ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPC40



# DEVELOPMENT OF AN ERL FOR COHERENT ELECTRON COOLING AT THE ELECTRON-ION COLLIDER

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

*Abstract*

The Electron-Ion Collider (EIC) is currently under development to be built at Brookhaven National Lab and requires cooling during collisions in order to mitigate the hadron beam emittance degradation due to intra-beam scattering and beam-beam effects. An Energy Recovery Linac (ERL) is being designed to deliver the necessary electron beam for Coherent electron Cooling (CeC) of the hadron beam, with an electron bunch charge of 1 nC and an average current of 100 mA; two modes of operation are being developed for 150 and 55 MeV electrons, corresponding to 275 and 100 GeV protons. The injector of this Strong Hadron Cooler ERL (SHC-ERL) is shared with the Pre-cooler ERL, which cools lower energy proton beams via bunched beam cooling, as used in the Low Energy RHIC electron Cooling (LEReC). This paper reviews the current state of the design.

## INTRODUCTION

The Electron-Ion Collider (EIC) is a partnership project between Brookhaven National Lab (BNL) and Thomas Jefferson National Accelerator Facility (TJNAF) to be constructed at BNL, using much of the existing infrastructure of the Relativistic Heavy Ion Collider (RHIC); a layout of the EIC is shown in Fig. 1. Collisions occur between the hadrons in the Hadron Storage Ring (HSR) and the electrons supplied by the Electron Storage Ring (ESR); in order to maintain a high average polarization of the ESR, bunches are frequently replaced using the Rapid Cycling Synchrotron (RCS). While most of the magnets for the HSR are repurposed RHIC magnets, already installed in the existing tunnel, both the ESR and RCS will have to be installed. In the current scope of the EIC, only one interaction region (IR) is supported, sited at the current IR6 of RHIC; however, it is highly desired that a second IR may be supported at IR8 in the future, and design efforts support that eventuality [1].

In order to achieve the design emittances of the hadron beam, a two-stage cooling system is necessary. First, hadron beams are injected into the HSR and cooled to the target emittances. After the target emittances are achieved, the HSR is ramped to the collision energy, and the hadron beam is cooled during collision in order to maintain the beam emittances; preserving the design emittances is critical to achieve the desired luminosity of the EIC. The electron cooler which provides cooling to the hadron beam is located in IR2 [1].

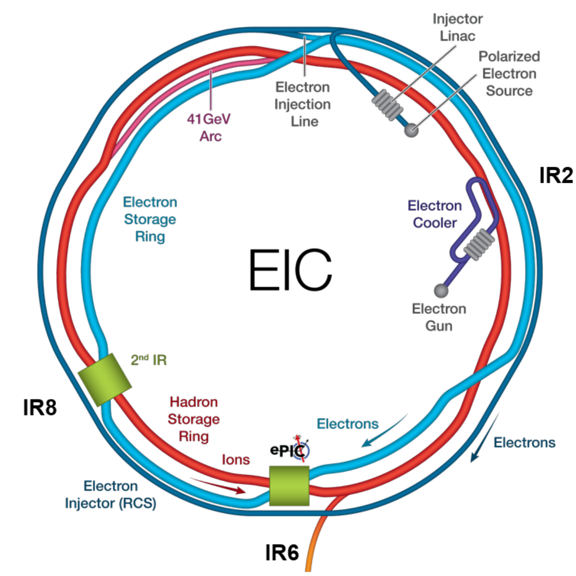


Figure 1: The current layout of a portion of the Electron-Ion Collider (EIC). The Hadron Storage Ring (HSR), Electron Storage Ring (ESR), and the Rapid Cycling Synchrotron (RCS) labels are color-coded to their respective rings; the current and proposed IRs are shown at IR6 and IR8, with the electron cooler in IR2.

## COOLING MECHANISMS

The two cooling stages use different cooling mechanisms in order to cool the hadron beam. The Pre-cooler, which cools during injection, uses non-magnetized bunched beam cooling, which is the mechanism currently used in Low Energy RHIC electron Cooling (LEReC) [2, 3]. In this scheme, three electron bunches at an energy of 13 MeV are used to cool each hadron bunch, which has an energy of 24 GeV.

