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ELECTRON ION COLLIDER STRONG HADRON COOLING INJECTOR AND ERL

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Abstract

Intra-beam Scattering (IBS) and other diffusion mechanisms in the EIC Hadron Storage Ring (HSR) degrade the beam emittances during a store, with growth times of about 2 hours at the nominal proton energies of 275 GeV, 100 GeV, and 41 GeV. Strong Hadron Cooling (SHC) can maintain good hadron beam quality and high luminosity during long collision stores. A novel cooling method – Coherent electron Cooling (CeC) – is chosen as the baseline SHC method, due to its high cooling rates. An Energy Recovery Linac (ERL) is used to deliver an intense high-quality electron beam for cooling. In this paper, we discuss the beam requirements for SHC-CeC and describe the current status of the injector and ERL designs. Two designs of injector and ERL will be presented: one for dedicated SHC and another one for SHC with precooler.

INTRODUCTION

The Electron-Ion collider(EIC) is the next nuclear facility in the US to be constructed at Brookhaven National Laboratory, collaborating with Thomas Jefferson Laboratory. It aims to deliver high current, high polarization electron, and polarized proton beams for a high luminosity collision to study nucleon structures. In the Hadron Storage Ring (HSR), the intra-beam scattering and other diffusion mechanisms such as the beam-beam effect can degrade the hadron beam emittance during a collision. To maintain the hadron beam quality for long collision runs, we need to cool the hadron beam. SHC will boost EIC luminosity by a factor of 3–10. The requirements for the EIC cooler is following:

1. Cool the proton beam at 275 GeV, 100 GeV, and 41 GeV.
2. The cooling time shall be equal to or less than the diffusion growth time from all sources.
3. Must cool the hadron beam normalized RMS vertical emittance from 2.5 µm (from injector) to 0.3 µm in 2 hours.
4. The cooling section must fit in the available IR space

The current baseline of the EIC project is using a novel cooling method -Coherent electron Cooling(CeC) to cool the 275 GeV and 100 GeV hadron beam [1]. We name a cooling technique that provides a strong cooling rate at high energies as strong hadron cooling (SHC). We also plan to use electron cooling to cool the initial hadron emittance at 24 GeV and possibly extend to cool the hadron beam at 41 GeV of collision energy. The SHC-CeC was proposed in reference [2] and several amplifier mechanisms are developed later [3]. It can be considered as a variant of stochastic cooling with the bandwidth raised from GHz RF frequency to tens THz optical frequency since we use electron beam as a signal instead of using cables and amplifiers. We choose one using a combination of drift with one-quarter of plasma oscillation length and a chicane micro-bunching amplifier as our EIC SHC baseline design as shown in Fig. 1.

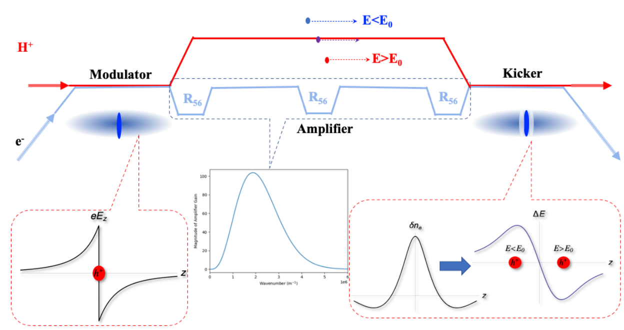

Figure 1: Schematic layout of SHC-CeC.It consists of a modulator, amplifier, and kicker section. The detailed explanations of the three sections can be found in [3]. The bottom figures show the hadron particle wake, amplification section gain, and micro-bunching electron wake.

A 1-D cooling code based on quasi-1D theory has been developed. Simulation results provide information on the saturation of the amplified cooling signal [4]. We simulate turn-by-turn hadron performance, and the interplay between cooling, diffusion, and IBS in longitudinal and transverse directions [5]. Currently, we use this code to optimize the cooling parameters. Table 1 shows the optimal electron parameters in the cooling section.

