ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPA016

DESIGN AND OPTIMIZATION OF AN ERL FOR COOLING EIC HADRON BEAMS

C. Gulliford*, J. Conway, D. Douglas, B. Dunham, R. Eichhorn, V. Kostroun, C. Mayes, K. Smolenski, N. Taylor, Xelera Research LLC, Ithaca, NY, USA
E. Wang, W. Bergan, A. Fedotov, D. Kayran, Brookhaven National Lab, Upton, NY, USA
S. Benson, K. Deitrick, Thomas Jefferson National Lab, Newport News, VA, USA
N. Wang, Cornell University, Ithaca, NY, USA

Abstract

The baseline scheme for hadron beam cooling in the Electron Ion Collider (EIC) calls for Coherent electron Cooling (CeC) of the hadrons with non-magnetized electrons at high energy (150 MeV electrons) and additional cooling via conventional bunched beam cooling using a precooler system. The electron beam parameters for these concepts are at or beyond the current state of the art, with electron bunch charges on the order of 1 nC and average currents on the order of 100 mA and requiring an Energy Recovery Linac (ERL) to produce such beams. Using specifications provided by BNL and JLab, physicists and engineers at Xelera Research are working on a complete design of an ERL system capable of cooling EIC hadrons.

INTRODUCTION

The Electron-Ion Collider (EIC), currently being designed by scientists at Brookhaven National Lab (BNL) and Thomas Jefferson Laboratory (JLab), will leverage the existing hadron infrastructure of the Relativist Heavy Ion Collider (RHIC) at BNL along with a new electron accelerator complex to deliver high luminosity polarized electron and proton beams for precision nucleon studies. One particular challenge of this machine is the preservation of hadron beam quality over the course of long experimental runs, with effects such as intra-beam scattering and the beam-beam effect causing degradation of the hadron beams. Thus it is desired to cool the hadron beams using electron beams provided by a separate accelerating system.

In this collaboration, EIC scientists have provided the ERL specifications required for efficient cooling, 3D CAD layouts of the existing RHIC infrastructure, as well as their own design solutions for various sections of the cooling accelerator systems. Incorporating this expertise has allowed the Xelera team to rapidly design ERL solutions that both satisfy the EIC cooling requirements as well as realistically live within the geometric constraints of the existing and/or planned facilities. The main simulation program used here is Tao [1], which in turn is built from the Bmad library [2]. General Particle Tracer and Impact-T are used for simulating the low energy, space-charge dominated sections of the machine(s). All initial particle distributions were generated using Distgen, an open-source python package for creating particle beams [3].

* colwyn.gulliford@xeleraresearch.com

SHC-CeC ERL

The Coherent electron Cooling mechanism for cooling hadron beams was first proposed in [4] and is currently the baseline approach for cooling EIC proton beams at 100 GeV and 275 GeV beam energies. The baseline design at the time of the work completed here features a drift with one-quarter of plasma oscillation length and a chicane micro-bunching amplifier. Further details of this cooling scheme can be found in [5, 6]. This machine features two modes of operation, with beam energies of 55 MeV and 150 MeV, corresponding to cooling protons at 100 GeV and 275 GeV, respectively. The electron bunch charge in both cases is 1 nC.

The primary result of this effort is a complete physics model of the EIC SHC-CeC ERL with a corresponding 3D model placing the machine in the BNL facility. An elevated view of this layout is shown in Fig. 1. The relevant main sections, in beamline order, are the injector featuring a 400 kV DC gun, as well as a 591 MHz SRF booster and third harmonic cavity, the low energy merger section, (IN & MG), the main linac (LA), the cooler sections (C1-7), the first turnaround (TA), the return line (R1-R4), and the second turnaround (TB).

In addition to constraints on the placement of the injector and linac complex, the physical constraints of setting the rest of the machine in the RHIC tunnel are challenging. For the cooler itself, the electron beamline must merge and demerge with the hadron beam two times, with tight constraints on path length and beam optics (e.g., r_{56}, average beta functions). Several other beamlines exist in the area, including the Rapid Cycling Synchrotron (RCS) and its injector, the electron storage ring (ESR), and the RHIC hadron beamlines.