The Strong Hadron Cooler (SHC), which cools during collision, uses Coherent electron Cooling (CeC) where the electron beam detects the hadron distribution, amplifies the imprinted distribution, and feeds back on the hadron beam to reduce the emittance of the hadron beam [4]. The cooling section of the SHC can be separated into three sections for each of these actions - modulator, amplifier, and kicker, re-

* kirstend@jlab.org

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPC40

Table 1: Electron beam parameters for the three proton beam energies. The electron beam longitudinal distribution is assumed to be a superGaussian of order ~2–4, and the bunched beam cooling assumes 3 electron bunches with a charge of 1.33 nC each for each hadron bunch.

| | **Proton Energy** | | |
|---|---|---|---|
| | **100 GeV** | **275 GeV** | **24 GeV** |
| Gamma | 106.6 | 293.1 | 25.58 |
| Bunch charge (nC) | 1 | | 3×1.33 |
| Avg. current (mA) | 98.5 | | 98.5 |
| *rms* bunch length (mm) | 9 | 7 | 40 |
| Slice energy spread $dp/p(10^{-4})$ | 0.6–1.5 | 0.4–0.8 | 5 |
| Norm. trans. emit. (mm−mrad) | 2.8 | | 1.5 |

spectively. The type of CeC to be used is microbunched electron cooling (MBEC), where chicanes and space charge provide the necessary amplification. While the EIC is intended to operate over a range of proton energies, only the 275 and 100 GeV proton beams are currently being considered to cool by Strong Hadron Cooling, corresponding to electron beam energies of 150 and 55 MeV, respectively [5–7]. A summary table of select electron beam parameters in the cooling section for both stages is shown in Table 1.

Given the significant electron beam power required by both cooling schemes, an energy recovery linac (ERL) is required - the operational power necessary to produce the desired electron beams with a linac is prohibitive. Instead of designing two separate ERLs, one for each stage of cooling, the two ERLs have a common injector, merger, and pre-cooler linac, and the beam is directed to either the Pre-cooler or SHC transport afterwards; additionally, the return line is shared. A conceptual layout (not to scale) of the cooling complex is shown in Fig. 2.

## STRONG HADRON COOLER ERL

Xelera Research had previously developed a complete model of the SHC-ERL, without the incorporated Pre-Cooler ERL, working with colleagues at BNL and TJNAF (Jefferson Lab). With the decision to incorporate the Pre-cooler ERL in the summer of 2022 and a change in the target electron beam parameters in the cooling section, the design had to be updated. One of the design aspects is that IR2 already contains the HSR, the ESR, and the RCS, making the geometry challenging [8].

The main sections of the SHC-ERL, in beamline order, are the injector (IN), the merger (MG), the pre-cooler linac (PL), the bunch compressor (PX), the main linac (LA), transport to the cooler section (HM), the cooler section (modulator, amplifier, and kicker), the first turnaround (TA), the return line, and the second turnaround (TB) – after which, the beam begins energy recovery; the high power beam dump for the SHC-ERL is located after the main linac.

In the current design, the injector consists of a DC gun, two 197 MHz quarter-wave cavities, and a 591 MHz single cell cavity to help linearize the longitudinal distribution. The pre-cooler linac consists of two 197 MHz quarter-wave cavities, two 591 MHz single cell cavities, and another two 197 MHz quarter-wave cavities. The main linac consists of eight 591 MHz five-cell cavities, with four 1773 MHz five-cell cavities placed in the center.

When pre-cooling was incorporated into the SHC, this resulted in a longer electron bunch out of the injector and introduced the necessity of bunching the beam before the main linac. However, due to the location of the bunch compressor, the beam is at different energies through the compressor depending on if it is accelerating or decelerating. Consequently, the bunch compressor has two lines - a low-energy line for the accelerating bunch and a high-energy line for the decelerating bunch; both lines are required to have the same time of flight.

An initial design has been completed for both the 150 MeV and 55 MeV SHC-ERL, with the optics shown in Fig. 3. The main simulation program used is *Tao* and the *Bmad* library [9], which has the capability to perform particle tracking in the low energy, space-charge dominated sections. For improved cooling behaviors, the longitudinal distribution is a superGaussian of order ~2–4 to approximate a top hat, as opposed to a more typical Gaussian distribution [8].