SHC needs a high-quality electron beam with a high current, small energy spread, and small noise in the beam. The noise of the electron beam shall be less than a factor of 2 of the Poisson noise at around the electron wake frequency. The cooling section lattice design and ERL considerations are discussed in Ref [6]. In this paper, we mainly discuss the injector and ERL designs.

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Table 1: SHC-CeC Electron Beam Parameters and Cooling Rate in Three Directions

Case	100 GeV	275 GeV
ebeam Energy (MeV)	55	150
ebeam Norm. Emit. (mm·mrad)	2.8	2.8
Rep. rate (MHz)	98.5	98.5
ebeam Bunch Charge (nC)	1	1
ebeam Peak Current (A)	8.5	17
ebeam Bunch Length (mm)	14	7
ebeam Slice σ_δ	10^{-4}	10^{-4}
Hor./Vert. Elec. β in M (m)	86.6 / 14.1	64/ 11
Hor./Vert. Elec. β in K(m)	49.7 / 10	16 / 2
Modulator Length (m)	55	55
Kicker Length (m)	55	55
H/V/L Diffusion Time (hr)	2.0/4.0/2.5	2.0/5.0/2.9
H/V/L Cooling Time (hr)	1.3/2.5/1.7	0.9/2.4/1.3

ACCELERATOR DESIGN I: DEDICATED SHC

The CW electron beam is generated by a High Voltage Direct Current (HVDC) photo gun. The bunch length is compressed by the balletic compress and then boosts the beam up to 5.6 MeV in the injector by SRF cavities. A dogleg with a dual-solenoid merger brings a beam into the LINAC that consists of eight fundamental frequency cavities together with four third harmonic cavities. A chicane and a dechirp cavity provide an extra knob to tune the bunch length to the desired value for different cooling energies. The electron beam is then transported to the 55 meters long modulator section and the 70 meters long amplification section, which includes three R56 tunable chicanes and quadruple triplets. Once the electron beam signal is sufficiently amplified, it merges into a 55 meters long kicker section.

Electron Source

We use a >400 kV DC gun with $K(Na)_2CsSb$ photocathode as the electron source to produce a 1 nC bunch charge with the repetition rate of 98.5 MHz and less than 2 mm·mrad of normalized emittance. Such high charge, high current, and high brightness electron guns haven't been demonstrated. One challenge of the electron source is to obtain one week lifetime. The power of a 10-20 watts laser can overheat the cathode and degrade the cathode's quantum efficiency(QE). We have designed and demonstrated cathode cooling with coolant through the high voltage feedthrough and maintaining the cathode at room temperature for EIC polarized gun [7] as one of the EIC R&D projects, the gun was designed to achieve 550 kV with a normalized emittance of about 1.1 mm·mrad and 10 Ampere peak current.

Injector and ERL Merger

The injector includes a bunching section and an energy booster section (see Fig. 2). The ballistic compression consists of 197 MHz normal conducting buncher and 2.5 meters drift which compresses the bunch length by a factor of three at 400 keV. Then the beam energy is boosted to 5.6 MeV by a 1.8 cell 591 MHz SRF cavity, and a single cell 1773 MHz cavity is used to reduce the energy spread caused by the 591 MHz RF curvature.

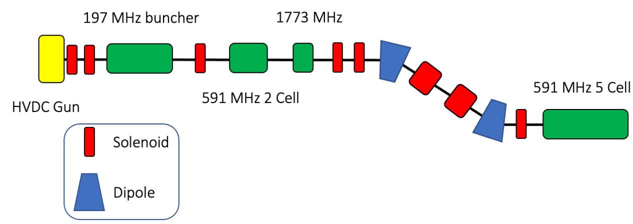

Figure 2: The layout of the injector.

