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MULTI-OBJECTIVE OPTIMIZATION OF STRONG HADRON COOLER ENERGY RECOVERY LINAC INJECTOR*

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Abstract

The Strong Hadron Cooler (SHC) proposed for the Electron-Ion Collider (EIC) requires high-current, low-emittance electron bunches with minimal energy spread. The Energy Recovery Linac (ERL) injector plays a critical role in shaping the beam before acceleration. We present a multi-objective optimization study of the SHC ERL injector and merger using space charge tracking in Bmad and parallel genetic algorithm. The optimized configuration reduces the normalized transverse emittance by 62% and energy spread by 85% from the original configuration.

INTRODUCTION

The Electron-Ion Collider (EIC) at Brookhaven National Laboratory is a next-generation facility designed to explore the structure of protons and nuclei through high-luminosity electron-hadron collisions. To achieve its target luminosity of $10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$, the EIC requires sustained low emittance in the hadron beam [1]. However, intrabeam scattering (IBS), beam-beam interactions, and other collective effects cause emittance growth, limiting performance.

To counteract these effects, a high-energy cooling system is required to achieve the luminosity and beam quality for hadron collisions. One proposed solution is the Strong Hadron Cooler (SHC), which utilizes a high-current, low-emittance Energy Recovery Linac (ERL) to deliver cooling electron beams at multiple energies.

A key challenge in delivering the required beam quality lies in the injector, where the beam is still at low energy and dominated by space charge effects. Accurate modeling of space charge and careful tuning of beamline elements are necessary to minimize transverse emittance and energy spread, while preserving the beam's uniformity and brightness.

To meet these requirements, we designed and optimized a DC gun-based injector using Bmad [2] for space charge simulation and Xopt [3] for multi-objective optimization. The optimization strategy using Non-dominated Sorting Genetic Algorithm (NSGA-II) [4] resulted in significant improvements in the transverse emittances and energy spread. This paper presents the injector and merger design, simulation framework, and results of the multi-objective optimization, demonstrating significant improvements in beam quality.

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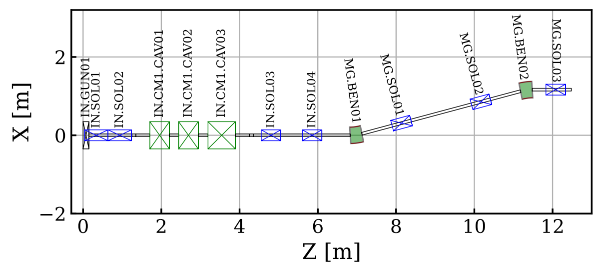

Figure 1: Layout of the ERL injector and merger used in this optimization study.

BEAMLINE MODEL AND SIMULATION

The injector and merger lattice, shown in Fig. 1, is designed to produce a high-quality 6 MeV electron beam for the Strong Hadron Cooler [5–10].

The system begins with a 400 kV DC gun that generates a 1 nC electron bunch. For this study, the initial particle distribution is a beer-can distribution generated using distgen [11]. It has a longitudinal 10th order SuperGaussian profile with $\sigma_t = 83$ ps. The transverse distribution is a Gaussian distribution of $\sigma_r = 3$ mm truncated at 1σ and the Mean Transverse Energy (MTE) is 130 meV. The injector section then accelerates the beam to approximately 6 MeV using two 197 MHz fundamental RF cavities and one 591 MHz third-harmonic cavity. The third-harmonic cavity is used to linearize the longitudinal phase space to counteract the energy chirp induced by strong space charge forces. Solenoids are placed along the injector to provide transverse focusing and control the beam size.

Following the injector, a merger section composed of dipoles and solenoids guides the beam onto the main ERL axis. This section is designed to be achromatic, with the goal of closing both horizontal and vertical dispersion at its exit to prepare the beam for downstream transport.

Beam dynamics are simulated using Bmad, which includes a 3D particle-in-cell algorithm to accurately model space charge effects [12, 13]. We track a distribution of

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10,000 macroparticles through the lattice. Given the beam's low energy, space charge forces are dominant throughout the injector and merger, making careful optimization of the lattice elements essential for preserving beam quality.

OPTIMIZATION STRATEGY

To achieve the desired beam quality at the end of the injector and merger, we applied a multi-objective optimization framework using the continuous NSGA-II algorithm implemented in Xopt. The optimization targeted both transverse and longitudinal beam properties under strong space charge forces, with independent objective functions and control parameters for each stage.