In Table 1, the required slice energy spread of the electron beam is a range – if the slice energy spread falls outside of this range, the desired cooling is not achieved. With the current injector design, the simulated slice energy spread is too small. We will use a laser heater after the main linac to increase the slice energy spread [10].

## PRE-COOLER ERL

The main sections of the Pre-cooler ERL, in beamline order, are the injector, the merger, the pre-cooler linac, the dogleg to exit the SHC-ERL, transport to the cooler, the cooler section, the first turn around, the return line, and the second turnaround – after which, the beam begins energy recovery; the high power beam dump for the Pre-cooler ERL is located after the pre-cooler linac.

The design of the pre-cooler transport between the pre-cooler linac and the cooling section is ongoing. Because the electron beam has both a high bunch charge and relatively low energy, the challenge of transporting the bunch from the pre-cooler linac to the cooling section while preserving the emittance is non-trivial.

Presently, no cooling solution exists for 41 GeV protons; the current concept is to add additional cryomodules to the pre-cooler linac to increase the electron beam energy to 22 MeV, and use bunched beam cooling with the pre-cooler at this higher energy. Consequently, we have included enough space after the pre-cooler linac to add two additional cryomodules [11].

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPC40



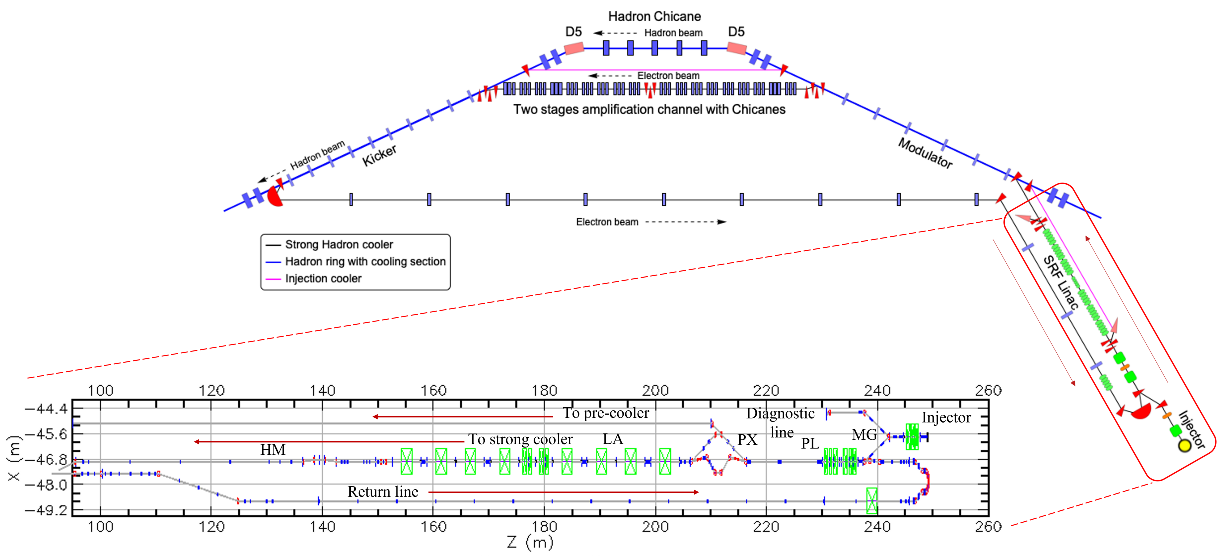


Figure 2: (Top) A conceptual layout of the cooling complex in IR2. At the bottom right, the shared injector and pre-cooler linac separate into two distinct transport lines to the HSR (shown at the top), one for the Pre-cooler and one for the SHC. Both lines merge with the HSR, demerging to take different paths in the center to bypass the hadron chicane (with the pre-cooler bypass between the amplifier section and the hadron chicane in the HSR), before both once again merge with the hadron line. A common return line is used in both paradigms to demerge with the HSR and return to energy recover. The red box indicates the area on this figure that is shown at greater size below the legend box. (Bottom) The current layout of a portion of the two ERL coolers corresponding to the red box in the top diagram. Represented is the injector, followed by the merger (MG), the pre-cooler linac (PL), the extraction to the pre-cooler transport to the cooler for the pre-cooler (top line) and the bunch compressor for the SHC (PX), the main linac of the SHC (LA), the SHC dump, SHC transport to the cooler (HM) (center line) and the shared return line from the cooler (bottom line).