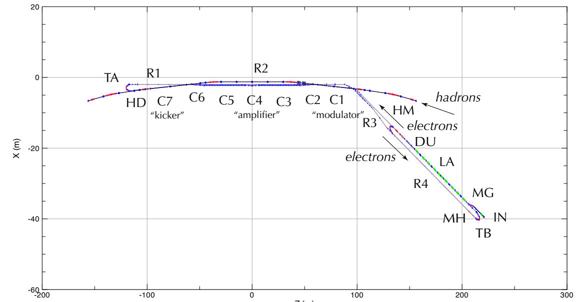

Figure 1: Inside tunnel geometry of the SHC-CeC ERL.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPA016

A complete, closed optics design from cathode to beam stop has been created for the high energy operation mode of the ERL (cooling 275 GeV protons). Figure 2 shows the lattice beta functions, dispersion functions, and beam energy through the full machine for the "inside tunnel" geometry. In addition to forming the physics solution shown, the Bmad lattice is used to create a 3D model of the system and place it in the RHIC tunnel. Figure 3 shows example renders of the 3D model made using Blender [7].

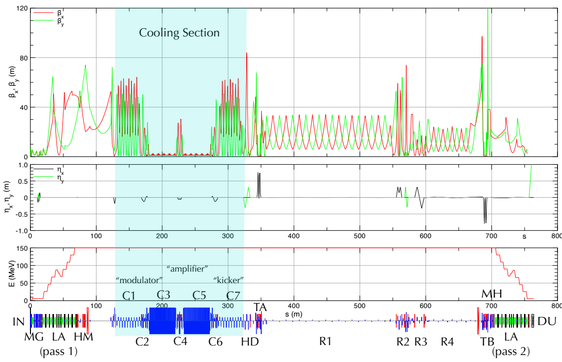

Figure 2: Optics for the 150 MeV operation mode.

Figure 3: Renders of the 3D model of the cooler and hadron beamlines in the RHIC tunnel. Left: the injector, low energy merge, linac entrance, and return line featuring a Bates bending system; right: the amplifier and hadron beamline.

COMBINED SHC-CEC AND PRECOOLER

In the summer of 2022, it was decided that the EIC baseline design would feature an additional ERL system called the Precooler, in addition to the SHC-CeC ERL, for cooling proton beams at 21 GeV and possibly 41 GeV. The Precooler system also requires a roughly 100 mA beam, which is used to cool ion beams via conventional bunched-beam cooling before the ions are accelerated to their final energy. Additionally, it was decided that this ERL system should share as many components with the SHC system as possible (in particular the injector system) in order to provide cost savings. To make both systems compatible requires changing the RF frequency of the accelerating cavities in the injector from 591 MHz to 197 MHz, and thus requires re-optimizing the injector system. The final electron energy in the Precooler is much lower than the electron energies in the SHC ERL (13 MeV vs. 55 or 150 MeV), and thus the electrons must be accelerated to roughly 13 MeV using a common set of RF cavities shared by both ERLs. This occurs in the precooler booster (PL) section. The precooler bunch charge is 2 nC. In the SHC mode, these cavities are run off-crest in order to provide an energy chirp to the beam which can be used to compress the beam. The precooler electrons are then extracted before the main SHC Linac and transported down to the cooling sections. The two systems then have their own merge points in the hadron cooling section. The combined cooling systems are shown in Fig. 4.

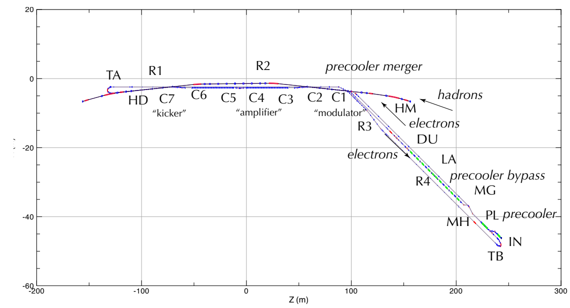

Figure 4: Proposed layout featuring 197 MHz injector and Precooler ERL system.