The ERL merger consists of an achromatic arrangement of two dipoles and two solenoids and brings the beam into the Linac section. We use Chevron dipoles that have focusing in both directions. The two solenoids are tuned to keep dispersion zero after the merger. To merge high-energy electrons with energies of 149.77 MeV, 54.46 MeV, or 22.33 MeV, we place a three-dipole chicane before the last merger dipole at the return beamline. The three energies' electron beams trajectories can be merged into the LINAC as shown in Fig. 3. We use GPT 3.4 with a multi-objective optimization code

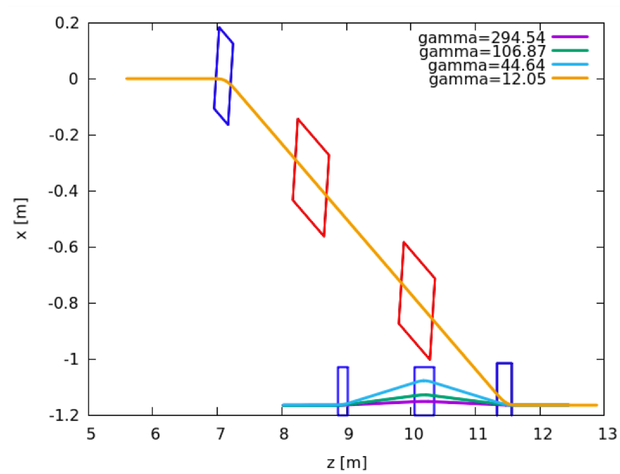

Figure 3: The lattice layout of the ERL merger. Blue boxes are dipole magnets and red boxes are the solenoids. It also shows four energies' of beam trajectories through the merger section.

to design the injector and merger. The goal is to minimize the energy spread and emittance at the exit of the 1st Linac where the x/y emittance is frozen. The normalized transverse emittance is about 2.1 mm·mrad before getting into the merger and increases up to 2.8/3.2 mm·mrad at the exit of 1st Linac. The emittance increase is due to the longitudinal space charge in the merger. Reducing the peak current and increasing bunch length will reduce the emittance, but increase the energy spread. To simplify the setup, we fully compressed the bunch length at the injector to the cooling required length.

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Linac and Bunch Stretching Section

The LINAC consists of eight 5-cell 591 MHz SRF cavities and four 1774 MHz SRF cavities. The electron bunch is on the crest to get maximum acceleration. Each 591 MHz cavity in its cryomodule provides 20 MV accelerating gap voltage. The 3rd harmonic, 1774 MHz SRF cavities with 8 MV gap voltage reduce the 1st pass beam energy and improve the bunch longitudinal linearity. At the exit of the last LINAC, we can get rms transverse emittance of 3.3 mm·mrad. The RMS σ_δ is 1.1×10^{-4} and the slice σ_δ is 5×10^{-5}. The longitudinal phase space is shown in Fig. 4.

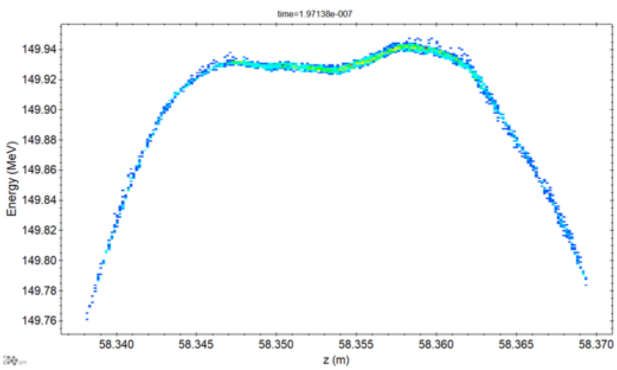


Figure 4: The bunch longitudinal phase space at the entrance of the cooling section. The head and tail of the bunch energy drop are caused by the RF .

The Linac section optics are computed using field tracking, and matched to a realistic incoming beam in the first pass, using BMAD. The 2nd pass beam loses the energy at 591 MHz cavities and gains the energy from the 1773 MHz cavities. In-between the cryomodules, there are doublet quads to match both 1st and 2nd pass beam as shown in Fig. 5.