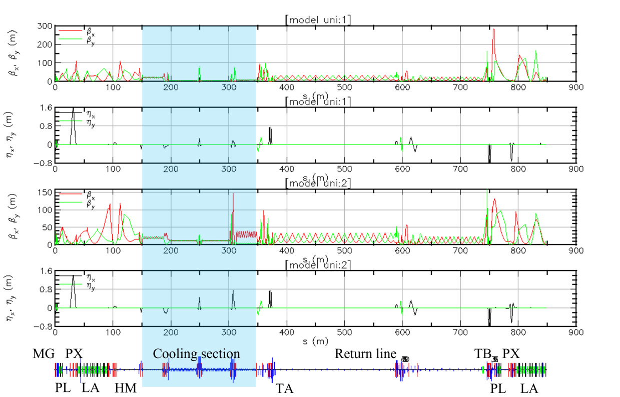


Figure 3: The preliminary designs of the 150 and 55 MeV electron coolers. Shown are the beta functions in meters (top) and dispersion in meters (bottom), all as a function of $s$ in meters, with the upper and lower pair corresponding to the 150 MeV and 55 MeV design, respectively. Below the four plots is the component layout, with the various sections labeled.

## CONCLUSION

Initial closed designs for both the 150 and 55 MeV SHC-ERLs have been completed, and no show stoppers have been identified; as collective effects and other beam dynamics are studied, the design will be iterated. Efforts will continue to mature the design while accommodating the design constraints required by the incorporation of the Pre-Cooler ERL.

## ACKNOWLEDGEMENTS

This work is supported by Jefferson Science Associates, LLC under U.S. DOE Contract DE-AC05-06OR23177 and Brookhaven Science Associates, LLC, Contract DE-SC0012704, while Xelera was supported by the U.S. DOE Small Business Innovation Research (SBIR) Phase II program under Federal Grant Number DE-SC0020514 during earlier stages of this work.

## REFERENCES

[1] C. Montag *et al.*, "The EIC accelerator -– design highlights and project status", paper MOPC67, this conference.

[2] A.V. Fedotov *et al.*, "Accelerator physics design requirements and challenges of RF-based electron cooler LEReC", in *Proc. NAPAC2016*, Chicago, IL, USA, Oct. 2016, pp. 867–869. `doi:10.18429/JACoW-NAPAC2016-WEA4CO05`

[3] A.V. Fedotov *et al.*, "Experience and challenges with electron cooling of colliding ion beams in RHIC", in *Proc. NAPAC'22*, Albuquerque, NM, USA, Aug. 2022, pp. 325–328. `doi:10.18429/JACoW-NAPAC2022-TUZD5`

[4] V.N. Litvinenko and Y.S. Derbenev, "Coherent electron cooling", *Phys. Rev. Lett.*, vol. 102, pp114801, 2009. `doi:10.1103/PhysRevLett.102.114801`

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPC40

[5] E. Wang *et al.*, "The accelerator design progress for EIC strong hadron cooling", in *Proc. IPAC'21*, Campinas, SP, Brazil, May 2021, pp. 1424–1427. doi:10.18429/JACoW-IPAC2021-TUPAB036

[6] 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

[7] W.F. Bergan *et al.*, "Design of an MBEC cooler for the EIC", in *Proc. IPAC'21*, Campinas, SP, Brazil, May 2021, pp. 1819–1822. doi:10.18429/JACoW-IPAC2021-TUPAB179

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

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

[10] Z. Huang *et al.*, "Measurements of the linac coherent light source laser heater and its impact on the x-ray free-electron laser performance", *Phys. Rev. Spec. Top. Accel. Beams*, vol. 13, no. 2, pp. 020703, 2010. doi:10.1103/PhysRevSTAB.13.020703

[11] A.V. Fedotov, D.Kayran, S. Seletskiy, "Accelerator physics requirements for electron cooler at the EIC injection energy", presented at COOL'23, Montreux, Switzerland, Oct. 2023.