15th International Particle Accelerator Conference,Nashville, TN JACoW Publishing
ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPC43

OPTIMIZATION OF COOLING DISTRIBUTION OF THE EIC SHC COOLER ERL*

N. Wang†, D. Sagan, G. H. Hoffstaetter de Torquat, Cornell University, Ithaca, New York, USA
K. Deitrick, S. Benson, I. Neththikumara, T. Satogata, N. Sereno,
Thomas Jefferson National Accelerator Facility, Newport News, VA, USA
W. Bergan, E. Wang, Brookhaven National Lab, Upton, NY, USA
C. Gulliford, C. Mayes, Xelera Research LLC, Ithaca, NY, USA

Abstract

The Electron-Ion Collider (EIC) Hadron Storage Ring (HSR) will use strong hadron cooling to maintain the beam brightness and high luminosity during long collision experiments. An Energy Recovery Linac is used to deliver the high-current high-brightness electron beam for cooling. For the best cooling effect, the electron beam requires low emittance, small energy spread, and uniform longitudinal distribution. In this work, we simulate and optimize the longitudinal laser-beam distribution shaping at the photocathode, modeling space charge forces accurately. Machine parameters such as RF cavity phases are optimized in conjunction with the beam distribution using a genetic optimizer. We demonstrate improvement of the cooling distribution in key parameters.

INTRODUCTION

The Electron-Ion Collider is the next nuclear physics facility to be constructed at Brookhaven National Laboratory. It is designed to deliver polarized electron and hadron beams to study the nucleon structure with a high luminosity of $10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ [1]. However, intrabeam scattering (IBS), beam-beam effects, and other mechanisms will cause emittance growth and degrade the luminosity during operation.

In order to maintain the design emittance of the hadron beam, one proposed cooling scheme is the Strong Hadron Cooler (SHC) using Microbunching Electron Cooling (MBEC) [2], a form of Coherent Electron Cooling (CeC). The SHC requires a high-quality electron beam with a high current, small energy spread, and small transverse emittance. Additionally, the cooling electron bunch should have a uniform charge density profile and consistent slice energy spread and slice emittance to obtain optimal cooling rates. An Energy Recovery Linac (ERL) will deliver the electron beam for cooling and recover its energy after recirculation. Table 1 summarizes the design parameters for the electron beam in the cooling section.

The space charge effect plays a significant role in the electron transport from the cathode to the cooling section because the relativistic gamma is small in this region, especially in the 55 MeV mode. Challenges to delivering a uniform beam to the cooling section arise when we include

Table 1: The Electron Beam Requirements for Coherent Electron Cooling

Proton energy	**100 GeV**	**275 GeV**
Electron Energy	55 MeV	150 MeV
Norm. Trans. Emit.	<2.8 mm−mrad	<2.8 mm−mrad
Bunch Charge	1 nC	1 nC
RMS Bunch Length	9 mm	7 mm
Peak Current	10 A	13 A
Slice Energy Spread	10^{-4}	5.9×10^{-5}

the non-linear space charge force. The beam dynamics are complex and the resulting beam does not retain its uniformity. Therefore, it is crucial to study the beam dynamics with an accurate space charge effect and optimize the accelerator accordingly.

In this paper, we simulate and optimize the longitudinal distribution of the beam at the photocathode and demonstrate that a uniform current and slice energy spread profile can be produced using this process before getting into the cooling section.

EIC SHC COOLER ERL

The current EIC SHC cooler ERL is designed to provide an electron beam to cool the proton beam at 100 GeV and 275 GeV [3–5]. The layout diagram of the ERL is depicted in Fig. 1. The section relevant to this study is divided into five subsections: the injector (IN), the merger (MG), the pre-cooler linac (PL), the bunch compressor chichane (PX), and the main linac (LA).

The electron beam is emitted from the photocathode with a Mean Transverse Energy (MTE) of 140 meV and accelerated to 400 keV at the gun. The bunch energy reaches 6 MeV at the end of IN, 13 MeV at the end of PL, and 55 MeV at the end of LA. Because the energy is low for a significant part of the lattice, the beam remains sensitive to the space charge effect until the main linac, which must be considered in simulations. This study focuses on the 100 GeV case where the space charge is the strongest.

We used Bmad to study the beam dynamics with space charge through the SHC ERL lattice [6, 7]. For all the simulations in this study, we use 10000 particles in the tracking, and the space charge effect has been turned on until the beginning of PL.

