control. 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.

In this paper, we present some studies done for the design of the degrader consisting of full beamline simulations of the electron beam evolution, the introduction and optimization of the solenoid, and transmission improvement by optimiz-

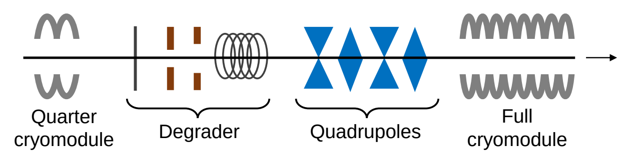

Figure 1: Schematic of a section of the CEBAF injector beamline with the position of the degrader. The arrow denotes continuation to the rest of the injector beamline.

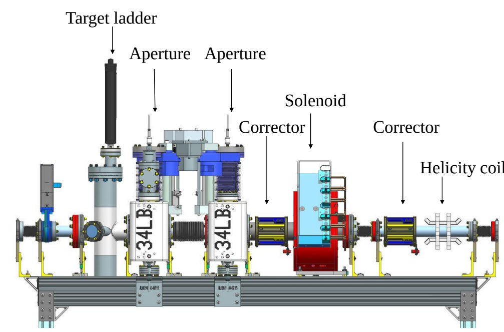

Figure 2: Model of the electron beam degrader.

ing the solenoid field and quadrupole gradient of the closest magnetic elements. For more details of the degrader design and other results, see [4, 5].

ELECTRON DEGRADER SIMULATIONS

The simulations were conducted using the GEANT4 and Elegant toolkits. The initial step involves generating a beam distribution at the target based on realistic beam parameters at that specific location in the injector beamline, followed by importing this data into GEANT4. Subsequently, the simulation models the beam interaction with the target and the two apertures. 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.

In these simulations, the dimensions of the beampipe and beamline elements is crucial because the degraded beam exhibits significantly larger emittance and beam size compared to a nominal beam. Therefore, an approximation of the CEBAF injector aperture size as a function of the longitudinal position was implemented to better estimate its impact on beam loss. At the moment, the transverse cutoffs have a rectangular shape, but they will be refined to a more realistic circular shape in the future. The simulation results showed that, even for a 1 micron carbon target, most of the beam is lost in the following 6 meters of the beamline. Consequently,

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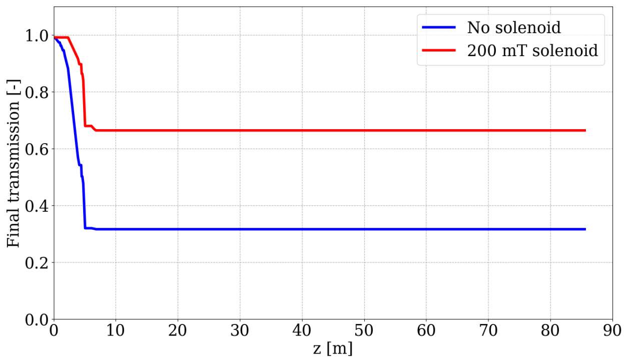

Figure 3: Simulated transmission comparison between runs without and with a 200 mT solenoid downstream of the second aperture. Target thickness for this run is 1 µm and the collimators aperture holes radius are 3 mm and 8 mm.

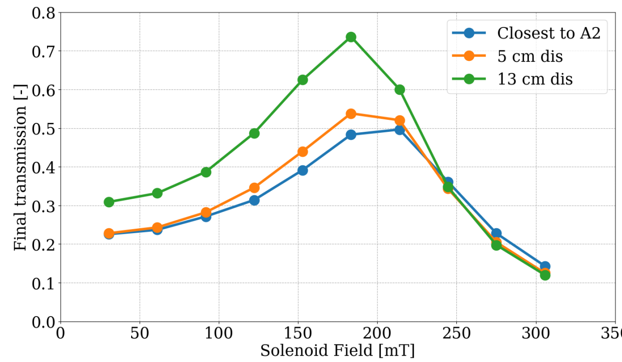

Figure 4: Simulated transmission at the end of the CEBAF injector chicane for different Solenoid field values and longitudinal displacement from the closest position to the second collimator. These simulations were done with a 1 µm thick target and collimator aperture holes of 3 mm and 6 mm radius.

it was decided to add a solenoid for beam divergence control. The initial position of the solenoid was as close as possible to the second collimator, with a maximum magnetic field of 200 mT on its axis. As shown in figure 3, substantial beam loss is still present in the next 10 meters, but the addition of the solenoid significantly improved transmission.

SOLENOID POSITION OPTIMIZATION

The next analysis was a 2-parameter scan varying the solenoid maximum magnetic field on axis and its longitudinal displacement from the closest position to the second collimator. This parameter scan was performed to optimize the transmission at the end of the injector beamline. The magnetic field range was from 30 to 300 mT, and the longitudinal displacement range from 0 cm to 13 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 back helps achieving better transmission because the focusing length has a better match to the next focusing element position. Also, there's an optimum magnetic field value (around 160 mT) after which there's an overfocusing effect that reduces the maximum transmission. From these results, it was decided to position the solenoid as further downstream as possible which would also give more space for other magnetic elements that are useful for nominal use.

MAGNETIC ELEMENTS OPTIMIZATION

Given that the position of the solenoid is now fixed, the next step is optimizing the beam transmission through the rest of the injector beamline by modifying the set values of other present magnetic elements. The region of interest is between the exit of degrader and the next accelerating cryomodule because of geometric emittance damping after acceleration. In this region, the only magnetic elements present are three normal and one skew quadrupole. The final free parameter is the degrader solenoid magnetic field since it was optimized with unchanged downstream beamline elements. Thus, there are five parameters: four quadrupole gradients and one central solenoid magnetic field.