Injector Optimization

The injector optimization was decoupled into two stages: longitudinal and transverse. The longitudinal optimization focused on minimizing the RMS energy spread while maintaining a target beam energy of 6 MeV at the injector exit. Control parameters included the RF phases and voltages of two 197 MHz cavities and one 591 MHz third harmonic cavity. The resulting improvement in the longitudinal phase space showing reduced energy spread is illustrated in Fig. 2.

In the transverse optimization, the RF settings were held fixed while the strengths of two solenoids were varied to minimize the normalized horizontal and vertical emittance.

Since the transverse and longitudinal dynamics are largely decoupled in this regime, we alternated between the two stages to iteratively converge toward a consistent global optimum. Each stage ran for 50 generations with 64 offspring per generation.

Merger Optimization

Unlike the injector, the merger section does not accelerate the beam, requiring only transverse optimization. The objectives were to minimize the projected transverse emittance and ensure closed horizontal and vertical dispersion at the merger exit. Five solenoids within the merger were used as optimization variables.

Initial optimization results showed good emittance performance at the merger exit but led to significant emittance growth in downstream sections [14]. Analysis revealed this was caused by chromatic aberrations: different energy slices of the beam experienced mismatched optics due to energy-dependent focusing. To address this, we introduced an additional objective to minimize the standard deviation of slice Twiss parameters across the beam. This encouraged better alignment of the slice phase spaces, resulting in improved downstream transport and reduced projected emittance growth.

RESULTS

The multi-objective optimization framework successfully identified an optimal solution that significantly improves the beam quality at the merger exit while respecting all operational constraints. The staged optimization of the injector,

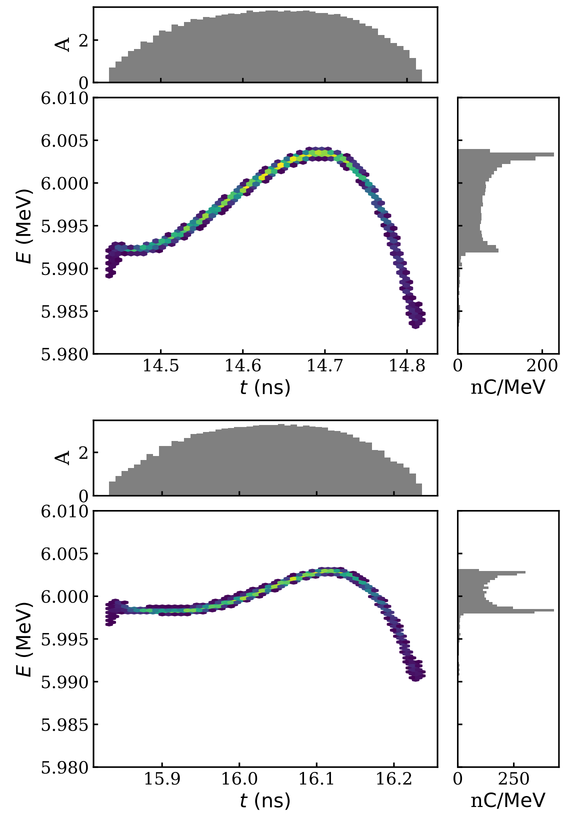

Figure 2: Longitudinal phase space at the injector exit. Top: before optimization. Bottom: after optimization with reduced energy spread.

followed by the comprehensive optimization of the merger, proved to be an effective strategy for navigating the complex, high-dimensional parameter space dominated by space charge effects. Figure 3 shows the evolution of key beam parameters through the injector and merger, illustrating the successful emittance minimization and dispersion closure.

Optimized Beam Parameters

The primary achievement of this work is the substantial reduction in transverse emittance and longitudinal energy spread. Table 1 provides a quantitative comparison of key beam parameters before and after optimization. The final normalized transverse emittances were reduced by 62%, and the RMS energy spread was decreased by 85%. The final beam energy was constrained to the target of 6 MeV.

Table 1: Key Beam Parameters Before and After Optimization

Parameter	Initial	Optimized	Unit
Beam Energy	5.89	6.00	MeV
Norm. Emit. X	6.21	2.28	mm−mrad
Norm. Emit. Y	5.82	2.25	mm−mrad
$\Delta E/E$	29.5	4.3	10^{-4}