* Work supported by Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy and the Office of Science Graduate Student Research (SCGSR) Program.
† nw285@cornell.edu

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPC43

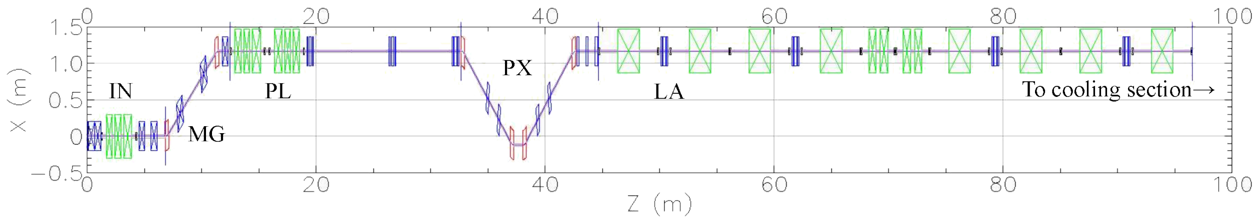

Figure 1: The current layout of the SHC cooler ERL from the cathode to the end of the linac. It is divided into five sections: the injector (IN), the merger (MG), the pre-cooler linac (PL), the bunch compressor chichane (PX), and the main linac (LA). The beam at the end of LA is delivered to the cooling section.

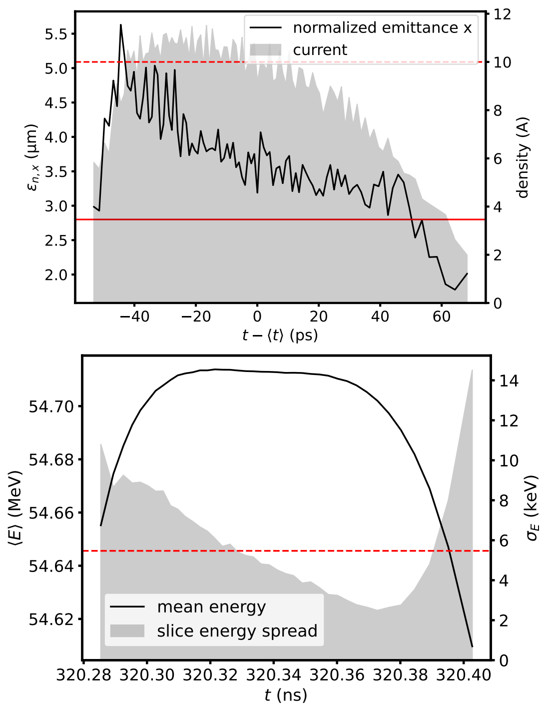

Figure 2: (top) Slice transverse emittance and peak current of a Super-Gaussian beam at the end of LA. Red lines indicate the target values for slice transverse emittance (solid) and peak current (dashed). (bottom) The average energy and slice energy spread at the end of LA. Red dashed line indicates the target slice energy spread.

The simple choice of initial distribution at the cathode is a so-called "beer can" distribution. It has a truncated Gaussian distribution in the transverse and Super Gaussian distribution in the longitudinal. The slice statistics of the final distribution are shown in Fig. 2, which do not meet the uniformity requirement. Therefore, we may employ laser shaping to optimize the slice statistics of the cooling distribution.

OPTIMIZATION

Laser shaping allows us to define the longitudinal distribution at the cathode. To model this process, we assume that the photocathode produces a smoothly varying distribution of arbitrary shape. The initial longitudinal distribution is parameterized by defining 8 equidistant points on the probability density function of electron emission time. They are interpolated with third-order splines into a smooth distribution. Particles are generated by Python package Distgen [8].

The RMS bunch length at the cathode is allowed to vary between 10 ps and 100 ps. Besides, the cathode laser can have a phase ranging between ±100 ps, effectively adding a collective phase to all the RF cavities. The initial longitudinal distribution together with the RMS bunch length and laser phase gave the optimizer 10 variables to explore.

After particle generation, the bunch is tracked through the SHC ERL to the end of the LA section in Bmad. The final distribution is written out for slice statistics.

To satisfy the design targets in Table 1, we mainly focus on three parameters: current uniformity, slice energy spread, and slice transverse emittance. The final distribution of each evaluation is sliced into 50 bins. Only the center bins within 1 RMS bunch length are counted in the objective calculation. The objective functions are defined as

$$\text{objective} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \text{target})^2}\Big/\text{target}\,, \quad (1)$$

where N is the number of center bins and x_i is the statistics of slice i. They describe the RMS distance to the target value, normalized by the target value.