Xelera scientists are currently working on developing closed ERL solutions for both systems. This work includes performing Multi-Objective Genetic Algorithm optimizations using the Continuous Non-Dominated Sorting Algorithm (CSNGA) provided by the python optimization toolkit Xopt [8] to find optimal solutions for the space-charge dominated dynamics in the shared injector, low energy merge, and precooler booster (labeled PL in Fig. 4) for both ERLs. Figure 5 shows the layout of the shared injector which features: a 400 kV DC gun; two 197 MHz quarter wave cavities and a third harmonic cavity; the merger section, which uses chevron dipoles and solenoids with opposite current to provide axis symmetric focusing and a closed dispersion function; and the precooler linac, featuring four 197 MHz quarter wave cavities and two third harmonic cavities.

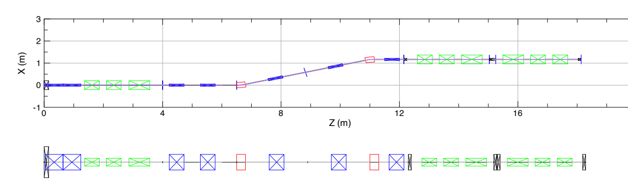

Figure 5: Layout of the shared injector, merger, and Precooler booster linac. Solenoids shown in blue, RF cavities in green, and dipoles in red.

The model used in the optimization of this layout is a hybrid GPT and Tao simulation via PyTao [9]. Particles are created using Distgen with a bunch charge of either 1 or 2 nC, for the SHC-CeC or Precooler, respectively. The initial laser distribution is a transversely truncated Gaussian with a 0.5 truncation fraction. The longitudinal distribution is a super-Gaussian tuned to produce a roughly flat-top distribution. The initial beam is imported into GPT and tracked through the injector for four meters. The particles are then extracted and imported into the Tao model of the merger and precooler

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPA016

booster. In both cases, reasonable beam parameters have been found by the optimization procedure. Figure 6 shows an example pareto front produced by Xopt for the precooler bunch parameters. Figure 7 shows example solutions from

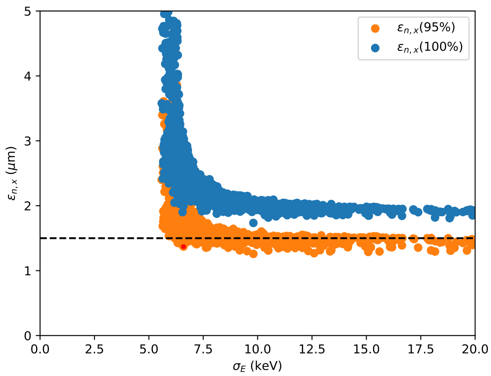

Figure 6: Example pareto front produced by Xopt for the Precooler bunch parameters.

the pareto fronts for both the SHC-CeC and precooler bunch parameters. The dashed line in the emittance plot specifies

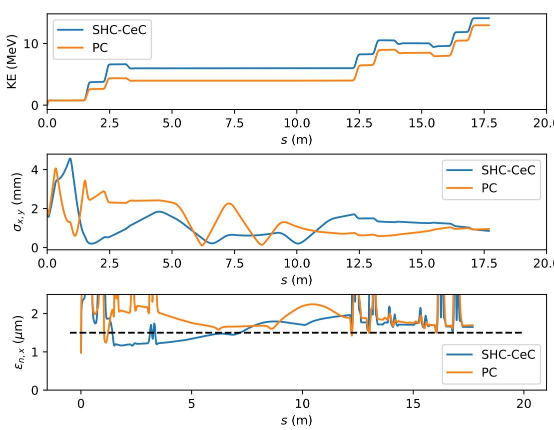

Figure 7: Example solutions for the SHC-CeC 1-nC bunch charge (blue) and precooler 2-nC bunch charge (orange) in the low energy section of the combined ERL systems. Top: total beam energy, Middle: transverse beam size, Bottom: transverse normalized emittance.

the target emittance of 1.5 µm in the precooler case and shows that although the 100% emittance is slightly higher than desired, the 95% emittance is within spec.