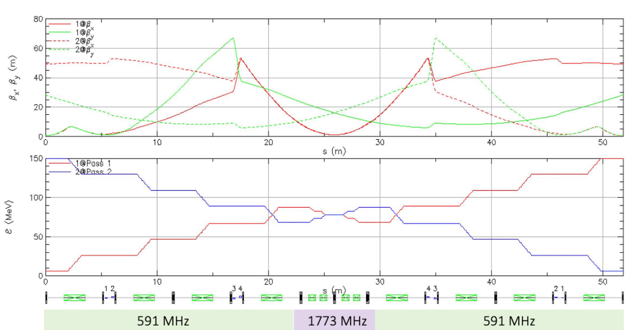
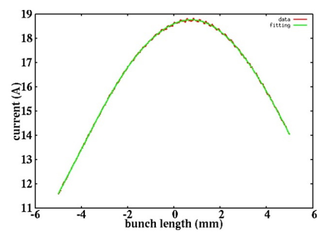


Figure 5: Two-pass ERL optics. The top figure shows the x, and y beta function of two passes beam, and the bottom one shows the two passes beam energy changes along the linac.

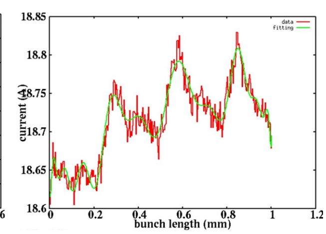
Table 1 shows that for 100 GeV cases, the optimal RMS bunch length is 14 mm. However, limited by the 591 MHz LINAC, we cannot generate long bunches while attaining the required energy spread. The bunch stretch section consists of R_{56} of 180 mm chicane and a dechirper cavity. The electron beam peak current can be reduced down to 8.5 A. By applying reversed chirp, we also can use the bunch stretch section as a compress section to increase the peak current. It gives an extra knob to find the optimal bunch length for 275 GeV.

Beam Noise Simulation

Because the CeC highly relies on the microbunched beam quality, it is essential to generate a very low noise beam before entering into the modulation section. The initial Poisson noise is generated in the electron source. Then, several mechanisms can enhance the unwanted microbunching gain such as coherent synchrotron radiation(CSR), and longitudinal space charge. We use the code IMPACT to track the beam from the gun to the cooling entrance using a full number of particles-6.25 billion [8, 9]. A random distribution of initial particles is generated from the cathode, and goes through the optics, as described above. The initial RMS relative current fluctuation is 4.67×10^{-4}.



(a) Bunch current along the full bunch length. The green curve is polynomial fitting.



(b) current along 1 mm bunch length. The modulation frequency is about 280 µm

Figure 6: The beam current at the end of the Linac

Figure 6 shows the beam current along the bunch length at the end of Linac. We observed an 280 µm modulation which is caused by the longitudinal space charge in the injector and Linac. The CeC amplifier gain frequency is < 5 µm. Removing the 280 µm modulation, the rest current fluctuation is about 7.5×10^{-4} which is comparable to the shot noise. We also observed the 280 µm modulation's relative current fluctuation amplitude is only twice the shot noise. Therefore, this modulation will not affect the cooling performance.

ACCELERATOR DESIGN II: SHC AND PRECOOLER HYBRID ERL

In the EIC baseline design, SHC is used for balancing the hadron IBS and diffusion to maintain the emittance in collision at 275 GeV and 100 GeV. The injection emittance and 41 GeV hadron have to be cooled by an electron cooler. Limited by the existing RHIC tunnel space, the SHC and precooler have to share the same cooling space. We consider that the SHC and Precooler have similar beam quality requirements such as bunch charge 1 nC versus 1.33 nC; normalized emittance 3 µm versus 2 µm; and relative energy spread 1e-4 versus 5e-4. We propose to combine the SHC and Precooler using the same ERL. Figure 7 shows the schematic layout of a hybrid ERL integrated SHC and precooler.