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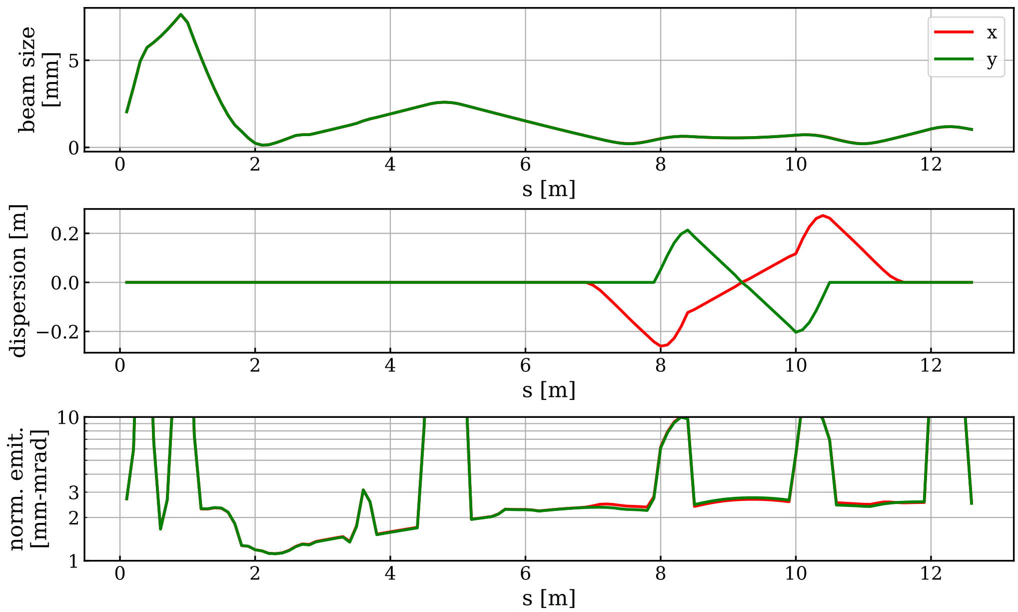

Figure 3: Evolution of horizontal beam size, dispersion, and normalized emittance along the injector and merger. Emittance is minimized, and dispersion is closed at the end of the merger.

Mitigation of Chromatic Aberrations

A key challenge in the merger section is the chromatic effects, which became apparent during the optimization process. Initial optimizations focused solely on minimizing the emittance at the merger exit. While successful at that specific location, this approach inadvertently created a beam with strong chromatic aberrations, leading to significant emittance growth in downstream transport. Figure 4 illustrates this effect by showing the horizontal phase space for different energy slices at the merger exit.

To correct this, we introduced an additional objective to minimize the standard deviation of the slice Twiss parameters across the bunch. This forces the optimizer to find a solution that aligns the phase space ellipses for all energy slices. The bottom plot of Fig. 4 shows the result after including this new objective. The phase space ellipses exhibit improved alignment.

CONCLUSIONS

We have successfully designed and optimized an ERL injector and merger for the Strong Hadron Cooler using a multi-objective genetic algorithm coupled with high-fidelity space charge simulations. The decoupled optimization of longitudinal and transverse dynamics in the injector, followed by a comprehensive merger optimization, proved highly effective. The introduction of an objective function to minimize the standard deviation of slice Twiss parameters effectively mitigated chromatic aberrations in the merger, ensuring the preservation of the low projected emittance in downstream beamlines.

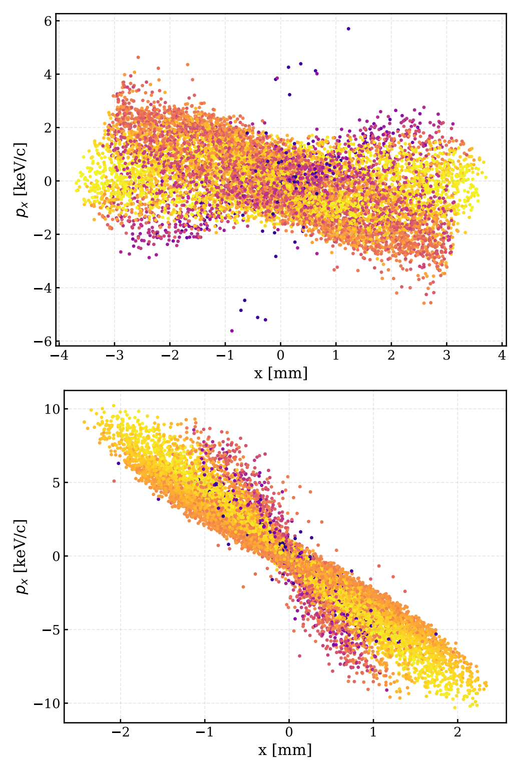

Figure 4: Horizontal phase space ($x - px$) at the merger exit, with particles colored by energy. Top: Severe phase space mismatch before optimization of chromatic effects. Bottom: After optimization with an objective to match slice Twiss parameters.

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