An initial solution for the lattice functions in the cooling section has also been found, and is shown in Fig. 8.

Additional studies for both the SHC-CeC ERL and precooler have also been performed but are still ongoing and not reported here.

CONCLUSION

Working with colleagues at BNL and JLab, the Xelera team has produced an initial complete design for an ERL

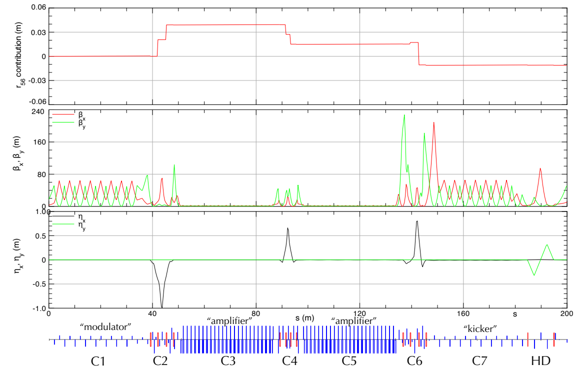

Figure 8: Optics solution in the new cooling section layout. Here the C2, C4, and C6 sections are tuned to have specific linear r_{56} transfer matrix terms as required by the cooling scheme.

for SHC cooling via the CeC process. Additionally, work is progressing in producing ERL design solutions for the combined SHC-CeC ERL and the Precooler ERL systems, with initial solutions for the shared injector, merger, and booster sections shown here. For the case of the SHC-CeC ERL, the optics functions in the cooling section have been matched.

ACKNOWLEDGEMENTS

We gratefully acknowledge the support of the US Department of Energy (DOE) for funding this research through the Small Business Innovation Research (SBIR) Phase II program. This project is conducted under the Nuclear Physics Accelerator Technology topic, focusing on the subtopic of Particle Beam Sources and Techniques. The Federal Grant Number for this project is DE-SC0020514. We would like to extend our sincere appreciation to Dr. Michelle Shinn, our program manager at the DOE, for her guidance and support throughout the project.

REFERENCES

[1] D. Sagan and J. C. Smith, "The TAO Accelerator Simulation Program", in *Proc. PAC'05*, Knoxville, TN, USA, May 2005, paper FPAT085, p. 4159.

[2] D. Sagan, "Bmad: A relativistic charged particle simulation library," *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 558, no. 1, pp. 356–359, 2006. doi:10.1016/j.nima.2005.11.001

[3] C. Gulliford, C. Mayes, and H. Slepicka, *ColwynGulliford/ distgen: Distgen v1.1.0*, version v1.1.0, 2023. doi:10.5281/zenodo.7863344

[4] V.N. Litvinenko and Y. S. Derbenev, "Coherent electron cooling," *Phys. Rev. Lett.*, vol. 102, p. 114801, 2009. doi:10.1103/PhysRevLett.102.114801

[5] E. Wang *et al.*, "The Accelerator Design Progress for EIC Strong Hadron Cooling", in *Proc. IPAC'21*, Camp-

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPA016

inas, Brazil, May 2021, pp. 1424–1427.
doi:10.18429/JACoW-IPAC2021-TUPAB036

[6] E. Wang *et al.*, "Electron Ion Collider Strong Hadron Colling Injector and ERL," in *Proc. of ERL'22*, Ithaca, NY, USA, 2022.

[7] Free, open source 3D creation suite by the Blender Foundation, https://www.blender.org

[8] C. Mayes, R. Roussel, J. Garrahan, Z. Zhang, H. Slepicka, and N. Kuklev, *ChristopherMayes/Xopt: Xopt v1.3.1*, version v1.3.1, 2023.
doi:10.5281/zenodo.7846662

[9] C. Mayes, D. Sagan, and H. Slepicka, PyTao, Available online at https://bmad-sim.github.io/pytao/, 2023.