Regarding the solenoid field, the field map comes directly from measurements. Then it is imported into GEANT4 to achieve more realistic beam dynamics. Simultaneously, it's desired to exploit the built-in optimizer in Elegant to identify the optimum setup with the highest possible transmission. To integrate this approach, it was decided to run the optimizer with a solenoid element in Elegant and then determine the equivalent field map. In the following sub-sections, the two solenoid models and their equivalence will be detailed.

Elegant implemented Solenoid

The solenoid element in Elegant is implemented as a 2nd degree 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 effect and Larmor rotation are approximately proportional to $B_0^2 L$ and $B_0 L$.

GEANT4 implemented Solenoid

The implemented solenoid model in GEANT4 is a little more complicated. We start with the measured magnetic field map, which is then fitted with the expression of the magnetic field of a solenoid with length L and transverse radius R. The longitudinal and radial components for this model 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 for different solenoid currents. Something to note is that L and R very close for the different current values, so it's possible to keep them fixed and only vary B_0 to model the solenoid at different currents. These fitted functions were implemented into the GEANT4 simulations because of their ease and speed to implement with almost no loss in accuracy.

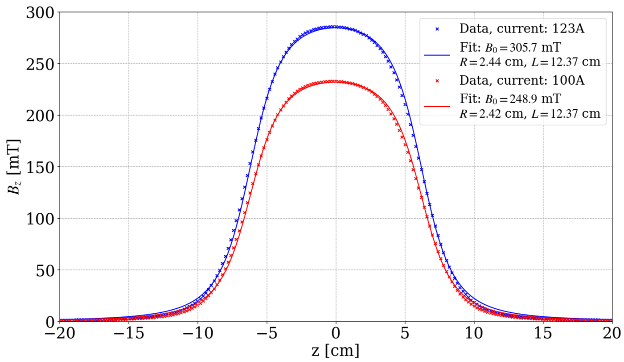

Figure 5: Fitted functions to measured Solenoid magnetic field map. Measurements were fitted to equations (1) via the B_0, L and R parameters.

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 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 focusing and Larmor rotation terms of the ideal solenoid.

Optimization results

The first step of optimization was performed with the Elegant implemented solenoid. First, the degrader part was simulated using GEANT4 and exporting the distribution at the back of the second collimator. Then this was imported to Elegant, running the optimizer to maximize the transmission

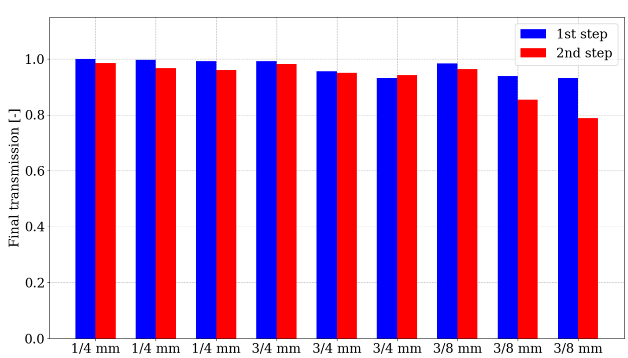

Figure 6: Optimized transmission from the end of the degrader to the end of the CEBAF injector chicane. Optimizations were performed for three different target thicknesses (1 µm, 5 µm, 10 µm) and three collimator aperture hole size combinations (1 mm/4 mm, 3 mm/4 mm, 3 mm/8 mm).

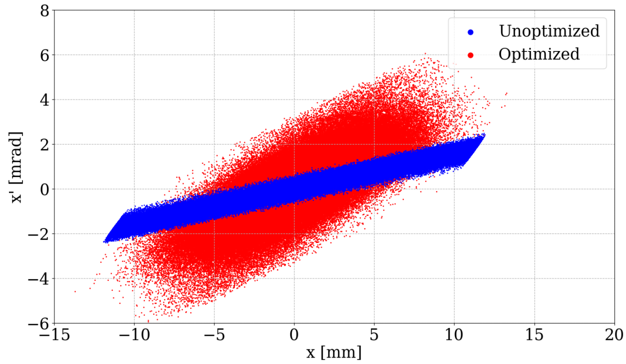

Figure 7: Horizontal phase space comparison between optimized and unoptimized runs. Target thickness for this run is 1 µm and the collimators aperture holes radius are 3 mm and 8 mm.

through the rest of injector beamline (including the solenoid region close to the degrader). This results in optimum set values for the quadrupole gradients and the solenoid magnetic field. Then, the corresponding GEANT4 field strength is calculated. The second step of optimization is performed using the GEANT4-implemented solenoid. Initially, GEANT4 degrader simulations are repeated incorporating the fitted field map. The final beam distribution is then exported back to Elegant. Lastly, the optimizer is run again, only adjusting the four quadrupole gradients to determine the optimal values that maximize the transmission. This optimization procedure resulted in an increase of 10 to 20% of the overall transmission for all cases. A comparison of the maximum transmission of both steps of optimization for different target thicknesses and aperture combinations is shown in Fig. 6. Finding the optimum settings can help preserve from 80% to 98% of the particles that make it past the degrader, depending on the target and collimator combination. To better illustrate the optimization, a comparison of the horizontal phase space right at the entrance of the closest cryomodule before and after optimization is shown in Fig. 7. It can be seen that the sharp collimation present in the unoptimized case is heavily mitigated in the optimized one.

OUTLOOK

The use of an external optimizer program, suited to scale the solenoid field map directly, will be explored. A more in-depth comparison between the different solenoid implementations will be done. The interaction of larger longitudinal phase space beam going into the degrader and its evolution through the rest of the CEBAF injector beamline will also be explored. Experimental measurements of the acceptance using the degrader are planned for later this year.

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