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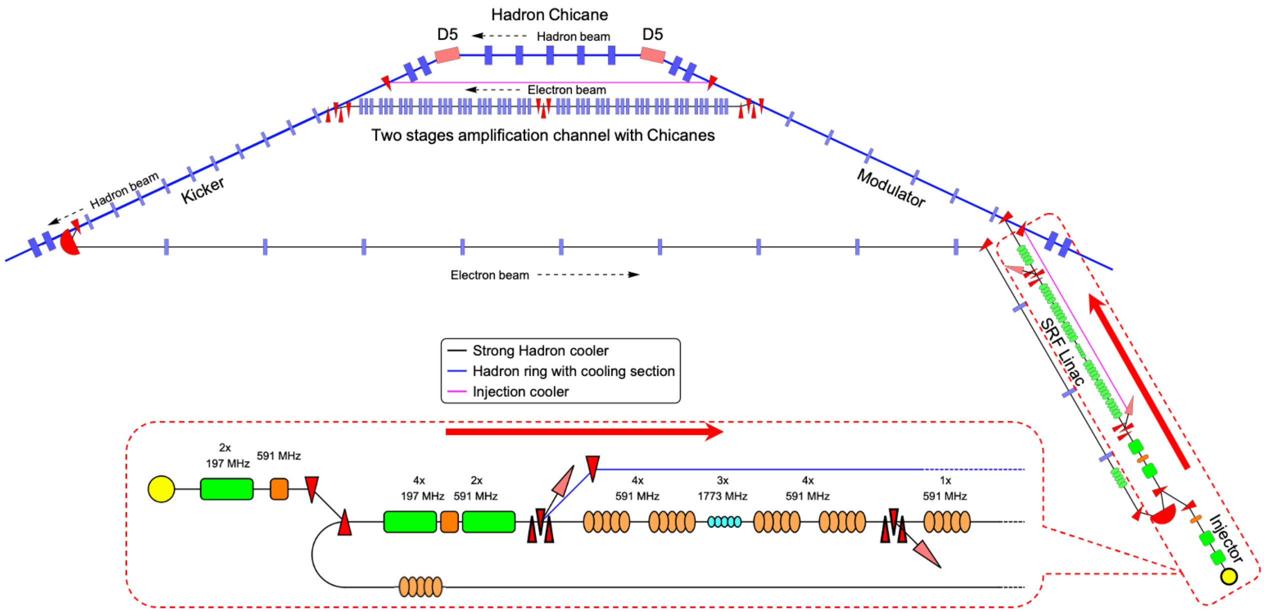

Figure 7: The schematic layout of a hybrid ERL with SHC and precooler. The bottom figure shows the detail of the injector and Linac section. The blue boxes are quadrupole magnets and red triangles are the dipole magnets

To get a small energy spread for precooler, we use 197 MHz SRF cavities as main Linac up to 14 MeV. For SHC, we leverage 197 MHz cavities' large longitudinal acceptance, boost the beam energy up to 14 MeV with energy chirp, then compress the bunch length by the factor of 3 using chicane. Then the electron beam goes through the 591 MHz Linac section, which is the same as the dedicated SHC design. At the entrance of the 1st chicane, the beam can be kicked out for the precooler. There is a beam dump upstream of the chicane to dump the precooler beam. Once the hadron beam's initial emittance is achieved, then the hadron beam will be boosted and operate in collision mode. The electron beam goes through the 591 MHz cavities for the SHC-CeC. The recovery beam will be dumped before the 2nd chicane as shown in Fig. 7.

Injector Design and ERL Merger

In this design, we will not compress the beam at 400 keV at the injector. 100 ps long beer-can distribution beam is generated from the HVDC gun. A single cryomodule consisting of two of 197 MHz quarter-wave resonator and a single cell 591 MHz cavity as shown in Fig. 8 is used for accelerating beam energy to 5.6 MeV which is same as the last design. We assume each 197 MHz cavity's gap voltage is 2.9 MV. Thus, we can use the same ERL merger. The beam is nearly on the crest of 197 MHz cavities with off-phase $< 0.2°$ to compensate for the longitudinal phase space caused energy chirp. A 3rd harmonic cavity(591 MHz) is placed after the 197 MHz cavity to linearize the bunch longitudinal phase space. At the end of the injector, the RMS normalized emittance is 1.57 mm·mrad with an RMS bunch length of 17 mm. At the exit of the ERL merger, the RMS normalized emittance is 1.88 mm·mrad. The emittance growth is much smaller than the 1st design, due to the lower peak current.

