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LONGITUDINAL LASER SHAPING AT THE EIC COOLER INJECTOR*

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Abstract

Laser shaping controls the initial particle distribution by changing the laser intensity on the cathode. The EIC cooler requires a flattop longitudinal distribution to achieve the best cooling rate. We optimized the initial longitudinal distribution to achieve such a uniform current profile under space charge effects at the end of the EIC cooler injector.

INTRODUCTION

The Electron-Ion Collider (EIC) is the next nuclear physics facility to be constructed at Brookhaven National Laboratory. It will deliver high current polarized electron and hadron beams to study the nucleon structure with a high luminosity of $10 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ during its operation [1]. Intra-beam scattering and other mechanisms can degrade the beam quality in the Hadron Storage Ring. The EIC will use a novel cooling technique named Strong Hadron Cooling (SHC) to maintain the beam brightness and high luminosity during long collision experiments. The luminosity of the EIC could benefit strongly from cooling the transverse and longitudinal hadron beam emittance with a factor of 3 to 10 (Fig. 1).

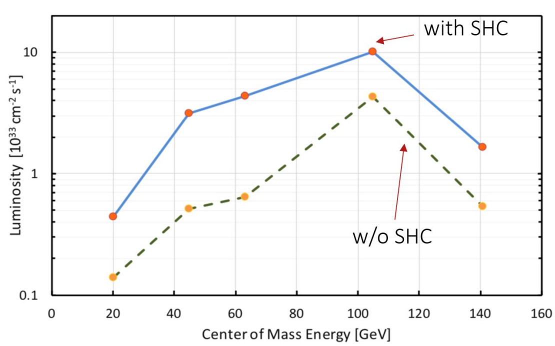

Figure 1: The luminosity of the EIC at different center-of-mass energies, which benefits strongly from cooling the hadron beam with SHC.

Strong Hadron Cooling requires a high-quality electron beam with a high current, small energy spread, and small beam noise. An ERL will deliver the electron beam for cooling and recycle its energy after the cooling section. The best cooling rate is realized when the electron beam has a desired uniform longitudinal current profile in the cooling section. However, the electron beam distribution changes during transport from the cathode to where it meets the hadron beam. In particular, the space charge forces play an essential role at the low-energy end and strongly affect the beam distribution. Our goal is to find the optimal laser shape on the cathode that produces the most suitable electron distribution. This technique is called laser shaping.

EIC COOLER INJECTOR

The EIC cooler ERL [2] is designed to provide high-current high-brightness electron beam for SHC to cool the hadron beam. The 400 kV HVDC gun generates 1 nC electron bunches with a normalized emittance of 1.1 mm-mrad and repetition rate of 98.5 MHz. Two 197 MHz quarter-wave cavities have a gap voltage of 2.9 MV and a single cell 591 MHz third-harmonic cavity is used to reduce the longitudinal energy spread. The electron energy at the end of the injector reaches 5.6 MeV. Three solenoids are used for focusing. The exact layout of the EIC cooler injector is shown in Figure 2. The injector is modeled in Bmad using fieldmaps for each element.

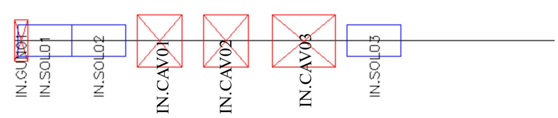

Figure 2: The layout of the EIC cooler injector as modeled in Bmad.

METHOD

This work focused on controlling the longitudinal current profile through the longitudinal laser shaping. This process entails adjusting the laser intensity to control the electron density via photoemission. We concentrated our optimization efforts solely to the injector section to demonstrate the feasibility and avoid overburdening computational resources.

We generated the initial particle distributions using the python library distgen developed by Colwyn Gulliford [5]. We assumed a uniform radial distribution of 3.78 mm radius. The longitudinal distribution was specified using an interpolation method. We defined several points of the longitudinal probability density function and interpolated to make a smooth curve. Several example distributions are shown in Figure 4. The total bunch charge is 1 nC with an MTE of 130 meV.

The electron bunch was simulated through the injector using space charge tracking in Bmad, which incorporates space charge forces and cathode image fields [3]. Bmad deposits particles on a mesh and calculates the space charge field using Integrated Green Functions (IGF) algorithm [4].

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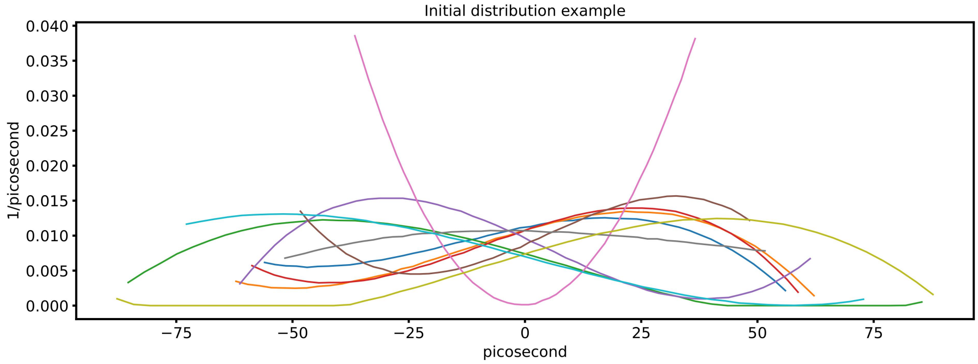

Figure 3: 10 sample initial longitudinal distributions generated by the optimizer.