This work uses the CNSGA-II algorithm from the Xopt Python package [9, 10]. The advantages of CNSGA-II are its ability to optimize multiple objectives and parallel evaluation. The non-dominated sorting algorithm builds the Pareto front in the multi-objective space and helps to show correlations and trade-offs between objectives. Additionally, each point in the population can be evaluated in parallel using MPI, adding a layer of parallelism and speeding up the optimization process.

RESULTS

We ran the optimizer using a population of 64 individuals and iterated over 500 generations. As plotted in Fig. 3, the optimizer was able to find a Pareto front in the objective space. We observe a clear trade-off between current uniformity and slice transverse emittance, whereas the current uniformity and slice energy spread improve in the same direction.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPC43

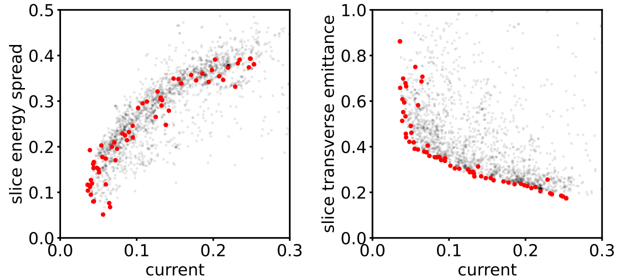

Figure 3: Data points evaluated by the optimizer (black) and the current population (red). Axes are objective functions as defined in Eq. 1.

We picked the solution at the pivot point for further investigation (Fig. 4). The corresponding initial longitudinal distribution is a two-peak formation, with a small pulse in the head and a larger pulse in the tail. The final longitudinal distribution now has large peak-to-peak energy spread due to time of arrival shifts at cavities caused by space charge. We observed that changing the initial longitudinal distribution and the laser phase could not fully compensate for this effect. Hence, it is necessary to tune the cavities in order to achieve a desirable energy profile.

The LA section has eight 591 MHz cavities and four 1773 MHz third-harmornic cavities. The 591 MHz and 1773 MHz cavity phases and voltages were adjusted to reach

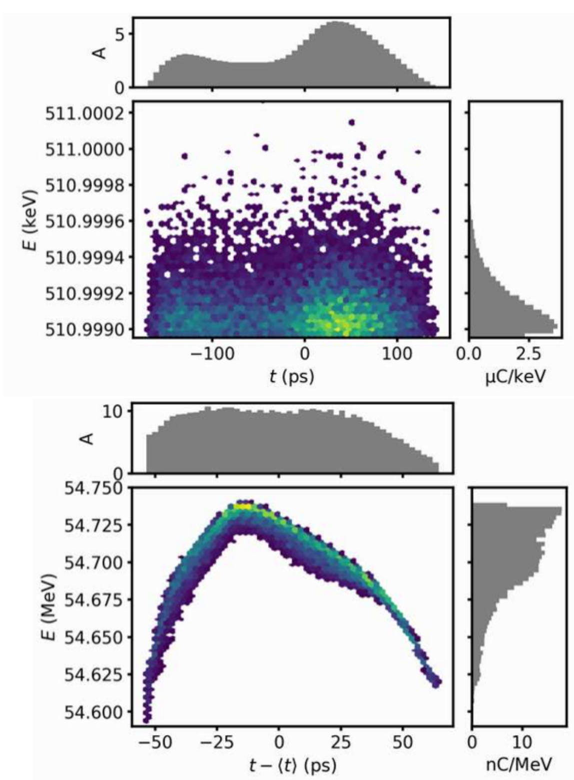

Figure 4: (top) Initial longitudinal distribution that resulted in the best cooling distribution at the end of the linac. (bottom) Optimized final distribution at the end of the linac that performs well in all three objectives.