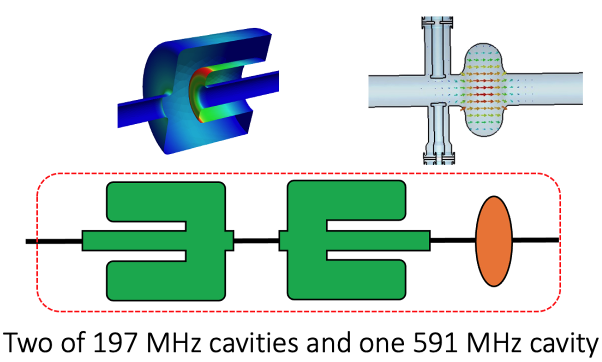

Figure 8: Two of 197 MHz cavities and one cell 591 MHz cavity in a single cryomodule.

Linac and Bunch Compression

We use two cryomodules, each containing two 197 MHz quarter-wave resonators and a single cell 591 MHz cavity. Similar to the injector cryomodule as shown in Fig. 8, but needs much lower power through the couplers due to energy recovery. The bunch is placed on 30° off the crest of 197 MHz cavity to generate 1.8% of RMS σ_δ energy chirp. A four-dipole chicane with R56=0.48 m compresses the bunch length from 17 mm to 7 mm, which is SHC-CeC's required bunch length. The 591 MHz Linac setup is similar to the dedicated SHC Linac. We placed 1.2° of the off-crest to remove the chirp generated in 197 MHz cavity. At the end of the linac, the RMS normalized transverse emittance is 2.5 mm·mrad, and slice σ_δ is about 2×10^{-5} as shown in Fig. 9. The peak current is 25% lower, which will

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help to reduce the longitudinal space charge. Table 2 shows the beam quality comparison of dedicated SHC design and SHC/precooler hybrid design. The latter one shows clearly an improvement in the beam quality.

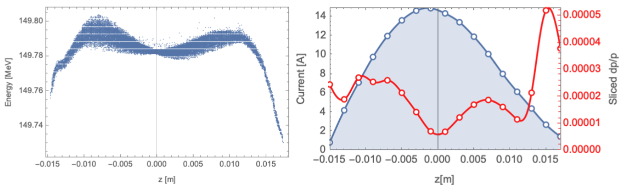


Figure 9: The left figure shows the bunch longitudinal phase space at the entrance of the cooling section. The right figure shows the current along the bunch and slices σ_δ.

Table 2: Electron Beam Parameters before Merging into Proton Beamline

Parameters	SHC only	SHC+precooler
Bunch charge [nC]	1	
Energy [MeV]	150	
$\varepsilon_{n\_x,y}$ [mm·mrad]	3.1 / 2.8	2.4 / 2.5
RMS σ_δ	1.1×10^{-4}	4×10^{-5}
Slice σ_δ	5.3×10^{-5}	2×10^{-5}

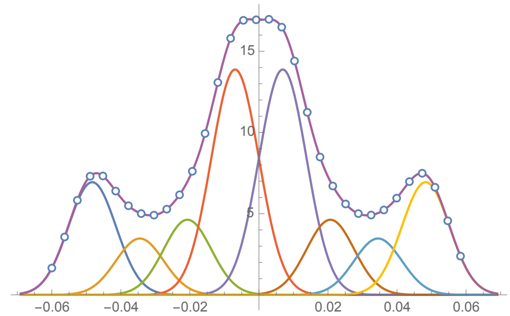
Another potential advantage of compressing the beam using chicane, rather than ballistic compression is that it is possible to generate super-Gaussian distribution as Eq. (2).

$$f(x) = ae^{-\{\frac{x^2}{2\sigma^2}\}^p} \tag{1}$$

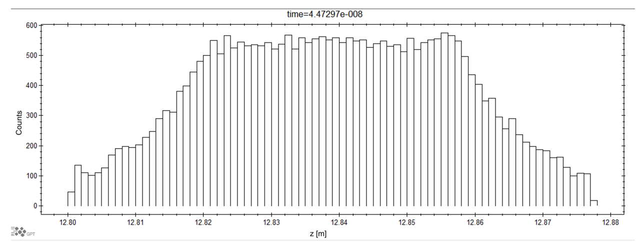
$$a = \frac{p}{\sqrt{2}\sigma\Gamma(\frac{1}{2p})} \tag{2}$$