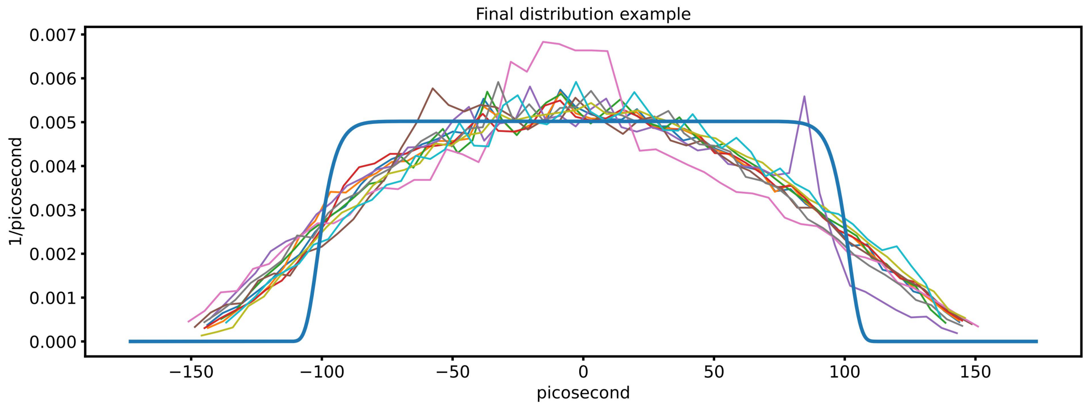

Figure 4: Final distributions corresponding to inputs in Figure 3 compared to the target distribution.

We then compared the final distribution at the end to a 200-ps long super Gaussian target distribution. The mean squared error between the target and simulation distributions served as a measure of beam flatness.

We utilized the python package Xopt [6] as our optimizer and employed the continuous NSGA-II algorithm. NSGA-II is a multi-objective genetic optimizer. We instructed the optimizer to adjust 4 points on the longitudinal distribution and explore the input space. The objective was to improve the beam flatness while maintaining an acceptable emittance after transport. The optimizer is parallelized with MPI to run simulations simultaneously.

RESULTS

The optimizer generated 200 input distributions and ran space charge simulation through the injector. We recorded their final longitudinal distribution and emittance. Final distributions with large emittance or significant particle loss are discarded. Figure 4 shows 10 of the final distributions corresponding to inputs in Figure 3 compared to the target distribution.

The best initial distribution to the target distribution is shown in Figure 5 and its final distribution at the end of injector in Figure 6. It suggests that having a hollow initial beam would be beneficial to achieve a flattop beam. The peaks from the initial beam smear out due to space charge and overlap to approach a uniform current profile. However, the best solution we have found is not uniform over the entire target width and there are potential to further flatten the distribution. More steps and computational resources are needed for the optimizer to fully converge. More importantly, the quality of the solution is limited by the number of input variables the optimizer was allowed to control. We would need to increase the number of interpolation points to allow more features in the initial distribution as well as allow the optimizer to adjust the distribution width. We will also like to expand the simulation to the full ERL lattice and optimize on the cooling distribution directly.

CONCLUSION

We studied the possibility to use laser shaping at the cathode to control the initial longitudinal distribution and achieve a flattop distribution after transport through the EIC cooler injector with space charge effects. The optimization utilized NSGA-II optimizer with Bmad space charge tracking. We demonstrated the feasibility of this approach and reported the current best solution. The number of input variables limited the quality of the solution, which will addresses in the future.

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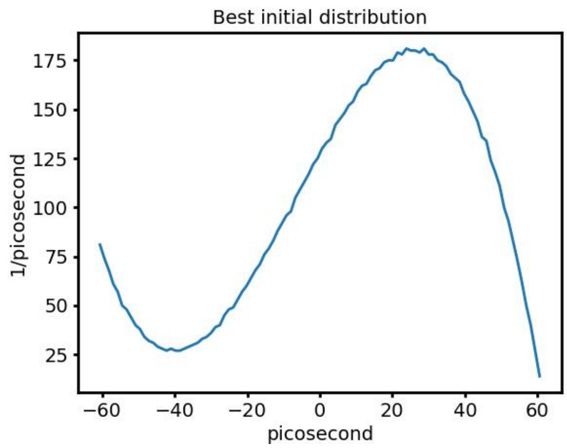

Figure 5: The best initial distribution that results in a uniform current profile at the end of the injector.

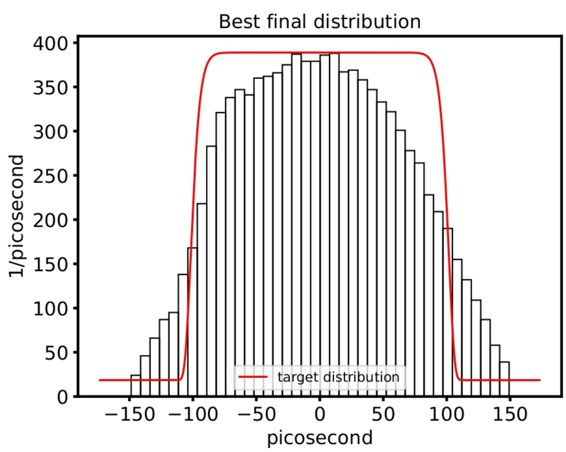

Figure 6: The best final distribution at the end of the injector compared to the target distribution.

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