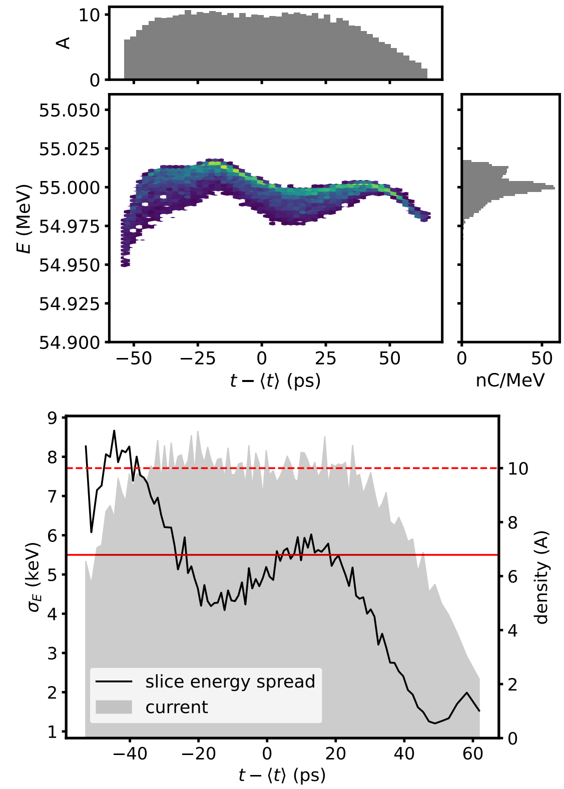

Figure 5: (top) Final distribution longitudinal phase space after tuning linac cavities. It now has a small peak-to-peak energy spread. (bottom) The slice energy spread and current profile of the final distribution. Red lines indicate the target values for slice transverse emittance (solid) and peak current (dashed). The current is very uniform around the center at the target current 10 A.

the target electron energy and reduce the peak-to-peak energy spread. The optimized linac settings gave a much smaller peak-to-peak energy spread than the previous iteration and the beer can distribution, while the uniform current profile and slice energy spread are maintained (Fig. 5). Therefore, we successfully meet two of the objectives.

With this optimized initial distribution and cavity settings, we observed significant transverse emittance blowup in the injector and bunch compressor. It occurs due to focusing mismatches caused by space charge in those regions, which is similar to the cause of the peak-to-peak energy spread we discussed above. Transverse focusing elements need to be tuned to keep the new beam in focus.

CONCLUSION

We optimized the longitudinal distribution at the photocathode and machine parameters such as RF cavity settings. A cooling distribution with uniform current and slice energy spread is demonstrated to meet two of the three main design objectives. Further tuning of the transverse focusing elements is needed to meet the slice emittance requirements as well.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPC43

REFERENCES

[1] "Electron-Ion Collider Conceptual Design Report 2021", BNL Technical Report BNL-22-1006, 2021. doi:10.2172/1765663

[2] W. F. Bergan, P. Baxevanis, M. Blaskiewicz, and E. Wang, "Design of an MBEC Cooler for the EIC", in *Proc. 12th Int. Particle Accelerator Conf. (IPAC'21)*, Campinas, Brazil, May 2021, pp. 1819-1822. doi:10.18429/JACoW-IPAC2021-TUPAB179

[3] E. Wang *et al.*, "The Accelerator Design Progress for EIC Strong Hadron Cooling", in *Proc.* 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, pp. 1424–1427. doi:10.18429/JACoW-IPAC2021-TUPAB036

[4] E. Wang *et al.*, "Electron Ion Collider Strong Hadron Cooling Injector and ERL", in *Proc. LINAC'22*, Liverpool, UK, Aug.-Sep. 2022, pp. 7–12. doi:10.18429/JACoW-LINAC2022-MO2AA04

[5] C. Gulliford *et al.*, "Design and optimization of an ERL for cooling EIC hadron beams", in *Proc. 14th Int. Particle Accelerator Conf. (IPAC'23)*, Venice, Italy, May 2023, pp. 73-76. doi:10.18429/JACoW-IPAC2023-MOPA016

[6] D. Sagan, "Bmad: A relativistic charged particle simulation library". Nucl. Instrum. Meth. A558, no. 1 (2006): pp. 356–359. doi:10.1016/j.nima.2005.11.001

[7] N. Wang *et al.*, "Cathode Space Charge in Bmad", in *Proc. 13th Int. Particle Accelerator Conf. (IPAC'22)*, Bangkok, Thailand, Jun. 2022, pp. 2380-2382. doi:10.18429/JACoW-IPAC2022-WEPOMS055

[8] C. Gulliford: Distgen — particle distribution generator. https://github.com/ColwynGulliford/distgen

[9] R. Roussel *et al.*, "Xopt: A simplified framework for optimization of accelerator problems using advanced algorithms", in *Proc. 14th Int. Particle Accelerator Conf. (IPAC'23)*, Venezia, May 2023. doi:10.18429/JACoW-IPAC2023-THPL164

[10] K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan, "A fast and elitist multiobjective genetic algorithm: NSGA-II," *IEEE Transactions on Evolutionary Computation*, vol. 6, no. 2, pp. 182-197, April 2002. doi:10.1109/4235.996017