Both Fig. 4 and Fig. 9 shows a Gaussian-like distribution at the entrance of the cooling section. Generating a more uniform current along the bunch can increase the cooling rate and may eliminate the bunch stretch session by reducing the total bunch length. The longitudinal laser shaping will be needed to generate the super gaussian beam at the end. The laser longitudinal shape can be varied by symmetric eight micro gaussian pulses, thus, four variables-Gaussian amplitude can be used for optimization as shown in Fig. 10a. The goal is set by the current mean square error at the RMS bunch length range to be a minimum. Figure 10b shows the beam current along the bunch length at the exit of the 197 MHz cavities in the Linac. Supergaussian fitting shows $p \simeq 1.9$, but normalized emittance increased to 4.3 mm·mrad due to the high peak current inside the gun.

The four dipoles chicane may cause the issue of the 1st pass beam and 2nd pass beam difference time of flight due to the different trajectories. We designed a chicane for a low-energy beam and placed a small three-dipole chicane in between the four dipoles to control the time of flight. Adding two quads on the high energy beam path to match on transverse direction. Figure 11 shows a lattice design to make 14 MeV, 40.4 MeV, and 135.7 MeV have the same time of flight.



(a) Laser longitudinal shaping using eight Gaussian micro pulses



(b) The beam current along the bunch at the exit of 197 MHz cavities in Linac

Figure 10: Beam current distribution using laser shaping

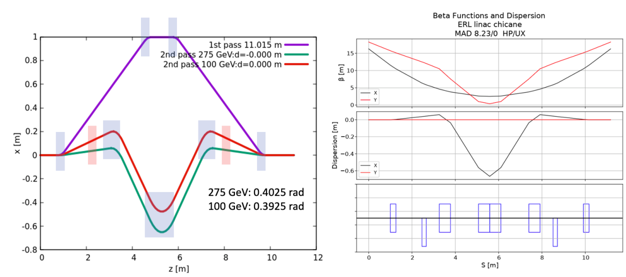


Figure 11: The Linac chicane lattice.

CONCLUSION

SHC will boost EIC luminosity by a factor of 3–10. We designed one version of injector and Linac for dedicated SHC and another version of injector and Linac for hybrid SHC and precooler. Both designs show the beam quality can meet the SHC requirement. The beam noise, longitudinal laser shaping, and using chicane in Linac have been well studied. The further study will focus on addressing high current ERL challenges.

REFERENCES

[1] F. Willeke, “Electron-Ion Collider Conceptual Design Report 2021”, doi:10.2172/1765663

[2] V. Litvinenko and Y. Derbenev, “Coherent Electron Cooling”, *Phys. Rev. Lett.*, vol. 102, p. 114801, 2008. doi:10.1103/PhysRevLett.102.114801

[3] G. Stupakov and P. Baxevanis, “Microbunched electron cooling with amplification cascades”, *Phys. Rev. Accel. Beams*, vol. 22, p. 034401, Mar. 2019. doi:10.1103/PhysRevAccelBeams.22.034401

ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-MO2AA04

[4] W. F. Bergan, "Plasma Simulations for an MBEC Cooler for the EIC", in *Proc. IPAC'21*, Campinas, Brazil, 2021, pp. 1823–1826. doi:10.18429/JACoW-IPAC2021-TUPAB180

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

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

[7] E. Wang *et al.*, "High voltage dc gun for high intensity polarized electron source", *Phys. Rev. Accel. Beams*, vol. 25, p. 033401, Mar. 2022. doi:10.1103/PhysRevAccelBeams.25.033401

[8] J. Qiang, R. D. Ryne, S. Habib, and V. Decyk, "An Object-Oriented Parallel Particle-in-Cell Code for Beam Dynamics Simulation in Linear Accelerators", *J. Comput. Phys.*, vol. 163, pp. 434-451, 2000. doi:10.1006/jcph.2000.6570

[9] J. Qiang, S. Lidia, R. D. Ryne, and C. Limborg-Deprey, "Three-dimensional quasistatic model for high brightness beam dynamics simulation", *Phys. Rev. ST Accel. Beams*, vol. 9, p. 044204, 2006. doi:10.1103/PhysRevSTAB.9.044204